**PROPOSED FINAL
ENVIRONMENTAL STATEMENT**

**LIQUID METAL
FAST BREEDER REACTOR
PROGRAM**

VOLUME IV

DECEMBER 1974

U.S. ATOMIC ENERGY COMMISSION

MASTER

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ENVIRONMENTAL STATEMENT

LIQUID METAL FAST BREEDER REACTOR PROGRAM

VOLUME IV

Volume I	Section 1	Summary
	Section 2	Background
	Section 3	LMFBR Program
Volume II	Section 4	Environmental Impact of the LMFBR Fuel Cycle
	Section 5	Economic, Social and Other Impacts
Volume III	Section 6	Alternative Technology Options
VOLUME IV	SECTION 7	MITIGATION OF ADVERSE ENVIRONMENTAL IMPACTS:
	SECTION 8	UNAVOIDABLE ADVERSE ENVIRONMENTAL IMPACTS
	SECTION 9	SHORT TERM BENEFITS AND LONG TERM LOSSES
	SECTION 10	IRREVERSIBLE AND IRRETRIEVABLE COMMITMENTS OF RESOURCES
	SECTION 11	COST-BENEFIT ANALYSIS
Volume V	Appendix	Comment Letters 1-25 and Responses
Volume VI	Appendix	Comment Letters 26-38 and Responses
Volume VII	Appendix	Comment Letters 39-66 and Responses

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EDITORIAL NOTE

This Environmental Statement has been prepared in seven volumes, each containing one or more Sections, the titles of which are listed on the flyleaf. A Table of Contents is contained in each volume and a summary is provided in front of each Section. The outline and contents of the Statement generally follow the subject coverage required by the National Environmental Policy Act (NEPA) of 1969.

VOLUME I contains a summary of the entire Environmental Statement and background information on the U.S. energy economy, the LMFBR Program and the relationship between the two. It includes discussion of the past, current and projected uses of energy and its importance to society, and describes the role of electricity, including that produced by nuclear reactors, in helping to meet the Nation's energy requirements. This volume also summarizes the origins and history of the LMFBR Program and provides a brief discussion of the several experimental and special purpose fast reactors that have been built in the United States since the late 1940's. Volume I also reviews the fast reactor programs in other industrialized nations. A discussion of the current U.S. LMFBR program is offered which highlights the important program planning mechanisms, the key reactor plants now under design and construction, and the various supporting studies on LMFBR costs, technology, environmental impacts, and program planning. This volume lays the background for examination of the environmental characteristics of the LMFBR.

VOLUME II describes the direct environmental impact of each element of the LMFBR fuel cycle. It examines the power reactors, fuel fabrication plants and fuel reprocessing plants that make up the LMFBR fuel cycle and discusses for each the siting considerations, plant characteristics, effects on the environment from construction and normal operation, and environmental monitoring programs that together entail a complete environmental evaluation. Volume II also includes an evaluation of the potential environmental impacts of various types of accidents in the facilities comprising the LMFBR fuel cycle. In addition, this volume examines the transportation of radioactive materials between these facilities and the management of radioactive wastes produced in LMFBR activities, and analyzes in detail the properties of plutonium and its behavior in the environment, and the resulting health effects. Extensive supporting data are provided in the appendices to Volume II. The volume concludes with an examination of the related sociopolitical impacts of the LMFBR.

VOLUME III examines individually the various alternative technologies, nuclear as well as nonnuclear, that might be utilized in conjunction with or instead of the LMFBR to satisfy the Nation's future electric power requirements. The options considered include the further implementation of various types of nuclear power reactors such as

the already existing Light Water Reactor and High Temperature Gas-Cooled Reactor, as well as the development of alternative breeder reactors such as the Gas-Cooled Fast Reactor, Light Water Breeder Reactor and Molten Salt Breeder Reactor. The development of another potential nuclear energy system, controlled thermonuclear fusion, is also addressed. The possibilities of increased emphasis on the use of conventional fossil fuels, namely coal, oil and natural gas, and the development of unconventional fossil fuels such as oil shale and domestic tar sands are discussed next, followed by consideration of the further development of additional nonnuclear energy sources such as hydroelectric power systems, geothermal energy, solar energy, and other potential sources of power. Each option is examined as to the extent of its energy resource base, the research and development program that would be required (if any) to bring the option into commercial use, the environmental implications of its utilization and the costs and benefits associated with its use, in order to assess its capability for satisfying projected energy requirements. This volume also discusses the use of improved energy conversion and storage devices such as gas turbines, fuel cells and magnetohydrodynamics, and concludes with an examination of the various elements of a potential national effort in energy conservation to assess their capabilities for reducing projected energy demands and thereby replacing partially or entirely the need for additional power sources such as the LMFBFR.

VOLUME IV provides a broad overview of the many implications of LMFBFR program implementation, up to and encompassing a fully developed LMFBFR power plant economy, including the secondary impacts, the unavoidable adverse environmental impacts, cumulative environmental impacts, and cost-benefit analyses, and also discusses alternative energy strategies. Under the heading of secondary impacts, it examines the national implications of the availability of electricity from LMFBFRs, and the specific economic impacts of the LMFBFR program. This volume also discusses the currently feasible alternatives and potential future alternatives for mitigating adverse environmental impacts of the LMFBFR fuel cycle, and in this context analyzes the problems of safeguarding special nuclear material from potential diversion to unauthorized purposes. Also covered in Volume IV are the cumulative environmental effects of LMFBFR operation to the Year 2020, the decommissioning of LMFBFRs and fuel cycle facilities upon the completion of their useful life, the irreversible and irretrievable commitments of resources that will accompany implementation of an LMFBFR economy, and an analysis of the costs and benefits of implementing the LMFBFR Program.

VOLUMES V - VII contain copies of all formal comments received on the Draft Statement and copies of the AEC's replies. Where appropriate, these comments have been identified and discussed in the text, and are further identified by footnotes indicating the letter and page number in which the comment appears. Finally, Volume VII includes information concerning the public hearing held on April 25-26, 1974.

ALPHABETICAL LIST OF ABBREVIATIONS,
SYMBOLS AND ACRONYMS USED IN THE STATEMENT

A	ampere	cm ³	cubic centimeter
AC	alternating current	Co	cobalt
ACRS	Advisory Committee on Reactor Safeguards	Cs	cesium
ADU	ammonium diuranate	CO	carbon monoxide
AEC	Atomic Energy Commission	CO ₂	carbon dioxide
AEC-RL	AEC - Richland Operation	DC	direct current
AI	Atomics International	DF	decontamination factor
AMAD	activity median aerodynamic diameter	DOD	Department of Defense
ANL	Argonne National Laboratory	DOP	dioctyl phosphate
ANPO	Aircraft Nuclear Propulsion Office	DOT	Department of Transportation
ARHCO	Atlantic Richfield Hanford Company	DTPA	diethylenetriaminepentaacetic acid
AWSF	Alpha Waste Storage Facility	diam.	diameter
Ag	silver	EBR-I	Experimental Breeder Reactor - I
Am	americium	EBR-II	Experimental Breeder Reactor - II
As	arsenic	EEI	Edison Electric Institute
Ar	argon	EHV	Extra High Voltage
Avg.	average	EIAP	Environmental Impact Assessment Project
BEIR	Biological Effects of Ionizing Radiation (Committee)	EIS	Environmental Impact Statement
Btu	British thermal unit	EPA	Environmental Protection Agency
BRC	Breeder Reactor Corporation	Eu	euporium
BWR	boiling water reactor	°F	degrees Fahrenheit
B&W	Babcock and Wilcox	FBI	Federal Bureau of Investigation
Bi	bismuth	FEA	Federal Energy Agency
Br	bromine	FHA	Federal Housing Administration
CCD	counter-current digestion (ore leach process)	FFTF	Fast Flux Test Facility
CE	Combustion Engineering	FPC	Federal Power Commission
CEA	Commissariat à l'Énergie Atomique	ft	foot (feet)
CEQ	Council on Environmental Quality	ft ²	square feet
CIA	Central Intelligence Agency	ft ³	cubic feet
CF	Confinement factor	Fe	iron
CFR	Code of Federal Regulations	GAC	Gulf Atomic Corporation
CRBR	Clinch River Breeder Reactor	GAO	General Accounting Office
CTR	Controlled Thermonuclear Reactor	GCFR	Gas Cooled Fast Reactor
CWP	Coal worker's pneumoconiosis (black lung)	GE	General Electric Company
Cf	californium	GI	gastro-intestinal
cfs	cubic feet per second	GNP	gross national product
°C	degrees Centigrade	GW	gigawatt
Ci	curie	GWe	gigawatt electric
C	carbon (carbide)	GWt	gigawatt thermal
Ca	calcium	g	gram
Ce	cerium	gal	gallon
Cm	curium	gpd	gallon per day
cm	centimeter	gpm	gallon per minute
cm ²	square centimeter	H	hydrogen
		H-3	tritium
		HCDA	hypothetical core disruptive accident
		HEDL	Hanford Engineering Development Laboratory

HEPA	high efficiency particulate air (filter)	MPC	maximum permissible concentration
HEW	Health, Education and Welfare (Dept. of)	MSBE	Molten Salt Breeder Experiment
HF	hydrogen fluoride	MSBR	Molten Salt Breeder Reactor
HPOF	high pressure oil filled (cable)	MT	metric ton (tonne)
HTGR	High Temperature Gas Reactor	MTU	metric ton of uranium (metal)
HVDC	high voltage direct current	MUF	material unaccounted for
hr.	hour	MW	megawatt
I	iodine	MWd	megawatt-day
IAEA	International Atomic Energy Agency	MWe	megawatt electric
ICC	Interstate Commerce Commission	MWt	megawatt thermal
ICRP	International Commission on Radiological Protection	m	meter
ID	inside diameter	m ²	square meter
IRAP	Interagency Radiological Assistance Program	m ³	cubic meter
in	inch (es)	mCi	millicurie (10 ⁻³ curie)
K	potassium	μCi	microcurie (10 ⁻⁶ curie)
Kr	krypton	MCi	megacurie (10 ⁶ curies)
Kv	kilovolt	μm	micrometer
k eff	effective multiplication constant	mg	milligram
kCi	kilocurie (1000 curies)	min	minute
kg	kilogram	ml	milliliter
km	kilometer	mph	miles per hour
kV	kilovolt	Mn	manganese
kW	kilowatt	mrem	millirem
kWe	kilowatt electric	NASA	National Aeronautics and Space Administration
kWhr	kilowatt-hour	NAS-NRC	National Academy of Sciences - National Research Council
kWt	kilowatt thermal	NEPA	National Environmental Policy Act
LASL	Los Alamos Scientific Laboratory	NFS	Nuclear Fuel Services
LAMPRE	Los Alamos Molten Plutonium Reactor Experiment	NGSF	Noble Gas Storage Facility
LE	limit of error	NRDC	Natural Resources Defense Council, Inc.
LET	linear energy transfer	NRTS	National Reactor Test Station
LLL	Lawrence Livermore Laboratory	NSF	National Science Foundation
LNG	liquid natural gas	NSSS	nuclear steam supply system
LMFBR	Liquid Metal Fast Breeder Reactor	Nb	niobium
LOCA	loss of coolant accident	Np	neptunium
LSA	low specific activity	NO ₂	nitrogen dioxide
LWBR	Light Water Breeder Reactor	NO _x	oxides of nitrogen
LWR	Light Water Reactor	nCi	nanocurie (10 ⁻⁹ curie)
l	liter	OD	outside diameter
lb	pound	OMB	Office of Management and Budget
Max	maximum	OP	oxygen pressure process (ore leach process)
MeV	million electron volts	ORNL	Oak Ridge National Laboratory
MHD	magnetohydrodynamics	PCRv	prestressed concrete reactor vessel
MIT	Massachusetts Institute of Technology	PMC	Project Management Corporation
		PNL	Pacific Northwest Laboratory
		PSAR	Preliminary Safety Analysis Report
		P&W	Pratt and Whitney
		PWR	Pressurized Water Reactor
		pCi	picocurie (10 ⁻¹² curie)

ppb parts per billion
 ppm parts per million
 psi pounds per square inch
 psia pounds per square inch, absolute
 psig pounds per square inch, gauge
 Pb lead
 Pm promethium
 Pu plutonium
 PuO₂ plutonium dioxide
 °R degrees Rankine
 R Roentgen
 R&D research and development
 RSSF Retrievable Surface Storage Facility
 rpm revolutions per minute
 Rb rubidium
 Ru ruthenium
 SAR Safety Analysis Report
 SEFOR South-East Fast Oxide Reactor
 SIPI Scientist's Institute for Public Information
 SNG synthetic natural gas
 SNM special nuclear material
 SRE Sodium Reactor Experiment
 STP standard temperature and pressure
 SWU separative work unit
 scfm standard cubic feet per minute
 sec second
 sq. ft. square feet
 Sb antimony
 Sr strontium
 SO₂ sulfur dioxide

SO_x oxides of sulfur
 TEG thermoelectric generator
 TFE thermionic fuel element
 TGLM task group lung model (ICRP)
 TVA Tennessee Valley Authority
 TVR Tennessee Valley Region
 Te tellurium
 Tonne metric ton
 U uranium
 UHV ultra high voltage
 UMRB Upper Mississippi River Basin
 UO₂ uranium dioxide
 U₃O₈ black oxide of uranium
 UF₆ uranium hexafluoride
 UNSCEAR United Nations Scientific Committee on the Effects of Atomic Radiation
 USAEC United States Atomic Energy Commission
 USGS United States Geological Survey
 W watt
 We watt electric
 WEP water extended polyester
 WLM working-level month
 wt.% weight percent
 w/o without
 Xe xenon
 Y yttrium
 yr year
 Zr zirconium

CONTENTS FOR VOLUME IV

7. MITIGATION OF ADVERSE ENVIRONMENTAL IMPACTS

<u>Section</u>	<u>Page</u>
SUMMARY	7S-1
7.1 INTRODUCTION	7.1-1
7.2 CURRENTLY FEASIBLE ALTERNATIVES	7.2-1
7.2.1 LMFBR Power Plants	7.2-1
7.2.2 Fuel Fabrication Plants	7.2-3
7.2.2.1 Construction	7.2-3
7.2.2.2 Operation	7.2-3
7.2.3 Fuel Reprocessing Plants	7.2-3
7.2.4 Transportation	7.2-4
7.2.4.1 Routing	7.2-4
7.2.4.2 Lower Radiation Levels Outside of Packages	7.2-5
7.2.4.3 More Stringent Accident-Damage Test Criteria ..	7.2-5
7.2.5 Radioactive Waste Management	7.2-5
7.2.5.1 High-Level Waste Management - Retrievable Surface Storage Facility	7.2-5
7.2.5.2 Other-Than-High-Level Waste Management	7.2-6
7.2.6 Plant Siting Concepts	7.2-7
7.2.6.1 Introduction	7.2-7
7.2.6.2 Offshore Floating Plant Concepts	7.2-7
7.2.6.3 Offshore Island Concept	7.2-12
7.2.6.4 Nuclear Energy Centers	7.2-14
7.2.6.5 Underground Siting Concepts	7.2-15
7.3 POTENTIAL FUTURE ALTERNATIVES	7.3-1
7.3.1 LMFBR Power Plants	7.3-1
7.3.2 Fuel Fabrication Plants	7.3-1
7.3.3 Fuel Reprocessing Plants	7.3-2
7.3.4 Transportation	7.3-3
7.3.5 Radioactive Waste Management	7.3-7
7.3.5.1 Disposal on Earth	7.3-9
7.3.5.2 Transmutation Concepts	7.3-13
7.3.5.3 Extraterrestrial Disposal Concepts	7.3-14
7.3.5.4 Geologic Disposal Pilot Plant	7.3-15
7.4 SAFEGUARDS.....	7.4-1
7.4.1 Introduction	7.4-1
7.4.2 Safeguards Objectives and Program Elements	7.4-3
7.4.3 The Nature of the Threat	7.4-4
7.4.3.1 Description of the Threat	7.4-6
7.4.3.2 Implication for LMFBR	7.4-8
7.4.4 Related Problem Areas	7.4-9
7.4.4.1 Vulnerability to Acts of War	7.4-9
7.4.4.2 Sub-National Diversion in Other Countries	7.4-13
7.4.5 Consequences of Successful Acts	7.4-15
7.4.5.1 Consequences of Successful Theft or Diversion .	7.4-15
7.4.5.2 Consequences of Successful Sabotage	7.4-19

CONTENTS (Continued)

<u>Section</u>	<u>Page</u>
7.4.6 Safeguards Aspects of LMFBR and Other Fuel Cycles	7.4-30
7.4.6.1 The LMFBR Fuel Cycle	7.4-30
7.4.6.2 The LWR and HTGR Fuel Cycles	7.4-34
7.4.6.3 Other Reactor Concepts	7.4-39
7.4.7 Description of the Current AEC Safeguards Program	7.4-41
7.4.7.1 Licensing Activities	7.4-42
7.4.7.2 Safeguards Requirements for Fixed Facilities ..	7.4-43
7.4.7.3 Safeguards Requirements for SNM In Transit	7.4-45
7.4.7.4 Inspection and Enforcement	7.4-46
7.4.7.5 Response to Theft or Sabotage	7.4-51
7.4.7.6 Adequacy of the Current AEC Safeguards System .	7.4-51
7.4.8 Future AEC Safeguards	7.4-54
7.4.8.1 The Future Structure of AEC Safeguards	7.4-54
7.4.9 Costs of Future Safeguards	7.4-64
7.4.9.1 General Framework for Analysis	7.4-66
7.4.9.2 Description of LMFBR Reference Module and Associated Safeguards	7.4-66
7.4.9.3 Estimated Costs of Safeguarding Reference LMFBR Fuel Cycle Module	7.4-78
7.4.9.4 Possible Changes in LMFBR Fuel Cycle to Improve the Effectiveness or Decrease the Costs of Safeguards	7.4-80
7.4.9.5 Comparative Costs of Safeguarding LMFBR and Alternative Nuclear Power Systems	7.4-83
7.4.9.6 Comparative Costs of Safeguarding the U.S. Projected Nuclear Power System in 2020, With and Without the LMFBR	7.4-89
7.4.9.7 Alternative Ways For Paying the Costs of Safeguards	7.4-91
7.4.10 Conclusions	7.4-92
REFERENCES FOR SECTION 7	7.4-94

8. UNAVOIDABLE ADVERSE ENVIRONMENTAL IMPACTS OF THE LMFBR

SUMMARY	8S-1
8.1 INTRODUCTION	8.1-1
8.2 FUEL CYCLE ENVIRONMENTAL IMPACT	8.1-1
8.2.1 LMFBR Power Plant	8.1-1
8.2.2 LMFBR Fuel-Fabrication Plant	8.2.3
8.2.3 LMFBR Fuel-Reprocessing Plant	8.2-4
8.2.4 Transportation	8.2-5
8.2.5 Radioactive Waste Management	8.2-5
8.3 RADIOACTIVE IMPACTS NORMALIZED FOR ONE REACTOR-YEAR	8.3-1
8.4 NON-RADIOLOGICAL IMPACTS NORMALIZED FOR ONE REACTOR-YEAR	8.4-1

CONTENTS (Continued)

<u>Section</u>	<u>Page</u>
9. POTENTIAL RELATIONSHIPS BETWEEN SHORT-TERM ENVIRONMENTAL BENEFITS AND LONG-TERM ENVIRONMENTAL LOSSES BROUGHT ON BY IMPLEMENTING THE LMFBR PROGRAM	
SUMMARY	9S-1
9.1 CUMULATIVE ENVIRONMENTAL EFFECTS TO THE YEAR 2020	9.1-1
9.1.1 Introduction	9.1-1
9.1.1.1 Projected Use of Electric Energy	9.1-2
9.1.1.2 Basis for Comparison of Electrical Power Generation Methods	9.1-11
9.1.2 Waste Generation and Disposal	9.1-11
9.1.2.1 Heat	9.1-11
9.1.2.2 Radioactive Wastes	9.1-16
9.1.2.3 Nonradioactive Wastes	9.1-22
9.1.3 Radiological Implications	9.1-22
9.1.3.1 Annual Dose from Nuclear Facilities	9.1-26
9.1.3.2 Dose Commitment from One Year's Exposure	9.1-31
9.1.3.3 Environmental Buildup of Radionuclides	9.1-32
9.1.3.4 Cumulative Population Dose	9.1-36
9.1.4 Effects on Local Ecosystems and Land Use	9.1-36
9.1.5 Plutonium Considerations	9.1-40
9.1.6 Transmission Lines and Corridors	9.1-40
9.1.7 Transportation Aspects	9.1-41
9.1.8 Health and Safety Considerations	9.1-41
9.1.8.1 Occupational Safety	9.1-41
9.1.8.2 Public Safety	9.1-45
9.1.8.3 Occupational Health	9.1-45
9.1.8.4 Public Health	9.1-45
9.1.9 Demographic Effects	9.1-51
9.1.10 Energy Conservation	9.1-51
9.1.11 Overall Impact to the Year 2020	9.1-52
References for Section 9.1	9.1-62
9.2 DECOMMISSIONING	9.2-1
9.2.1 LMFBR Power Plants	9.2-1
9.2.2 LMFBR Fuel-Cycle Facilities	9.2-5
References for Section 9.2	9.2-7
10. IRREVERSIBLE AND IRRETRIEVABLE COMMITMENTS OF RESOURCES	
SUMMARY	10S-1
10.1 NATURAL AND OTHER RESOURCES	10.1-1
10.1.1 Introduction	10.1-1
10.1.2 Land Resources	10.1-1
10.1.3 Water and Air Resources	10.1-2
10.1.4 Material Resources	10.1-2
10.1.4.1 Fuel	10.1-3
10.1.4.2 Construction Materials	10.1-3
10.1.4.3 Consumable Materials	10.1-8

CONTENTS (Continued)

<u>Section</u>	<u>Page</u>
10.2 MANPOWER RESOURCES	10.2-1
10.2.1 Introduction	10.2-1
10.2.2 Manpower Directly Applied to LMFBR Facilities	10.2-1
10.2.2.1 Power Stations	10.2-1
10.2.2.2 Other Facilities and Transportation	10.2-6
10.2.3 Indirect Manpower	10.2-8
10.2.3.1 Nuclear Manufacturing Industry	10.2-8
10.2.3.2 Personnel Education and Training Requirements	10.2-8
10.2.3.2 Government Personnel	10.2-9
10.2.4 Perspective on Manpower Projections	10.2-10
10.3 FINANCIAL COMMITMENTS	10.3-1
References for Section 10	10.3-3
11. COST-BENEFIT ANALYSIS OF IMPLEMENTING THE LMFBR PROGRAM	
SUMMARY	11S-1
11.1 FORMULATION OF THE COST-BENEFIT ANALYSIS	11.1-1
11.1.1 Introduction	11.1-1
11.1.2 Alternatives to the LMFBR	11.1-7
11.1.2.1 Alternative Technologies and Energy Sources ...	11.1-7
11.1.2.2 Alternative Strategies for Future Electric Generation Systems	11.1-22
11.1.3 Environmental Cost-Benefit Analysis of the LMFBR-External Costs	11.1-27
11.1.3.1 Cumulative External Impacts of Alternative Strategies of Electric Energy Supply	11.1-27
11.1.3.2 Cumulative Human Effects	11.1-29
11.1.3.3 Fuel Resource Requirements	11.1-29
11.1.3.4 Discussion of Overall Impacts	11.1-31
11.2 ECONOMIC COST-BENEFIT ANALYSIS OF THE U.S. BREEDER REACTOR PROGRAM	11.2-1
11.2.1 Introduction	11.2-1
11.2.1.1 Summary of Benefits	11.2-2
11.2.1.2 Basic Input Data and Assumptions	11.2-5
11.2.1.3 Results	11.2-15
References for Section 11.2.1	11.2-31
11.2.2 LMFBR Program Costs	11.2-32
11.2.3 Method of Calculation and Major Assumptions	11.2-41
11.2.3.1 Method of Calculation	11.2-41
11.2.3.2 Discount Rate	11.2-46
11.2.3.3 Electric Energy Demand	11.2-53
11.2.3.4 Capacity Factors for Generating Plants	11.2-60
11.2.3.5 Constraint on Reactor Capacity Introduced	11.2-60
11.2.3.6 Mass Balance and Reactor Performance	11.2-65
11.2.3.7 Uranium Cost Versus Supply	11.2-67
11.2.3.8 Capital Costs	11.2-78

CONTENTS (Continued)

<u>Section</u>	<u>Page</u>
11.2.3.9 Plant Operating and Maintenance Costs	11.2-94
11.2.3.10 Fuel-Cycle Component Charges and Times Required for Fuel-Cycle Steps	11.2-94
11.2.3.11 Uranium Enrichment (Separative Work)	11.2-96
11.2.3.12 Fossil Fuel Costs	11.2-101
11.2.4 Results of Updated Cost-Benefit Study	11.2-104
11.2.4.1 Range of Parameters Considered	11.2-104
11.2.4.2 Details of Benefit Analysis	11.2-110
11.2.5 The Logic of Cost-Benefit Models as Related to Utility Planning Methods	11.2-184
11.2.5.1 A Utility View of the LMFBR	11.2-185
11.2.5.2 Economics of the LMFBR in 1990	11.2-189
11.2.5.3 Cost Reductions for Plants Built Before 1990 ..	11.2-193
11.3 CONCLUSION	11.3-1

APPENDICES

Appendix IV.A RECENT AEC SAFEGUARDS REVIEWS	IV.A-1
Appendix IV.B LMFBR ADVANCED DESIGN CONCEPTS	IV.B-1
IV.B.1 Advanced Core Design	IV.B-1
IV.B.1.1 Fuel	IV.B-5
IV.B.1.2 Core Specific Power	IV.B-6
IV.B.1.3 Doubling Time	IV.B-7
IV.B.2 Advanced Fuels and Materials Development	IV.B-10
IV.B.2.1 Core Structural Materials Development	IV.B-11
IV.B.2.2 Advanced Fuel Materials Development	IV.B-12
Appendix IV.C SUMMARY OF LMFBR ADVANTAGES	IV.C-1
Appendix IV.D DETAILED RESULTS OF LMFBR COST-BENEFIT CALCULATIONS	IV.D-1

VOLUME IV

LIST OF TABLES

7. MITIGATION OF ADVERSE ENVIRONMENTAL IMPACTS

<u>Table</u>		<u>Page</u>
7.4-1	Damage Radii for Various Effects of Nuclear Explosions as Functions of Yield	7.4-18
7.4-2	Estimated Radioactivity Releases to Environment Resulting From Hypothetical Sabotage of Unprotected LMFBR Packages (Current Design)	7.4-27
7.4-3	Materials Present in LMFBR Fuel Cycle	7.4-33
7.4-4	Materials Present in LWR Fuel Cycle (with Pu Recycle)	7.4-36
7.4-5	Materials present in HTGR Fuel Cycle	7.4-40
7.4-6	Inspection of Licensees	7.4-48
7.4-7	Event Table	7.4-55
7.4-8	Characteristics of LMFBR Reference Fuel Cycle Module (Fixed Facilities)	7.4-69
7.4-9	Characteristics of LMFBR Reference Fuel Cycle Module (Transportation Link)	7.4-71
7.4-10	Annual Shipments in 80,000 MW(e) LMFBR Module - Summary	7.4-72
7.4-11	LMFBR Module Costs (Excluding Safeguards Costs)	7.4-73
7.4-12	Capital Costs of LMFBR Safeguards Equipment	7.4-75
7.4-13	Safeguards Security Personnel for LMFBR Module	7.4-77
7.4-14	LMFBR Module Safeguards Cost Summary	7.4-79
7.4-15	Comparisons of LMFBR, LWR, and HTGR 80,000-MWe Modules	7.4-84
7.4-16	Security Personnel for Safeguarding Different 80,000-MWe Modules	7.4-85
7.4-17	Costs of Safeguarding Different 80,000-MWe Modules (millions of 1974 dollars)	7.4-87
7.4-18	Costs of Safeguards for Alternative Reactor Mixes, 2020	7.4-90

8. UNAVOIDABLE ADVERSE ENVIRONMENTAL IMPACTS

8.3-1	Maximum Individual Doses Due to the LMFBR Fuel Cycle	8.3-2
8.3-2	Yearly Average Population Total-Body Doses Due the LMFBR Fuel Cycle	8.3-3
8.4-1	Nonradiological Impacts of LMFBR Fuel Cycle	8.4-2

9. POTENTIAL RELATIONSHIP BETWEEN SHORT TERM ENVIRONMENTAL BENEFITS AND LONG TERM ENVIRONMENTAL LOSSES BROUGHT ON BY IMPLEMENTING THE LMFBR PROGRAM

9.1-1	Capacity Contributions of Electrical Generation Peaking Facilities	9.1-2
9.1-2	Electrical Energy Usage of Various Conversion Techniques ...	9.1-12
9.1-3	Equivalent Process Heat Usage	9.1-15
9.1-4	Generation of Radioactive Wastes per Gigawatt-year	9.1-17
9.1-5	Accumulation of Transuranic Wastes	9.1-19
9.1-6	Representative Release Rates of Radioactive Elements	9.1-20
9.1-7	Selected Nonradioactive Waste Data	9.1-23
9.1-8	Summary of Year 2000 Study Results	9.1-25
9.1-9	Public Exposure to Radiation from Nuclear Fuel Cycles	9.1-27

LIST OF TABLES (Continued)

Table		Page
9.1-10	Occupational Exposure to Radiation	9.1-29
9.1-11	Land Use by Various Energy Conversion Techniques	9.1-38
9.1-12	Transportation Requirements for Various Fuel Cycles	9.1-42
9.1-13	Occupational Safety Aspects of Energy Conversion	9.1-43
9.1-14	Health and Safety Aspects of Electrical Energy Generation	9.1-44
9.1-15	Summary of Environmental Impact with LMFBR Present	9.1-46
9.1-16	Summary of Environmental Impact with LMFBR Not Present	9.1-53
9.1-17	Summary of Environmental Impact of LMFBR Program Through the Year 2020	9.1-58
10. IRREVERSIBLE AND IRRETRIEVABLE COMMITMENTS OF RESOURCES		
10.1-1	Fuel Requirements for a 1000-MWe LMFBR	10.1-4
10.1-2	Estimated Quantities of Composite Materials Contained in a Typical 1000-MWe LMFBR Power Plant	10.1-5
10.1-3	Estimated Basic Materials Used in Construction of a 1000-MWe LMFBR Power Plant and Comparison with Production, Uses, and Reserves of these Materials	10.1-6
10.2-1	Cumulative Generating Capacity - U.S. Central Station LMFBR Power Plant	10.2-3
10.2-2	Average Personnel Per Year for a 2 Unit LMFBR Station	10.2-7
10.2-3	Manufacturing Manpower Estimates	10.2-9
10.2-4	Population and Manpower Projections	10.2-10
11. COST-BENEFIT ANALYSIS OF IMPLEMENTING THE LMFBR PROGRAM		
11.1-1	Projected Contributions of Oil and Natural Gas to Total and Electrical Energy Consumption	11.1-8
11.1-2	Distribution of Energy Production	11.1-23
11.1-3	Energy Sources for Electricity Production in the Year 2000 Without the Breeder	11.1-24
11.1-4	Energy Sources for Electricity Production in the Year 2020 Without the Breeder	11.1-25
11.1-5	Base-Case Energy Source Distribution for Electric Energy Generation	11.1-25
11.1-6	Cumulative Human Impacts of Expanding Electrical Energy Supply (1974-2020)	11.1-30
11.1-7	Fuel Resources Committed for Electrical Generation	11.1-32
11.2-1	LMFBR Design Characteristics	11.2-14
11.2-2	Summary of Estimated LMFBR Program Costs	11.2-33
11.2-3	Detail of LMFBR Program Cost Projections (1975 thru 2020) LMFBR Introduction Date 1987	11.2-34
11.2-4	Average 1972 Electric Utility Cost of Capital	11.2-50
11.2-5	Fixed Charge Rate on Depreciable Capital	11.2-50
11.2-6	Fixed Charge Rate on Nondepreciable Capital	11.2-51
11.2-7	National Economic Energy Forecast	11.2-53
11.2-8	National Electric Generating Capacity Forecast	11.2-58
11.2-9	Typical Reactor Characteristics Assumed in Cost-Benefit Analysis	11.2-68
11.2-10	Estimated U.S. Uranium Resources	11.2-67
11.2-11	Projected U_3O_8 Price-Quantity Relationships	11.2-72

LIST OF TABLES (Continued)

<u>Table</u>		<u>Page</u>
11.2-12	Power Plant Capital Cost Estimates	11.2-79
11.2-13	Detailed Breakdown of Plant Capital Costs	11.2-80
11.2-14	Assumed Annual Operation Costs for Plants in Study	11.2-95
11.2-15	Fabrication and Reprocessing Costs (1974 Dollars) Generated with FUELCO	11.2-97
11.2-16	Fuel Cycle Times	11.2-98
11.2-17	Projected Coal Costs	11.2-103
11.2-18	Ranges of Conditions Considered in Cost-Benefit Study	11.2-105
11.2-19	Factors Contributing to LMFBR Benefits--LMFBR Introduction	11.2-120
11.2-20	Development of Breeder Benefits for Differing Introduction Dates	11.2-129
11.2-21	Summary of Effects of LMFBR Introduction Date on Benefits	11.2-131
11.2-22	Effects of HTGR Constraints on System Energy Costs in a Nonbreeder Economy	11.2-135
11.2-23	Effects of HTGR Capacity Constraints on LMFBR Benefits	11.2-137
11.2-24	Effects of Uranium Resource Availability of LMFBR Benefits (1987 LMFBR Introduction)	11.2-149
11.2-25	Effects of LMFBR Capital Costs on Benefits	11.2-156
11.2-26	Benefits (10% Discounted) for Uranium Resources	11.2-175
11.2-27	Benefits (7.5% Discounted) for Uranium Resources	11.2-175
11.2-28	Summary of Projected U.S. LMFBR Program Costs	11.2-177
11.2-29	Effective Rates of Return from LMFBR Program Implementation and Comparisons with Benefit/Cost Ratios (1987 LMFBR Introduction)	11.2-183
11.2-30	Base Cost Projection of U ₃ O ₈ Price Versus Cumulative Availability (Escalated to 199 at 4%/Year)	11.2-190
11.2-31	Price of U ₃ O ₈ Versus Time	11.2-191
11.2-32	Thirty-Year Levelized Fuel-Cycle Costs for Plants Built in 1990-1991	11.2-192
11.2-33	Summary of the Differences in Discounted 30-Year Power Costs for Plants Installed in 1990, Case 3 (With Breeder) Relative to Case 1 (No Breeder)	11.2-193

APPENDICES

IV.B-1	Typical LMFBR Reactor Characteristics	IV.B-2
IV.B-2	Advanced LMFBR Systems	IV.B-8
IV.B-3	Potential Improvements for Oxide Fuel LMFBR	IV.B-9
IV.D-1	Summary of Cost-Benefit Study Results Discounted at 10% to Mid-1974	IV.D-1
IV.D-2	Summary of Cost-Benefit Study Results Undiscounted	IV.D-6
IV.D-3	Summary of Cost-Benefit Study Results Discounted at 5% to Mid-1974	IV.D-11
IV.D-4	Summary of Cost-Benefit Study Results Discounted at 7.5% to Mid-1974	IV.D-16

LIST OF FIGURES

7. MITIGATION OF ADVERSE ENVIRONMENTAL IMPACTS

<u>Figure</u>		<u>Page</u>
7.2-1	Concept of Offshore Floating Plant - Shallow Water	7.2-9
7.2-2	Concept of Offshore Floating Plant - Deep Water	7.2-10
7.2-3	Concept of Underground Site - Competent Rock	7.2-16
7.2-4	Concept of Underground Site - Unconsolidated or Poorly Cemented Materials	7.2-19
7.3-1	An LMFBF Spent-Fuel Shipping-Cask Design	7.3-6
7.4-1	LMFBF Fuel Cycle	7.4-31
7.4-2	LWR Fuel Cycle	7.4-35
7.4-3	HTGR Fuel Cycle	7.4-38
7.4-4	Adversary Action Sequences	7.4-57
7.4-5	An Example Adversary Action Sequence and Associated Interruption Activities	7.4-59
7.4-6	Iterative Program for Safeguards Improvement	7.4-62
7.4-7	LMFBF Fuel Cycle Module	7.4-67

8. UNAVOIDABLE ADVERSE ENVIRONMENTAL IMPACTS OF THE LMFBF

No Figures in Section 8

9. POTENTIAL RELATIONSHIP BETWEEN
SHORT TERM ENVIRONMENTAL BENEFITS AND LONG TERM
ENVIRONMENTAL LOSSES BROUGHT ON BY IMPLEMENTING THE LMFBF PROGRAM

9.1-1	Projected Demand for Electrical Generating Capacity 1970-2020	9.1-3
9.1-2	Projected Central Station Capacity by Energy Source: 1970-2020	9.1-5
9.1-3	Projected Central Station Capacity by Energy Source Without the LMFBF; 1970-2020	9.1-6
9.1-4	Projected Utilization of Fossil Fuels for Generation of Electric Power 1970-2020	9.1-7
9.1-5	Projected Role of Natural Gas in the Electrical Generation Industry	9.1-8
9.1-6	Projected Use of Residual Fuel Oil in the Electrical Generation Industry	9.1-10
9.1-7	Projected Heat Rates of Various Energy Conversion Techniques	9.1-14
9.1-8	Average Airborne Tritium Concentrations in U.S.A.	9.1-33
9.1-9	Average Airborne Kr-85 Concentrations (not including recirculation) in U.S.	9.1-34
9.1-10	Average Airborne Concentration of Alpha-Emitting Transuranics in U.S.A.	9.1-35
9.1-11	Potential Use of Once-Through Cooling in the U.S., 1970-2000	9.1-39

LIST OF FIGURES (Continued)

Figure		Page
	10. IRREVERSIBLE AND IRRETRIEVABLE COMMITMENTS OF RESOURCES	
10.2-1	U.S. LMFBR Electric Power Plants - Annual Requirements for Plant Construction Workers	10.2-4
	11. COST BENEFIT ANALYSIS OF IMPLEMENTING THE LMFBR PROGRAM	
11.2-1	Dollar Benefits from the LMFBR	11.2-3
11.2-2	Interpretation of LMFBR Benefits	11.2-4
11.2-3	The Reduction in Electrical Power Cost Produced by the LMFBR by Major Category Discounted at 10%	11.2-6
11.2-4	Projected Nuclear Industry Growth Pattern	11.2-7
11.2-5	Projected Electrical Energy Requirements	11.2-9
11.2-6	Marginal Price of U ₃ O ₈ Versus Cumulative Supply	11.2-10
11.2-7	Reactor Capital Costs Versus Time	11.2-12
11.2-8	LMFBR Benefits in Billions of Dollars Using a Specified Construction Schedule with a 10% Discount Rate	11.2-16
11.2-9	Sensitivity of Dollar Benefits to Variations in the Basic Input Data with a 10% Discount Rate for 1987 LMFBR Introduction	11.2-17
11.2-10	Sensitivity of Dollar Benefits to Large Variations in Energy Demand and LMFBR Capital Cost with a Specified Construction Schedule	11.2-18
11.2-11	Sensitivity of Dollar Benefits to Large Variations in Energy Demand and LMFBR Capital Cost with No Construction Schedule	11.2-19
11.2-12	Cumulative U ₃ O ₈ Requirements	11.2-23
11.2-13	Maximum Annual Separative Work Requirement	11.2-24
11.2-14	Reactor Construction Rate	11.2-26
11.2-15	LMFBR Benefits as a Function of the Doubling Time with a 7-1/2% Discount Rate and Without a Construction Schedule ...	11.2-27
11.2-16	Effect of LMFBR on Capital Requirements for U.S. Power Systems	11.2-29
11.2-17	Effect of LMFBR on Power System Costs	11.2-30
11.2-18	Cost Benefit Analysis Economic Model	11.2-42
11.2-19	Load History Curves Assumed for Central Station Power Plants	11.2-61
11.2-20	Estimates of Uranium Availability from Geological Formations and Oceans in the U.S.	11.2-69
11.2-21	Separative Work Unit	11.2-100
11.2-22	Electrical Energy Projections Used in Study	11.2-107
11.2-23	Nuclear Capacity Projections Assumed in Study	11.2-108
11.2-24	Uranium Price--Availability Schedules Assumed for Study	11.2-109
11.2-25	Composition of the Nuclear Power Economy Without the LMFBR	11.2-111
11.2-26	Annual Rates of Nuclear Capacity Additions Without LMFBR	11.2-112
11.2-27	Composition of the Nuclear Power Economy with LMFBR	11.2-113
11.2-28	Annual Rates of Nuclear Capacity Addition with LMFBR	11.2-114
11.2-29	Effect of LMFBR Introduction Date on Nuclear System Composition	11.2-115

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
11.2-30	Effect of Nuclear--Fossil Competition on Nuclear System Capacity without LMFBR	11.2-117
11.2-31	Effect of Nuclear--Fossil Competition on Nuclear System Capacity with LMFBR	11.2-118
11.2-32	Accrual of Benefits from LMFBR Introduction	11.2-121
11.2-33	Benefits Variation with Conditions	11.2-124
11.2-34	Benefits Variation: Plant Mix and Fuel-Cycle Parameters (1987 Introduction)	11.2-125
11.2-35	Effects of LMFBR Benefits on Introduction Date for Different Assumptions of Uranium Resource Availability	11.2-127
11.2-36	Effects of Varying HTGR Capacity Restraints on HTGR Operating Capacity	11.2-139
11.2-37	Effects on Energy Demand Variations on LMFBR Benefits--Varying Introduction Dates	11.2-141
11.2-38	Sensitivity of Breeder Benefits to Energy Demand--1987 LMFBR Introduction	11.2-143
11.2-39	Effects of Breeder Introduction on Uranium Consumption	11.2-144
11.2-40	Effects of Breeder Introduction on Price of Uranium	11.2-145
11.2-41	Effects of Breeder Introduction on Separative Work Demand	11.2-152
11.2-42	Effects of LMFBR Capital Costs Differential on Benefits	11.2-157
11.2-43	Effects of Doubling Time on LMFBR Benefits	11.2-160
11.2-44	Effects of Doubling Time on LMFBR Uranium Consumption	11.2-161
11.2-45	Effects on LMFBR Cooling Time on Plutonium Availability	11.2-164
11.2-46	Effects of LMFBR Annual Fuel Cycle Utilization of Fissile Plutonium	11.2-167
11.2-47	Fissile Plutonium Production--Consumption Balance without LMFBR	11.2-169
11.2-48	Fissile Plutonium Production--Consumption Balance with LMFBR	11.2-170
11.2-49	Fissile Plutonium Production Consumption Balance without Carbide Fuel Availability--120 Day Cooling	11.2-171
11.2-50	Fissile Plutonium Production--Consumption Balance with 365-Day Cooling Review--Carbide Fuels Available	11.2-173
11.2-51	LMFBR Cost/Benefit Ratios (10% Discount)	11.2-179
11.2-52	Comparison of Benefit/Cost for Different Discount Rates	11.2-180

APPENDICES

No Figures in Appendix IV

VOLUME IV

SECTION 7

**MITIGATION OF ADVERSE
ENVIRONMENTAL IMPACTS**

SUMMARY FOR SECTION 7

Mitigation or elimination of adverse environmental impacts will be an important objective in the design, construction, and operation of individual LMFBR fuel cycle facilities and in the associated transportation operations. A number of facility design alternatives that appear to have potential for mitigation of adverse impacts are currently considered to be feasible. Decisions on use of these alternatives would be made during the planning, design, and licensing activities required for individual facilities. Other alternatives may be identified as a result of continued or newly-initiated research and development efforts leading to improved facility design features.

Currently feasible alternatives to reduce the environmental impact of the LMFBR are discussed in Section 7.2. These include the use of wet cooling towers for waste heat disposal and the recycle of chemicals at LMFBR fuel cycle facilities. Actions that might be taken to mitigate the environmental impact of shipping radioactive materials involve trade-offs, because reducing one impact or risk may lead to increasing another impact or risk for all actions considered. The use of nuclear energy centers, where feasible, would greatly reduce the impact of transportation for the fuel cycle operations and would alleviate potential problems in the safeguarding of nuclear fuel.

The retrievable surface storage facility water-basin concept has been selected as the reference design for high-level radioactive waste management for purposes of this Statement and represents proven technology. However, several alternative concepts for retrievable surface storage of solidified high-level waste are being considered. One alternative, the sealed-storage-container concept, provides for the canisters of solidified waste to be sealed in thick-walled steel cylinders, placed inside cylindrical concrete radiation shields, and stored in the open above ground. The containers would provide confinement and protection against natural forces and could serve as shipping containers for transfer of waste to an ultimate disposal site at a future date. This concept would use less water and electrical power than the water basin concept. It would, however, use 12 times as much steel, approximately 20 times as much concrete and about 10 times as much land.

Alternative nuclear power plant siting concepts are also discussed in Section 7.2. The principal nuclear power plant siting concept continues to be land-based, above ground siting. The principal alternative siting concepts discussed are underground siting, offshore floating plants, offshore island siting, and nuclear energy centers.

Potential future alternatives to reduce the environmental impact of the LMFBR are discussed in Section 7.3. These include the use of dry cooling towers for waste heat disposal and the recycle of liquids and gases at fuel fabrication and reprocessing plants.

When the AEC made the determination to use retrievable surface storage as the near-term technique for managing commercial high-level radioactive waste, it was recognized that while this approach is simple, straightforward and safe, it does impose a long-term requirement for surveillance and maintenance. Although this requirement for continued human action in no way reduces the safety of the surface storage approach to management of high-level radioactive waste, the development of equally safe and economically acceptable management techniques would eliminate or minimize this requirement. For this reason, an extensive program is being conducted to identify, evaluate, and possibly demonstrate alternate disposal techniques for potential future use.

The AEC's safeguards system provides protection against the illegal use of special nuclear material (SNM)* and other radioactive materials present in commercial fuel cycles. Potential illegal uses include fabrication of nuclear explosives or radiological weapons and sabotage of facilities or transport to create radiological incidents. Although the safeguards problem is not unique to the LMFBR, the introduction of the LMFBR would substantially increase the quantities of plutonium in commercial use.

Illegal use of SNM and other radioactive materials may be attempted by a variety of adversaries ranging from psychotic individuals acting alone to organized terrorist groups. Of these, the terrorist group is perhaps the most difficult to deal with, because it may embody all the attributes of other threats. Some understanding of the nature of potential terrorist threats can be gained from review of recent events. However, to characterize terrorist or other threats with certainty is not possible. Thus, the safeguards system must be designed to make its effectiveness as independent as practicable of the nature of the threat.

In considering the vulnerability of the LMFBR to acts of war, only an overt strategic attack is considered plausible. The consequences of a nuclear attack on facilities in the LMFBR fuel cycle would not add appreciably to the major destruction caused by the nuclear weapons involved in a massive strategic attack.

*Plutonium, U-233, or uranium enriched in U-235.

The threat of sabotage and nuclear materials diversion will no doubt exist in other countries. The U.S. has urged and will continue to press for the expansion and modification of foreign security measures, including physical security to preclude diversion, through our bilateral contacts and through the International Atomic Energy Agency.

The consequences of hypothetical illegal nuclear explosions are severe. Clearly, if an illicit device of even modest yield were cleverly placed and detonated before detection, thousands of people could be killed. Considering the sequence of goals that must be attained by an adversary (theft, conversion, weapon design and fabrication, emplacement, and successful detonation), the overall probability of successful explosion of an illicit weapon is extremely low. That such a weapon would be in the multikiloton range is doubtful. The AEC bases the design and implementation of its safeguards system on the premise that making an illicit nuclear explosive is within the range of skills and resources available to persons or groups operating outside the law.

The use of radiological weapons does not appear to be consistent with observed behavior of terrorists or extortionists. While this indicates a low probability of the attempted use of radiological weapons, the presumption of a finite probability, however small, is used as the basis for safeguards against the theft of materials with this potential.

The consequences of successful sabotage of LMFBR facilities are considered to be similar in magnitude to the consequences of accidents. Further analysis will be required to confirm this statement. Preliminary analysis of the consequences of sabotage of LMFBR materials in transport has been performed to provide early guidance toward the development of additional safeguards measures for the future.

The AEC safeguards program embodies a number of elements: development and imposition of safeguards requirements, inspection of safeguards implementation, research and development, and continuous review of the overall safeguards problem to assure that necessary changes are recognized and carried out. Within this general framework and working from the base provided by the present safeguards system, the AEC plans to take a systematic and comprehensive approach to the development of future safeguards. This approach, some elements of which have already been initiated, involves analysis of those actions that an adversary would have to accomplish to achieve his goals, and selection of a mix of countermeasures that will provide multiple opportunities to thwart these actions. The countermeasures will be required to assure

very low probability of successful completion for those sequences of actions leading to extremely severe consequences. A broad range of possible countermeasures will be considered, including facility co-location, facility and transport hardening, improved monitoring and communications systems, strengthened legal sanctions, and others. Preliminary projections on the nature and configuration of the future safeguards systems, as it would be applied to the LMFBR fuel cycle, have been made. The financial costs of such a system have been estimated to increase the projected cost of electrical power by about 1.4%.

The societal effect of a rigorous safeguards system will not be disruptive. Although the requirements imposed on the nuclear industry will likely require additional regulations, the portion of U.S. industry and the relative number of employees affected will be small. In any case, the relative impact of safeguards on society could only be assessed in the light of other societal changes that will or could arise. This reflects the fact that the safeguards problem is, in fact, the nuclear aspect of the overall national problem posed by an evident increase of violence and terrorist activities.

Clearly, many of the safeguards-related risks associated with the LMFBR will exist whether or not the LMFBR is fully exploited. Many of these risks will exist even if the U.S. were to abandon fission reactions as a source of energy. With full recognition of the need to provide adequate protection against the consequences of theft or sabotage involving nuclear materials, the Commission concludes that there is no safeguards-related reason to delay the further development of LMFBR.

7.1 INTRODUCTION

Mitigation or elimination of adverse environmental impacts will be an important objective in the design, construction, and operation of individual LMFBR fuel cycle facilities and in the associated transportation operations. As described in Section 4, a number of facility design alternatives that appear to have potential for mitigation of adverse impacts are currently considered to be feasible. Decisions on use of these alternatives would be made during the planning, design, and licensing activities required for individual facilities. Section 7.2 provides summary information on such currently feasible alternatives. Also addressed is the subject of alternative concepts for the siting of nuclear power plants, both currently feasible and potentially feasible alternatives, with emphasis on the possibilities for mitigation of adverse environmental effects.

Additional mitigation of adverse impacts associated with individual elements of the fuel cycle may be possible as the result of continued or newly initiated research and development efforts leading to improved facility design features. Section 7.3 describes a number of these facility design alternatives whose feasibility remains to be established and provides information on their potential benefits.

Finally, Section 7.4 addresses the various aspects of the special nuclear materials safeguards problem and describes the AEC program for assuring that unauthorized diversion or misuse of such materials is and will continue to be extremely unlikely.

7.2 CURRENTLY FEASIBLE ALTERNATIVES

7.2.1 LMFBR Power Plants

Many of the potential effects of construction activities can be reduced by appropriate selection of a site and by application of proper construction practices and controls. For example, a site on previously industrialized land, strip-mined land, or a former power plant site would not be subject to the effects that would be realized with a site on farm land or recreational land. Many techniques are known to minimize wind and water erosion of land. These include protecting the bare soil by restoring vegetation, covering with mulch, sprinkling, stabilizing with gravel, grading and shaping the spoil piles, scheduling the time that ground is disturbed to avoid critical periods such as spring thaw, conservation of topsoil to recover exposed subsoil, and others. Some of these same methods can be used to reduce dust raised by vehicles traversing exposed soil.

Impacts on a natural watercourse from dredging and installation of water intake and discharge structures can be kept to an acceptable level by several means, including scheduling of the work during low water periods, care in avoiding biologically sensitive areas such as spawning grounds, use of equipment appropriate to control dispersion of the bottom materials to be removed, and others.

As for all other steam-electric power plants, the major direct impacts from future LMFBR power plants result from the discharge of waste heat released in the condenser. This heat can be rejected either to natural bodies of water or directly to the atmosphere by use of alternative heat rejection systems (cooling ponds or cooling towers). The "best" system for a particular plant can be determined only after a study of the plant requirements, the environmental features of the site, the use of bodies of water, the expected environmental effects of each system, and the benefit-cost relationships.

The once-through system requires the largest supply of water. It is usually the most economic system with respect to cost and plant efficiency if acceptably low levels of environmental damage can be achieved. Most of the adverse effects can be reduced by withdrawing and rejecting much less water by the use of constructed cooling ponds or spray canals, separate from the natural watercourse. Cooling ponds require a large amount of land (up to 2000 acres for a 1000-MWe plant), whereas spray systems require much less land; but drift from the open sprays results in loss of water, carry over of dissolved salts onto adjacent land, and

icing on nearby vegetation and structures in winter time. None of these systems results in visual intrusion on the landscape as viewed from a distance.

Wet cooling towers, which also require withdrawal of less make-up water than once-through systems, intrude visually on the landscape; the large natural-draft towers much more so than mechanical-draft towers. The major impact of wet cooling towers results from the vapor plume emitted from the towers. This plume may extend several miles and be visible from great distances, depending upon weather conditions. Ground fog is a possible hazard within about 1/4 mile of mechanic-draft cooling towers, and some rime ice may deposit on structures and vegetation close to the towers in winter. Proper location of cooling towers with respect to highways, roads, airports, and other structures would mitigate such factors. Salts carried by drift droplets may be deposited on the ground and on vegetation near cooling towers but, except for saltwater-cooled systems, would not be expected to be harmful.

Chemical additives are currently used to prevent fouling and loss of capacity in heat dissipation systems that utilize water. Alternatively, mechanical methods for cleaning condensers are in service. Cooling towers would still require defouling with chemicals. Close control of the addition of such chemicals will mitigate their adverse effects. Other chemical wastes, such as those from regeneration of ion exchangers, could be disposed of in land disposal areas rather than discharging them to the waterways, if the latter is found to be harmful to the environment.

Losses of fish and other aquatic biota by impingement on water intake screens can be greatly minimized (but probably not eliminated entirely) by proper siting of the intake and selection of screening equipment and by control of waterflow patterns and velocities. Small organisms that pass through the screens will likely suffer damage in passing through the condenser; however, keeping transit time short and temperature rises less than 10°C (18°F) will do much to minimize the effects. The magnitude of both of these effects is determined by several factors, including the quantity of water passed through the cooling system.

The effects of thermal discharges on the biota of the receiving water depend on several factors, many of which can be controlled by appropriate site selection and by proper design and operation of equipment. Several alternative designs of discharge structures are in use today, and performance data are being evaluated to provide designers with information with which to make an optimum choice considering

the site, characteristics of the water body, and plant operating parameters. Losses of aquatic biota can be limited by the proper choice of equipment.

All currently feasible alternatives to limit the routine releases of radioactive material from LMFBR power plants are already incorporated in the model plant design.

7.2.2 Fuel-Fabrication Plants

7.2.2.1 Construction

Actions taken to mitigate the adverse environmental impact due to the construction of an LMFBR fuel-fabrication plant would be similar to those discussed in Section 7.2.1 for LMFBR power plants. All of the land areas disturbed during construction would be planted with grass, shrubs, or trees as appropriate to minimize the long-term impact on the environment.

7.2.2.2 Operation

An adverse impact (described in Section 4.3.5.3) associated with the operation of a fuel-fabrication plant was the release of small quantities of radioactive material in the liquid effluents. About 99% of the annual dose to individuals from the liquid effluents from the fuel-fabrication plant is due to the releases from the UO_2 section of the plant.

Although these releases are currently thought to be as low as practicable, additional waste treatment systems (e.g., an ion exchange operation to further reduce the uranium in the ADU process effluent, recycle of liquids, and evaporation of excess liquids) could be used to reduce the radioactive material released from the fuel-fabrication plant to 0.0001 or less of that described in Section 4.3.5.3.2.

Recycle of process liquids and evaporation of the excess water would also eliminate the release of aqueous solutions of NH_3 ; however, the dissolved NH_3 could also be substantially reduced by systems designed specifically for reclaiming the NH_3 for re-use in the process. Such technology is under development by manufacturers of LWR fuel. A 5-metric ton/day fuel-fabrication plant would require either such technology or siting where minimum river flows of at least 6000 cfs would be available in order to be within environmental standards (see Section 4.3.6.3.2).

7.2.3 Fuel Reprocessing Plants

Actions taken to mitigate the adverse environmental impacts due to construction of

LMFBR fuel-reprocessing plants would be similar to those discussed in Section 7.2.1 for LMFBR power plants.

Means are currently available and being developed by which the rate of emission of radioactive particulates and nitrogen oxides can be reduced. The emission rates for these materials were judged to be as low as practicable on the basis of conservative estimates of current technology (see Section 4.4.4). In any event, the release of particulates can be reduced by addition of even more stages of HEPA filters. The release of nitrogen oxides can be reduced by increasing the pressure and residence time in the scrubbers, if necessary. These alternatives might be considered in overall plant designs for LMFBR fuel-reprocessing plants.

7.2.4 Transportation

As noted in Section 4.5, primary reliance for safety in the transportation of radioactive material is placed on the packaging, which must meet applicable federal and state regulatory standards (see Appendix II.M). Most shipments of radioactive materials move in routine commerce via conventional transportation equipment. Therefore, shipments are subject to the same transportation environment, including accidents, as nonradioactive cargo. Although a shipper may impose some conditions on his shipment, such as speed limitations or providing an escort, most of the conditions to which his shipment is subjected and the probability of his shipment being involved in an accident are not subject to his control. The public and transport workers are protected from radiation during the shipment of radioactive materials by the container designs and limitations on the contents. The limitations are set according to the quantities and types of radioactivity and to the standards and criteria for package design and control.

A number of actions that, in some cases, might mitigate the environmental impact of shipping radioactive materials, have been considered. In most cases, this appears to be a trade-off. That is, by taking some of these actions, one significant risk or impact might be reduced, but other similar risks or impacts might be increased. Some examples of such trade-offs are given in the following paragraphs.

7.2.4.1 Routing

Routes for shipping radioactive material could be required to be selected so as to avoid centers of population, special risk areas due to local road or rail

conditions, areas of high accident frequency, extremes in ambient conditions such as very cold or very hot weather, high elevations, and delays. In many cases, such restrictions could reduce the probability of an accident occurring and reduce the probable damage. However, if the shipping distances were increased to avoid the conditions, the number of accidents per shipment might be increased. Examination of local conditions would be required in each case to determine whether such restrictions would be advantageous or not.

7.2.4.2 Lower Radiation Levels Outside of Packages

Heavier packaging with additional shielding can be designed and built, and by reducing the amount of radioactive material in a package, the radiation levels outside the package can be reduced. The weight of casks of present designs is approaching the limits of the available handling and transport facilities. Extra package weight means a smaller number of packages per vehicle, which would mean more shipments or a shift from truck to rail transport. More shipments would be required if the content of present packages were reduced. Increasing the number of shipments increases the total number of accidents.

7.2.4.3 More Stringent Accident-Damage Test Criteria

The radiological risk due to accidents that involve packages of radioactive material might be reduced by imposing more stringent accident-damage test criteria on package designs. However, increasing the severity of the test conditions might require heavier or larger packaging designs to meet the criteria. Extra weight of packaging could reduce the ratio of weight of radioactive contents to package weight. Larger and heavier packages, in many cases, would mean a smaller number of packages per vehicle and would increase the number of shipments from an individual reactor. Increasing the number of shipments would increase the total number of accidents.

7.2.5 Radioactive Waste Management

7.2.5.1 High-Level Waste Management--Retrievable Surface Storage Facility

Several alternative concepts for retrievable surface storage of solidified high-level waste are being considered.* These concepts are based on an enclosed basin (or

*Regarding the retrievable surface storage facility, NRDC stated in their letter of April 29, 1974:

The AEC's short-term plans for a near-surface storage facility is inaccurately put forward as a potential satisfactory "permanent" storage scheme.

As discussed in Sections 4.6 and 7.3.5, permanent storage schemes are considered as distinct from the interim storage techniques discussed in this section.

vault) type of storage with air- or water-cooling of the waste. The water-basin concept (Section 4.6.3.1.2) was selected as the reference design for this Statement and represents technology comparable to that which has already been reduced to practice.

One alternative to the water-basin concept is the sealed-storage-cask concept (Section 4.6.3.1.3), which provides for the canisters of waste to be sealed in thick-walled steel containers and stored inside cylindrical concrete radiation shields in the open above ground. The casks would provide containment and protection against natural forces and may serve as shipping containers for transfers of waste to an ultimate disposal site at a future date. The sealed-cask facility would provide safe storage at a cost comparable to the water basin facility and would use one-tenth as much water and one-fourth as much electrical power as the water basin facility. It would, however, use 12 times as much steel, approximately 20 times as much concrete, and about 10 times as much land. No massive concrete vaults, continuous mechanical cooling systems, or emergency backup facilities would have to be provided.

Another alternative to the water-basin facility is the air-cooled vault facility (Section 4.6.3.1.4) in which the waste canisters would be sealed inside another 1/2-in.-thick steel container and placed inside concrete vaults to be cooled by natural-draft convection. Such a facility would also provide safe storage at a cost comparable with that of the water-basin facility. Water and electrical use requirements would be significantly less than the water-basin facility but about the same as the sealed-cask facility. It would use about six times as much steel and approximately three times as much concrete as the water-basin facility. Final decommissioning would be somewhat more difficult than for the water-basin facility if it required dismantling the concrete vaults. There would be no radiation shielding problem.

7.2.5.2 Other-Than-High-Level Waste Management

An alternative to the commercial burial grounds (Section 4.6.3.2.1) for the other-than-high-level waste materials* would be a storage vault to contain these wastes in a manner similar to the retrievable surface storage facility for high-level waste. A principal difference, however, would be that the other-than-high-level waste would require no cooling facilities. Compared with burial, this method would be

*Other than bottled noble gases or alpha wastes.

considerably more expensive but probably not a serious burden to the nuclear power industry. More importance would be attached to concentrating and compacting the waste in the event this type of storage is used. Also, more consideration would be given to high-integrity, long-lasting containers. The waste storage area would be more compact than in the case of the land burial facilities and, consequently, less land area would be required for storage. Whether or not a significant reduction in radiation hazard would result has not been established. However, present use of commercial burial grounds is thought to be quite adequate for other-than-high-level waste and will not foreclose the use of alternative disposal methods should future decisions be made in that regard.

7.2.6 Plant Siting Concepts

7.2.6.1 Introduction

The principal power plant siting concept continues to be that developed through the years--the land-based above ground concept. This concept has also been used for the model LMFBF and is described in considerable detail in Section 4.2.2.

A number of alternative siting concepts have been proposed for various reasons. Any alternative siting concept must be measured against certain general requirements that need to be met by all sites. Section 4.2.2 includes a discussion of site-specific factors such as seismology, hydrology, geology, meteorology, population density, and use characteristics of the site environs.

The general discussion that follows is only a rough assessment of siting alternatives because of the multitude of site-specific characteristics that must be considered. Detailed evaluations can only be done on a case-by-case basis.

7.2.6.2 Offshore Floating Plant Concepts

The offshore floating plant concept for power plant siting, in which the plant is mounted on a floating platform and moored a few miles from the shoreline, offers several advantages by opening up a great many new sites for consideration and providing a potential for locating plants closer to coastal load centers. Plants sited offshore in thermally stratified water would be able to withdraw cooling water from the colder lower layers and discharge the heated effluent on the surface at a temperature very near that of the natural surface water. Also, in the pre-fabricated plants, disturbances at the shoreline during construction are minimized.

For units moored in shallow water, as shown in Figure 7.2-1, a conventional nuclear power plant is mounted on a floating platform and moored within a breakwater surrounding the plant and creating the basin in which the plant floats. The basic plant design is the concept proposed by Offshore Power Systems* and requires water depths of at least 44 ft for the 31-ft platform draft and for tide changes and storm surges. As depths are increased, the breakwater costs increase substantially. The shallow water concept may involve placement closer than three miles from shore. Siting such a plant only one mile from shore could require a longer discharge pipe, perhaps 3300 ft rather than the 1000 ft assumed for other offshore designs, but this is still substantially shorter than the roughly 8500-ft length that would be required of shoreline plants to reach a location permitting adequate dispersion of the heated effluent. Multiple plant sites and multiple units in one breakwater offer some economies of scale.

Layout of the facilities on the platform involves location of the containment near the center and arrangement of the other structures to properly distribute the weight. Generally the buildings on the platform are similar to those at land-based plants. The platform would be divided into a number of watertight compartments.

The breakwater communicates with the open sea so that the plant's circulating water is taken from the basin inside the breakwater and is discharged to the sea. The mooring system, circulating water discharge, and electrical power connections accommodate movement of the plant due to tides, winds, and other environmental phenomena.

The sequence of manufacture of this facility would be as follows. Fabricated members would be assembled into a complete platform structure in a graving dock where other equipment and structures within the platform would also be installed. The platform would then be launched from the graving dock and moved through a series of erection and outfitting stations where the plant is built on the platform in stages. The final station would be for testing of systems and equipment. Nuclear fuel loading would be done after the plant has been towed to the owner's site for installation within the breakwater.

An alternative approach, which could be used for mooring in deep water (see Figure 7.2-2), would be to arrange the major buildings in a long narrow configuration and to package the entire facility within the hull of a ship, similar to a large ocean-

*Westinghouse-Tenneco joint venture.

7.2-9

CONCEPT OF OFFSHORE FLOATING PLANT - SHALLOW WATER

Figure 7.2-1

7.2-10

CONCEPT OF OFFSHORE FLOATING PLANT - DEEP WATER

Figure 7.2-2

going tanker.* The ship could be towed to the desired location and moored in place in the same manner as large bulk oil carriers utilizing heavy-duty deep-water mooring terminals. Many of these terminals are designed to hold 300,000-ton ships fast in 18-ft waves and 56-knot winds. A similar concept has been evaluated for a floating nuclear seawater desalination/electric power generating station in 150 to 2000 ft of water.

With the exception of the concrete hull, fabrication and operation of this system may be within the present state of the art, including subsystems and equipment, large tanker hull, and deep-water mooring designs. However, omnidirectional ocean currents and severe sea state conditions complicate the tanker-mooring system design, making it more costly to provide in some offshore areas. On the other hand, this facility could be easily relocated to a different site and might even be moved to shore for major modifications, if required.

Some equipment for this concept would have to be specially designed in sizes to withstand motions to which the vessel will be subjected. Also, demonstration would likely be required to show that the systems can safely function and be shut down under adverse sea conditions. Perhaps the principal disadvantage of such a facility is the absence of a protective breakwater which increases the risk of collision with other vessels. Whether a reliable, yet economic collision deterrent can be designed is uncertain.

The offshore floating plant has a number of features that make it attractive from an environmental and safety standpoint. Offshore siting offers the potential for siting plants more closely to some load centers. Thus, not only are certain visual presence and land-use difficulties avoided, but modest improvements in overall efficiency are possible through reduction of transmission losses. Additional improvement in efficiency is available through use of once-through condenser cooling, provided the heated effluent water does not cause an unacceptable adverse impact. Stations in deeper water would also have the potential ability to withdraw cooler water from the depths and discharge it at or near the temperature of the surface waters. Because the plants are built at a single site, construction effects are minimized. At most, transmission lines and shoreline docking facilities would be required.

*No such power plant (of any type, including LMFBR) has ever been seriously considered by U.S. utilities.

Although the concept solves some of the problems inherent in land-based nuclear plants, both surface or underground, there are other problems that must be satisfactorily addressed either by analysis or by demonstration to ensure the necessary degree of safety and reliability. Shipwrecks and sea storms are hazards that are unique to offshore floating plant systems. Within the breakwater basin, waves and seiche would be greatly reduced, if not eliminated, so that motions to the platform would be minimal. However, the forces acting inside a breakwater system during a seismic event are complex. Horizontal and vertical components of ground shaking cause hydrodynamic forces to be transmitted to the barge bottom not only directly, but also by reflection from the breakwater mooring. Faulting potentials further complicate the forces the barge may be called on to respond to. Movements of the mooring line anchor points and of the breakwater itself impose unique forces to which land-based plants are not subject. The deep-water version of this concept is free from most of these seismic aspects because of the absence of a breakwater (leading to the increased risk of collision with ships). Also, transportation of fuel and radioactive materials over water may carry some added risk. Design concepts for shipping containers would be expected to reduce such risks to acceptable levels. Finally, the relative inaccessibility of the plant will require a higher degree of self-sufficiency than a coastal plant, and operations similar to those supplying offshore oil drilling platforms will be required.

The concept of an offshore floating plant is concluded to be technically feasible. The concrete rafts proposed as elements of the deep-water floating station are similar in size to concrete dry docks constructed and used (for over ten years) by the U.S. Navy, and the shallow-water version is already on order. Overall, the concept appears to present certain environmental and safety benefits. The floating-station concept offers the possibility of greater choice of offshore location, of possible improvements in safety through earthquake resistance and large exclusion distance, and of probable cost reductions as a result of factory assembly. Considerable development will be required, however, before the potential benefits of floating stations can be realized.

7.2.6.3 Offshore Island Concept

There are a number of offshore islands that might be considered potential locations for nuclear power plants. Their advantage is in remoteness from heavily populated areas and the added protection that such distances afford. In areas where offshore islands are not available for siting power plants, there are at least two alternative possibilities for stable masses on which to place the facility. One is an

island made of fill materials, and the other is a platform similar to those used for drilling operations. Although drilling platforms have been successfully used for many years, they are rather costly, and a man-made island appears to offer both stability and cost benefits.¹ A plant on an island (either natural or artificial) would occupy approximately 11 acres and would be similar to a land-based above-ground plant. The island could be provided with a causeway to make it more readily accessible and to carry utility and transmission lines.

The concept has a number of disadvantages over the other coastal concepts. The cost of construction will be increased by at least the labor travel time between the mainland and the island and by the cost of transloading and shipping materials and equipment. Added costs are incurred by the required marine operations and the dockside support needed for those operations. Operating costs similarly will be greater.

Of the offshore concepts, the use of an island, particularly a natural island, affords the most stable and reliable platform, with less vulnerability to many of the natural and man-induced hazards faced by other concepts. At the same time, the exposure to seismic motion is not better than that of a land-based plant. Because of the distance offshore, cooling water intake and discharge lines may be much shorter than would be required at the mainland shore since dispersion can be achieved more readily in the deeper waters adjacent to the island.

The earthwork in constructing an artificial island will impact on the shore area near the site. Support equipment, materials stockpiles, and logistics will interfere with other onshore activities, probably requiring a support area of about 20 acres during construction. The artificial island can be improved aesthetically and even could be expanded to provide a recreational marina environment. Examples are islands used for drilling in the Long Beach Harbor in California, some of which are located as close as 1000 ft from the shore.

Overall, the offshore island concept seems to provide only modest reductions in adverse environmental impact and in safety considerations. Even though the concept is technically feasible, its application seems restricted to rather specialized situations.

7.2.6.4 Nuclear Energy Centers

Clustering of nuclear facilities into nuclear energy centers has been suggested as a siting concept with the potential for reducing certain costs and environmental impacts, in particular those related to shipment of spent fuel. A nuclear energy center could consist of a reprocessing plant and several nuclear power reactors, with other types of nuclear fuel cycle facilities (fuel-fabrication plant, isotopic separation plants, waste storage facilities, etc.) potentially present; centers from 10,000 to 50,000 MWe have been postulated. The nuclear energy center would offer an alternative siting concept in and near areas with relatively high load growth rates.

In the past, utilities have found it advantageous to plan additional nuclear plants on sites where one or more such plants have been built or authorized. There are sites with specific plans for six to eight light-water-cooled nuclear power plants in the 1000-MWe power range. This tendency for clustering of power plants at an acceptable site is expected to grow. Thus, nuclear energy centers for power production might evolve gradually.

Currently, the AEC is evaluating the benefits of nuclear energy centers of different types and is considering whether, and to what extent, this siting concept should be encouraged.

Development of nuclear energy centers will be subject to the various individual constraints applied to a particular region. Consequently, it is difficult to generalize about the possibilities and advantages of such clustering of nuclear facilities. Nevertheless, some indication of these can be obtained from Report WASH-1288² and the results of analyses carried out for a portion of the country--the Upper Mississippi and Lower Missouri River Basins. These latter two studies have been reported in the "Year 2000 Study"³ and in a report on shipping irradiated nuclear fuels.⁴

The land requirements for a nuclear energy center vary widely with sites in different geographical regions and with different characteristics. The ultimate size, composition, and rate of development of nuclear energy centers will be limited by technical constraints and institutional relationships. Some of the technical constraints that may be limiting are availability of cooling water,⁵ capability of the local environment to accept the large thermal discharges,⁵ limits on the discharge of radioactive material, and available transmission

capacity. These constraints are related to local conditions that would need to be evaluated for each specific site. Before nuclear energy centers can be constructed, present nuclear power plant site criteria will have to be modified somewhat and new site criteria developed for application to such energy centers.

LMFBR power plants would be well suited for location in nuclear energy centers. With the appropriate mix of LWRs, LMFBRs and fuel cycle facilities, a nuclear energy center would minimize the shipment of fissionable materials as well as the shipment of radioactive wastes.

The nuclear energy center seems to offer advantages in decreased construction costs through economics of scale, modular construction practices, and the retention of a permanent construction force. However, there are questions related to the visual impact of large concentrations of cooling towers, power plants, and transmission facilities and to environmental constraints due to waste and radioactive material discharges. The nuclear energy center also offers some potential for reducing the total adverse environmental impact of the nuclear fuel cycle by reducing the transportation of radioactive materials and by making more effective use of land.

7.2.6.5 Underground Siting Concepts

The possibility of underground siting for nuclear power plants has been suggested as a solution to various siting problems. Major advantages have been postulated for underground siting, but perhaps the most attractive is the hypothesis that underground containment could permit "absolute" containment of fission products from any conceivable accident situation. This containment would be accomplished by the additional barrier to the movement of fission products provided by the surrounding rock and earth. Additionally, much of the "visual presence" of the plant would be removed and the amount of land pre-empted for the plant would be reduced from that for the reference concept.

In the underground concept, as much of the plant as possible is placed below grade in caverns or structures created for that purpose. Figure 7.2-3 illustrates this approach for a coastal plant. Plants for which supplemental condenser cooling (as from a cooling tower) is required would additionally require above ground structures for the supplemental cooling device.

A few research reactors and power reactors have been built in underground locations in Europe or have been considered for underground siting. In the U.S., the general

7.2-16

CONCEPT OF UNDERGROUND SITE--COMPETENT ROCK

Figure 7.2-3

use of underground locations for the safe siting of nuclear power plants, particularly breeder reactors, has been suggested,⁶ and several studies pertinent to various aspects of the subject can be found in the literature. No engineering design exists for an underground nuclear power plant in the U.S., and no application has been filed to locate a plant at an underground site.⁷

There are two general methods for locating a power plant underground: excavation of caverns to contain the equipment and structures or excavation of a pit to contain buildings housing the plant components and burial of these buildings. The first approach is clearly restricted to competent rock (such as unfaulted igneous or sedimentary rock), while the second may be applied in unconsolidated or poorly cemented materials. In both cases the plant is compartmentalized into five or six units placed in separate compartments and connected by passageways.

In competent rock, the plant is placed above the water table in six caverns housing the containment structure, the turbine-generator building, the transformer-switchyard area, the fuel-auxiliary building, the control room, and the administration building. Excavation of these caverns would be accomplished by mining from horizontal tunnels, which would later become the service roads during operation of the plant. Five vent structures are required: an intake and an outlet for the air conditioning system, an exhaust for the purge system serving the containment building and other areas where airborne radioactivity may be present, and vents for the turbine building and the switchyard area.

In addition to the main plant structures, a pumphouse would be located near the cooling water source. This facility can also be underground where the topography permits. Coolant discharge lines can parallel the intake lines to the pumphouse with appropriate placement of the outfall to minimize recirculation. For those sites that require cooling towers, the towers would be placed above ground in a location that minimizes the additional pumping required.

To avoid costly roof support during construction, the cover above each facility must be sufficient for the rock roof to be self-supporting with the aid of rock anchors and rock bolts. The roof thickness for this purpose depends largely on the jointing of the material and is not determinable without extensive exploratory drilling and testing. Preliminary investigations indicate that with the use of rock anchors, the roof thickness should be at least equal to the clear span, or about 120 to 150 ft to provide the strength for spanning without structural support. In general, the technologies required for design, excavation, construction,

and operation of the underground nuclear power plant are within the present state-of-the-art. However, the span widths of 140 ft or more for the turbine building and containment buildings, respectively, are large and unprecedented for permanent facilities. Spans of 80 ft or so represent the limit of experience to date, but extensive testing and rock instrumentation during excavation could validate the acceptability of longer spans.

Caverns such as these can be made in both igneous and sedimentary rock, with few differences in design or layout. In the layered sedimentary rock, some rearrangement may be required according to the "tilting" of the planar structures. However, there is greater probability of encountering water or gases in sedimentary rock, and construction could be hampered by excessive overbreak during blasting and the resulting need for added support in the facility.

The plant could also be placed above the water table in fractured and poorly cemented materials not capable of being mined without considerable structural support during construction. In this case, construction would be either cut and cover (attempting to balance cut and fill quantities to minimize offsite haulage) or pit excavation and backfill. Figure 7.2-4 illustrates the general approach. Facility layout and building designs are similar to those in the cavern design except that the containment building also houses the facilities found in the fuel-auxiliary building and the control room. An additional structure to house turbine-generator auxiliaries is provided to minimize the size of the turbine-generator building. This same approach can be used in unconsolidated materials (such as a beach). In either case, roughly 3 ft of cover would be provided, with penetrations as required for access and ventilation. If the plant is placed below the water table, a "freeze-wall" technique, already demonstrated on a smaller scale, could be used to solidify the surrounding materials.

One disadvantage of the underground concept is the increased schedule requirements caused by mining and construction operations, which could add as much as two years to the construction period. Also, overall plant design, construction costs, and interest during construction will be increased due to the difference in approach. These increased costs are somewhat offset by reductions in construction of some building walls. Other disadvantages of underground facilities are longer piping and cable runs due to the extended distance between buildings and increased air conditioning and ventilation requirements, especially in areas normally in the open in a surface plant, such as the switchyard area. Perhaps the greatest concern

7.2-19

CONCEPT OF UNDERGROUND SITE--UNCONSOLIDATED OR POORLY CEMENTED MATERIALS

Figure 7.2-4

is the probable elevation of the water table and resulting potential for leakage of water into the plant.

One of the advantages suggested for underground siting of power plants is the expectation that the surrounding rock and earth would provide a form of "absolute" containment to virtually any conceivable fission product release. Some information on the capability of cavities in competent rock to retain fission products has been obtained in the weapons testing programs at the Nevada Test Site. The relevance of this experience to reactor siting is uncertain, but these weapons test site experiences in retaining fission products have generally been favorable, with occasional releases attributed to inadequate access tunnel and instrumentation penetration seals. Unfortunately, the underground designs considered feasible for reactor installation involve even more penetrations; the likelihood of guaranteeing the integrity of seals for these penetrations is similarly uncertain and would require considerable study.

Location of a power plant underground removes the aspect of "visual presence" (intrusion on the landscape of man-made devices) from consideration. For plants with once-through cooling, there are virtually no aboveground effects except for the transient effects during construction and the impact of the transmission lines. However, plants with supplementary cooling requirements will still need large cooling towers (a cooling pond may not be compatible with underground siting in terms of topography and groundwater) which will intrude on the landscape and which will expel large quantities of water vapor. Other advantages typical of underground facilities include protection from surface accidents (missiles, airplanes, weather disturbances) and isolation of the turbine in a separate containment area (improved protection from rotating element failure).

These advantages are offset somewhat by the fact that underground operation will entail some decrease in efficiency because of the added lighting and ventilation requirements. The capability, or even feasibility, of providing adequate long-term seals for the large access tunnels, ventilation and cooling water ducts, and power line and instrumentation penetrations that would be required for a power plant has not been demonstrated. Accomplishing this objective at a suitable rock-base site with adequate cooling water supply seems especially difficult. This position is reinforced by the experience to date with sealing the relatively simple penetrations of conventional containment vessels and keeping them sealed adequately over the plant life. The threat of flooding is a major unknown.

The few studies of underground siting that have been made are only partial scoping studies at best. Significant efforts would be required to fully establish the adequacy of the design of an underground plant. In the absence of definitive engineering studies and assessments of flooding potential, many problems associated with underground siting seem formidable, and it is difficult to foresee whether the net effect of underground siting would be of greater or lesser environmental impact, as compared with surface siting. Clearly, however, significant added costs are associated with the various underground siting concepts.

7.3 POTENTIAL FUTURE ALTERNATIVES

7.3.1 LMFBR Power Plants

The major potential future alternative for mitigating the adverse environmental impact of LMFBR power plants is the use of economical and reliable dry cooling tower systems for power plant waste heat disposal. If once-through systems and wet cooling tower systems prove to be environmentally unacceptable in certain locations (and sufficient land is not available for cooling ponds at these locations), dry cooling towers could be considered instead. Environmental problems, other than visual impact, arising from the use of wet cooling towers can be effectively eliminated by use of dry cooling towers, assuming successful development and demonstration of the reliability of such towers.

At present, dry cooling towers are not in use in sizes comparable with those that would be required for a 1000-MWe LMFBR power plant since the costs for dry cooling towers compatible with existing power plant turbines are so high. If turbines designed to operate at higher back pressures become available, then dry cooling towers would be much more economical. A program to demonstrate economical and reliable dry cooling for power plants is presently under way (see Section 2).

Research on ways to reduce the release of tritium from LMFBR power plants is being planned. The advanced sodium purification systems that are planned to be investigated are to be used primarily for removing the small quantity of tritium remaining in the sodium after cold trapping. These advanced purification traps include such concepts as gettering materials and metallic diffusion membranes. (Gettering materials preferentially leach tritium and hydrogen from the sodium and form stable tritides and hydrides.) As the gettering material becomes saturated with tritium and hydrogen, it is periodically removed from the sodium system and replaced by a fresh getter. In the case of a metallic diffusion membrane tritium purification system, a material like nickel--which is easily permeated by tritium and hydrogen but not by sodium or other impurities, is structurally strong, and is insoluble in sodium--might be used. Once the tritium diffuses through the membrane, it would be moved by an inert sweep gas to a tritium oxidizer trap.

7.3.2 Fuel Fabrication Plants

Releases of radioactive material and other pollutants from fuel fabrication plants would be as low as practicable (see Section 4.3.5). No further reductions in effluents are probably justified.

If, for some reason, much lower releases are desired, this could be accomplished. A drastic reduction in effluent volume is thought to be the most practical route to attainment of substantially larger confinement factors.* It is thought that confinement factors can be achieved which are orders of magnitude higher than those predicted for the model plant.

7.3.3 Fuel Reprocessing Plants

The potential future alternatives to reduce releases of radioactive material from fuel reprocessing plants are centered on employment of a process for removing tritium from the feed material prior to dissolution and/or recycle of essentially all liquids and gases brought into the plant (see Section 4.4.4.4.2).

Neither the tritium removal process nor the fluids recycle technique has been tested in plant-scale operation; hence, projected improvements in fission product retention are speculative.

Use of the voloxidation process for tritium removal from irradiated oxide could permit retention of from 90 to 99% of the tritium. Employment of the fluids recycle technique in conjunction with exhaustive treatment of all effluent streams by the most effective means available is expected to provide normal operation confinement factors for various nuclides, or classes of nuclides, as follows:

Tritium	10^3
Krypton	10^3
I-131	10^9
I-129	10^7
Ruthenium	10^{12}
Nonvolatile particulates	10^{13}

Use of the recycle system is expected to severely reduce releases of radioactive material from most accidents occurring within the cell complex by greatly reducing the amount of building air that must be filtered prior to release.

Model plant confinement factors (see Table 4.4-5) for these various nuclides were:

Tritium	1
Krypton	10^2

*Ratio of input radioactivity to released radioactivity.

I-131	10^4
I-129	10^4
Ruthenium	10^9
Nonvolatile particulates	5×10^9

Thus, doses due to releases could be reduced by several orders of magnitude if these processes are developed.

7.3.4 Transportation

From experience and analysis of a broad spectrum of conceivable accidents and potential package damage, the conclusion has been made that spent fuel shipping casks designed to meet the current regulatory standards for type B fissile material packages provide a high degree of resistance to damage in severe transportation accidents. Even in the event of breach of a shipping cask for LMFBR spent fuel allowed to decay 360 days before shipment, the release of activity has been shown to be small (see Section 4.5.5.16--less than 2000 Ci, mostly Kr-85) and resulting doses are acceptable (within 10 CFR 100 guidelines).

An objective of the LMFBR development program is to establish technology for safely shipping spent LMFBR fuel allowed to decay as little as 30 days prior to shipment. After 30 days of decay, typical spent LMFBR core plus axial blanket fuel will contain about 12 orders of magnitude more I-131 and will give off about 10 times more decay heat and penetrating radiation than fuel allowed to decay for 360 days. The technical feasibility of producing a basic cask design having adequate shielding and heat dissipation capability has been established in currently ongoing AEC research programs.

The much greater quantities of radioactive material that could potentially be released if the cask were to suffer a breach of containment require the use of special design features aimed at preventing this occurrence in an accident when fuel cooled for periods less than one year is shipped. The development effort is aimed at achieving a cask design such that even though the consequences of breachment may be severe, the probability of a breach of containment is so low as to be considered incredible, and, therefore, the risk to the environment is considered to be of no major concern.

The approach being taken in the development effort is two-pronged, involving (1) a continuing analysis of available transportation experience and options (to minimize the probability and severity of accidents, limit their consequences, and provide highly proficient and prompt recovery capability) to more quantitatively establish

the relationship between package damage and accident conditions and (2) a comprehensive testing program to verify experimentally the extremes of mechanical and thermal stress a particular cask design can endure. The combined outputs of these investigations will result in cask designs that provide a known degree of protection against any set of accident conditions deemed credible.

Fire and impact are the accident conditions of principal concern. Protection against impact damage is assured when the total kinetic energy associated with a cask in motion can be absorbed by the cask and/or surrounding objects without producing a leak rate in the cask containment of greater than a specified acceptable amount. The allowable leak rate for 30-day-decayed fuel shipments would be limited in current cask concepts by the allowable I-131 release rate.

Obviously, impact against an unyielding object requires all of the kinetic energy to be absorbed by the cask. Mechanical stresses produced in the cask components will depend largely upon how and where the kinetic energy is absorbed (i.e., where cask distortion occurs during impact). Cask deceleration can be controlled by providing appendages to, or superstructures around, the cask body which absorb the energy by sacrificial deformation, thus limiting destructive involvement of the cask shield or closure. However, impact against objects that yield might result in higher shock loading for casks using shock-limiting techniques that could be reduced by deformation of the target. Higher shock loadings could result, causing higher stresses. Thus, the unyielding target is not necessarily the most severe case. Such phenomena must be adequately quantified and reflected in the cask's performance.

During a fire, the massive gamma shield of the cask along with the latent heat absorption capability of the neutron shield can provide a large heat sink both for the heat absorbed from the fire and for the decay heat from the fuel. The degree of fire protection provided by a particular cask design is, therefore, dependent mainly upon the heat capacity of the shield and the heat transfer characteristics of the cask surface exposed to fire. These are the major determinants of the length of time a cask that contains a given quantity of heat-producing fuel can be exposed to a specified fire temperature. Simply stated, the cask can absorb a given quantity of heat before the internal cask temperatures become unacceptable, and the quantity absorbed is dependent upon the heat input to the cask and the time of exposure to a fire. The cask can endure very high temperatures, and consequently high heat inputs, for short periods of time or lower heat inputs for longer periods of time. Any design feature that effectively increases the heat capacity of the

cask shield provides additional fire protection. The loss in strength of the cask structural material at high temperature combined with the expected internal pressure imposes the time-temperature exposure limitation in the long-duration fire.

One concept under development for a cask to ship short-decayed fuel is shown in Figure 7.3-1. The cask body is steel with a wall thickness that varies from 12 to 19 in. Penetrations into the cavity, the most likely paths for leakage, have been reduced to one. This one penetration provides access to the fuel assemblies in the cask cavity. An internal magazine containing the fuel assemblies is rotated by means of an auxiliary drive inserted through the fuel access port when needed during cask loading and unloading operations.

The fuel access port is provided with three all-metal, high-temperature seals in series that are capable of being tested for leak-tightness prior to each shipment. The space between the seals is filled with helium gas under pressure. Each seal is held in place by a nut having interrupted threads, similar to the breach-lock mechanism on large artillery pieces. Special gaskets are used which tolerate a small amount of axial movement and prevent radial movement of the closure surfaces.

The cask is designed with massive steel rings around the middle and on the ends of the cask. These rings are capable of absorbing large amounts of energy as they deform in extremely severe impacts. The steel is estimated to be capable of absorbing all the kinetic energy in the 75-ton cask if it impacted at 60 mph (not counting energy absorbed in deformation of the collision target).

The neutron shield, external to the steel gamma shield, uses a eutectic mixture of LiOH and NaOH and is solid at normal operating temperatures. This mixture melts at 430°F and has a substantial latent heat of fusion. After melting, the liquid acts as a convection fluid to transport heat from the cask gamma shield to the exterior wall of the neutron shield where it is dissipated to the atmosphere. The principal features of this neutron shield concept have been tested. Calculations based on these tests indicate that an 18-assembly cask loaded with 30-day-decayed fuel could survive a fire lasting longer than 11 hr.

The design of the neutron shield permits only very low heat transmittance in order to provide the significant protection from most accidental fires to which the cask might be exposed in an extremely severe accident. This means, however, that, during routine use, decay heat must be removed by a secondary coolant system. Coolant channels are located near the interior wall of the cask for this purpose. The

7.3-6

AN LMFBF SPENT-FUEL SHIPPING-CASK DESIGN

Figure 7.3-1

primary and secondary coolants do not come in contact with each other, thereby eliminating that path of escape of radioactive materials from the cask cavity.

This cask concept is designed to reduce the possibility of human error to an absolute minimum in loading and sealing the cask prior to shipment. The integrity of the cask will not be violated by any forces or fires likely to be encountered in the most severe transportation accidents.

In addition, administrative controls can be used to mitigate the consequences of any accident that does occur to the cask. One type of control is to provide an organization that is responsible for maintaining contact with each shipment and for knowing its position at all times and that has the capability to limit the exposure of a cask to a long-duration fire. A second type of control is to require shipment of LMFBR casks by barge when feasible. Barges move at slow speed, making protection against impact damage an easy engineering problem. Because the barges move only over water, protection against a long-duration fire is an even easier engineering problem.

Assuming research and development programs continue to provide more definitive data on impact and fire protection measures, there appears to be no reason to believe that short-decayed LMFBR spent fuel cannot be transported in the future with acceptable risk to the environment.

7.3.5 Radioactive Waste Management

This section provides a highlight summary of the continuing comprehensive evaluation studies of alternatives which are discussed in depth in the referenced reports.

When the AEC made its decision to use retrievable surface storage as the near-term technique for managing the commercial high-level radioactive waste, it recognized that while this approach is simple, straightforward and safe, it does impose a requirement for surveillance and maintenance.⁸ The AEC development program is based on the belief that management techniques can be developed which are equally safe and which would eliminate, or at least minimize, this requirement and which will eventually be used.

The Mid-America Coalition for Energy Alternatives in their letter of April 24, 1974,* pointed out that, all other factors being equal, approaches that do not require

*Comment Letter 22, p. 9.

perpetual surveillance may be safer since the potential for human error would be reduced. The AEC agrees with this view.

Some years ago, the AEC began a rather extensive program to identify, evaluate and possibly demonstrate other feasible disposal techniques for later use (see Section 4.6.1.1). This involves, first, laboratory and test facility studies of a disposal technique that has promise of becoming proven and acceptable in the near term-- disposal in bedded salt formations; and, second, studies, analyses, and evaluations of other potentially usable, but not now proven feasible, alternative methods of disposal, such as: (1) use of geologic formations other than bedded salt, (2) transmutation, or (3) extraterrestrial disposal.⁸

At present, the AEC plans further study of several promising geologic formations other than bedded salt, including study of specific promising sites, to bring the knowledge of these other formations up to the same level as that of present knowledge of bedded salt. The goal of this further study is to permit a comparative evaluation of these formations and the selection of the optimum formation or formations for pilot plant operations. In the early 1980's, this further study and evaluation program is expected to permit a decision and a request to Congress for authorization and appropriation for a specific geologic disposal pilot plant at a specific site. A draft environmental statement will be issued in support of such a request. Construction of a geologic disposal pilot plant and successful completion of the pilot phase could lead to availability of permanent disposal by two to three decades from now.

The AEC is currently making an evaluation of potentially attractive near- and long-term disposal concepts^{9,10} in order to: (1) assure that no feasible concept has been overlooked and (2) lay the groundwork for future programs.¹¹ A major input to all future decisions on the development of disposal methods will result from the comprehensive study now being made on possible disposal methods--whether currently feasible or not. The purpose of this assessment is to identify feasible and potentially feasible long-term waste management systems and their components, identify the research and development necessary for their establishment, and estimate the schedules and costs associated with selected systems. Three basic types of waste management concepts are under study: (1) disposal on earth, (2) conversion by nuclear processes (called transmutation), and (3) disposal in space. The earth disposal concepts involve use of geologic formations, major ice sheets, and the seabed. Transmutation involves elimination of some of the long-lived radionuclides by

neutron irradiation. The space disposal concept involves transporting waste to various orbits or trajectories in space.

7.3.5.1 Disposal on Earth

7.3.5.1.1 Geologic Disposal Concepts

A number of geologic disposal concepts, other than bedded salt disposal, are being investigated.^{9,10} Disposal of radioactive waste in geologic formations has the potential of isolating the waste from man's environment for extended time periods (millions of years). Geologic environments exist that have been physically and chemically stable for millions of years, are isolated from man's environment, and can potentially provide effective barriers between waste and man's environment for the time periods required. The basic requirement for any geologic environment to be suitable for disposal of radioactive waste is the capability to safely contain the emplaced radioactive material until decay has reduced the radioactivity to nonhazardous levels. The geologic environment should (1) be adequately far removed from man's environment, (2) not permit waste transport readily, and (3) remain relatively stable over geologic time periods.

There are several ways a geologic formation can be penetrated and altered to provide a suitable cavity for waste emplacement purposes. Present studies are considering the use of drilling, mining (mechanical and dissolution), hydraulic fracturing, and nuclear cavity formation. All of these methods become more difficult with increasing depth. At depths up to about 10,000 ft, any of the methods may be used. Drilling has the potential of going to great depths; the present record is around 30,000 ft (about 5.6 miles).¹⁰

The alternative methods under consideration for disposal of radioactive waste in a geologic formation include:

- (1) Placing solidified waste directly into geologic formations in mined cavities or drilled holes.
- (2) Placing solidified waste in man-made containment barriers within geologic formations.
- (3) Placing solidified waste in a geologic formation in a configuration to allow the waste to melt and form a rock-waste matrix that eventually cools and solidifies.
- (4) Converting liquid waste in-place within a geologic formation to form a solid waste or a rock-waste matrix.

All of the geologic concepts appear to be technically feasible, but a number of years would be required for development to prove the safety of any concept. Cavities and holes could be made today with the possible exception of very deep holes (e.g., ten miles deep). A deep hole could probably be drilled today in areas with very low geothermal gradients. New technology is required for the moderately large holes needed at the great depth (10 miles) and for the high down-hole temperatures.

7.3.5.1.2 Seabed Disposal Concepts

Disposal of high-level waste within the floors of the world's oceans offers another possibility for permanent isolation of the waste from man's environment.^{9,10} The depth to the floor or seabed would provide isolation and safety from natural disasters such as storms, as well as from sabotage or accidental disturbances. The basement rock would provide geologic isolation of the waste. The known high ion-exchange capacity of the seabed sediments would aid in immobilizing waste material if any waste escape should occur.

A number of seabed disposal concepts that differ mainly in site characteristics are being evaluated. The following geologically distinct types of sites on the seabed are being considered.

- (1) Stable deep sea floor. Areas such as stable marine desert areas and abyssal plains, which are considered geologically stable. The waste would be placed in the seabed below the unconsolidated sedimentary cover.
- (2) Subduction zones. Areas where, according to crustal plate tectonics theory, one edge of certain crustal plates is moving under other crustal plates and down into the earth's mantle. The waste would be placed in these areas to be carried down, or subducted, into the earth's mantle with the crustal plate.
- (3) Deep sea trenches other than subduction zones. Areas where deep trenches occur in the sea floor. The waste would be placed in the dense seabed at the bottom of these trenches.
- (4) High sedimentation-rate areas. Areas where major rivers are building deltas into the ocean. The waste would be placed in the seabed below the accumulating deltaic sediments.

The radioactive waste would be in a solid form and enclosed in a durable sealed canister. To further isolate wastes, the canisters would be placed in prepared holes in the seabed, after which the holes would be sealed. The depth of the prepared holes would depend on the nature of the seabed at the disposal site.

Implementation of the seabed disposal concepts in the stable deep sea areas, and in the areas of rapid sedimentation, could be attained with today's technology, but a number of years would be required for development to prove the safety of the concept. New drilling and emplacement technology would have to be developed to implement disposal in the very deep sea areas of the trenches and the subduction zones. Final sealing of the disposal holes to maintain isolation for the long time periods of concern would need to be tested (and improved if necessary) for radioactive waste disposal.

Disposal of radioactive waste in the seabed has the potential for isolating waste from man's environment for periods on the order of millions of years, depending upon confirmation of inferred knowledge by future seabed exploration.

A primary concern is the impact of a transport vessel sinking en route to the disposal area. The consequences of this accident depend on design considerations and have not been fully defined. The above sea-level land use involved in the various sea disposal concepts would be confined to a dockside transfer and loading facility.

The ecologic impact should be small. Although the ocean-bottom environment will be disturbed during the drilling operation, the productive near-surface zones should be essentially undisturbed by normal operation. The aesthetic impact would be negligible since only a modest transfer facility would be involved on shore. Truck or rail shipment would be required to the port of embarkation. In addition, the impact of ocean transport requirements must be considered.

7.3.5.1.3 Ice Sheet Disposal Concepts

Alternative concepts for radioactive waste disposal in the major ice sheets of the world (Greenland and Antarctica) are being evaluated.^{9,10} Potential advantages are great thicknesses of ice, remoteness from man's activities, and low likelihood for future development. The ice and cold temperatures could provide effective direct cooling for the waste and, at the same time, maintain isolation from man's environment.

Four potential disposal concepts are being evaluated for the ice sheet areas such as Antarctica or Greenland.

- (1) Meltdown or free flow. The waste canister would be placed in an individual shallow drilled hole in the ice and allowed to melt down through the ice sheet to bedrock.

- (2) Anchored emplacement. The waste canister would be placed in an individual shallow drilled hole in the ice but connected to surface anchors by cables or chains, which stop its descent and maintain its position (500 to 1500 ft below the ice surface) for up to about 100 years. After that, the waste canisters would move slowly towards the ocean with the ice.
- (3) Surface storage/disposal. The waste canister would be placed in a temporary hot-cell type of storage facility with jack-up piers on the ice sheet surface. After about 50 years, the facility would become covered by accumulating snow and would eventually be buried in the ice sheet for final disposal.
- (4) Disposal in permafrost areas. The waste canisters would be placed in solid rock in ice-free areas within the ice sheet areas. This is, in effect, geologic disposal in remote ice sheet areas.

The implementation of all ice sheet disposal concepts could be done with today's technology, but a number of years would be required to prove the safety of any concept. The disposal system aspects of containerization, transportation, and emplacement could all be accomplished by modification of current technology. Final sealing of the waste could be performed by natural refreezing of the water around the waste in all concepts.

Disposal of radioactive waste in ice sheets is considered to have an uncertain potential for isolating waste from man's environment, depending largely on ice sheet stability. Estimated times for transport of waste material to the oceans vary from one thousand to perhaps hundreds of thousands of years. Present capability does not exist to predict the existence of the ice sheets for more than a few thousand years.

A primary concern is the impact of a transport vessel sinking en route to the disposal area. The consequences of this accident depend on design considerations and have not been fully defined.

The commitment of land in this concept would entail a port of embarkation facility, a staging area (including an airport) at the debarkation point, several support stations en route to the disposal area, and a large disposal site. The disposal area in ice would be large because the canisters would be deposited singly on about 5000-ft centers. (The disposal area in the permafrost areas or the surface storage facility could be smaller.)

The ecology of the ice sheet area is extremely fragile and can be compared in many respects with that of the tundra areas of the Arctic region. Areas where the limited flora and fauna are concentrated would be avoided as much as possible. The noise of surface and air support vehicles might disrupt the mating cycles of birds and animals.

7.3.5.2 Transmutation Concepts

Another possible approach to the management of radioactive waste is the use of nuclear processes themselves to change (transmute) the hazardous long-lived radioactive waste constituents into short-lived radioactive waste or nonradioactive isotopes.^{9,10} Transmutation is generally defined as any process whereby a nuclide absorbs or emits radiation and is thereby transformed into another nuclide. The primary waste-management transmutation concept currently under study is based on selected radionuclides in the waste absorbing neutrons and thus being converted to less hazardous (i.e., shorter half-life or stable) species.

The feasibility of this concept hinges on achieving:

- (1) A transmutation rate that substantially exceeds the natural rate of radioactive decay.
- (2) A resulting significant reduction in the inventory of long-term hazardous radionuclides.
- (3) A favorable energy balance such that the energy produced from the original nuclear fuel in generating the waste is significantly greater than the energy required for waste transmutation.

Current studies indicate that elimination of most actinides and selected fission products appears to be technically feasible by recycling them in fission and fusion devices. Assuming that transmutation of actinide elements takes place in LWRs, little or no additional land commitment should be required over and above that needed for the already-planned reactors and supporting fuel cycle services. As in the case of extraterrestrial disposal, the basic version of this concept disposes of only actinides; hence, in considering environmental impacts, one must add those to be expected from the disposal of the remaining waste constituents. The total extra land affected would be very small. The additional impact on water supplies would be minimal. The incremental ecologic impact from the added fuel cycle activities would be negligible. The impact from geologic disposal of the remaining bulk wastes discussed earlier would also apply to this case. The transportation

impact would be increased somewhat in all phases of the fuel cycle. The fuel elements containing the actinides would require shielded containers comparable to those used in the shipment of irradiated fuel.

7.3.5.3 Extraterrestrial Disposal Concepts

Disposal of radioactive waste by removing it from the earth with rockets is another disposal concept being evaluated.^{9,10} If a stable non-earth-intercept trajectory or orbit can be assured, extraterrestrial disposal offers a method for the complete removal of long-lived nuclear waste constituents from the earth. The primary unfavorable features are that the concept deals with only part of the waste and there are possible launch safety problems.

Extraterrestrial disposal of the total waste constituents and of only the actinides have both been considered. However, primarily because of the high space transport cost per unit of weight, space disposal of just the actinides is believed to be the most practical scheme. The remaining waste would have to be disposed of by some other means. Typically, the launch deployment sequence would require a shuttle to be launched into a low earth orbit where tugs or upper stages would then be launched to carry the waste package to its final destination.

The implementation of space disposal of actinide waste could be achieved with current technology, but the safety of the concept must be established. This current technology is considered to include the space shuttle (with separately retrievable and reusable lift-off-assist rockets) and the space tug, which are advanced vehicles but which would use existing engineering technology. The primary safety questions concern waste containers to withstand launch pad accidents and accidental atmospheric re-entry. Extraterrestrial disposal has the potential for permanent removal of radioactive waste constituents from the earth, depending largely on incentives and improved knowledge of deep space travel. A primary concern is the impact of an aborted mission which will largely depend on container design and has not yet been fully defined.

The land use for extraterrestrial disposal would be a combination of the land allocated to the launch site and that devoted to the disposition of the separated fission products. The latter disposal may be assumed to be the same as for the mixed fission products and transuranic elements discussed under geologic disposal concepts. Aside from the consumptive use impact on water, there is the potential for pollution of surface waters that would arise from an aborted mission in which propellant or oxidizer was released. Each launch would release a significant

weight of combustion products into the air. The aural impact is potentially more serious, and during the launch operation a maximum safe 115-B noise level would be exceeded within a 3-mile radius.

7.3.5.4 Geologic Disposal Pilot Plant

In addition to these studies of high level waste disposal techniques, the AEC is planning a pilot plant demonstration of high level waste disposal.¹² The purpose of the geologic disposal pilot plant (GDPP), which would presumably operate in the early 1980's, is to determine the acceptability of a specific site and technique for disposal, using actual waste canisters. The following essential features distinguish the pilot plant concept from ultimate disposal concepts:

- (1) All waste placed in the GDPP will be readily retrievable so that any time after placement of the waste in the geologic formation the waste can be removed by preplanned methods and the formation left in a contamination-free condition.
- (2) Reserve space will be maintained in the retrievable surface storage facility at all times sufficient to hold the entire inventory of the GDPP.
- (3) The GDPP will not be converted to a full-scale repository until the public has accepted the philosophy of radioactive waste disposal in geologic formations and until the analytical and laboratory predictions of the effects of the radioactive heat-producing waste on the specific geologic formations have been verified.

Since no waste will be placed in the GDPP until after the retrievable surface storage facility is constructed and in operation, the probable design features of the GDPP can only be described in a general way. The basic elements of the GDPP will probably be:

- (1) Waste receiving and inspection equipment on the surface, largely similar to the waste receiving and inspection facilities for the retrievable surface storage facility.
- (2) Mine shafts and hoists, arranged to separate the movement of radioactive waste from movement of personnel and nonradioactive materials, with filters and monitoring devices for exhaust air.
- (3) A mine-level shielded receiving station to allow completely remote transfer of waste canisters from the waste shaft to a transporter.

- (4) A motorized transporter with a shielded cask and fittings and controls to permit movement of canisters through the mine tunnels and their installation in sleeved storage holes.
- (5) The excavated mine tunnels, rooms, and canister holes, with sleeved fittings in the holes to prevent contact of the canisters with the geologic medium during the pilot phase.

7.4 SAFEGUARDS

7.4.1 Introduction

Certain materials present in nuclear reactor fuel cycles must be considered as possible targets for illegal diversion and subsequent use in the fabrication of nuclear explosive devices or in dispersal to create radiological incidents. The possibility of sabotage of facilities and vehicles resulting in radiological incidents must also be considered.

The AEC has had the authority and responsibility to protect the public against the effects of potential illegal use of special nuclear material (SNM)* and other radioactive materials since the inception of the atomic energy program in the United States. The body of procedural and physical controls developed to carry out this responsibility is the AEC safeguards system. Over the years, the safeguards system has been continuously modified as appropriate to the growth of nuclear activities, both military and commercial. These modifications are made as the result of the planning and research and development activities that constitute the AEC safeguards program.

This section of the Environmental Statement examines the safeguards implications of the postulated future LMFBR mode of electric power generation, taking into account that the LMFBR fuel cycle would be only one of several commercial fission reactor fuel cycles requiring safeguards. The purpose of this examination is to present as much information as is possible at this time on the nature and scope of the future AEC safeguards system as it would be applied to the LMFBR.

In present-day commercial fuel cycles (predominantly LWR), plutonium and the radioactive fission products resulting from reactor operation are the materials of primary concern. Plutonium would come into increasing use with the advent of plutonium recycle in LWRs and the later introduction of the LMFBR. In the year 2020, about 550 LMFBR electrical generating stations (averaging 4000 MWe each), about 28 fuel fabrication plants, and about 28 reprocessing plants could be in operation.** In the same year, there might be about 5000 metric tons of fissile plutonium present in the U.S. LMFBR fuel cycle, about half of which would be in reactors. The extent of future plutonium product transportation between facilities would be strongly influenced by facility siting practices; assuming a dispersed industry, about 100,000 shipments (highway and rail) might be made in the year 2020.

*Plutonium, uranium-233 or uranium enriched in the isotope 235.

**Section 10.2.2 provides the basis for these estimates.

The LMFBR fuel cycle would also involve generation, transport, and storage of substantial quantities of radioactive wastes, as discussed in Section 4.5.

The safeguards problem exists now to a limited extent and will exist in the future with or without LMFBR. All fission energy systems that are viable for the long term produce and use strategic special nuclear materials (SSNM).^{*} Some of these materials are also radiotoxic. All fission reactors also produce radioactive fission products.

The broad safeguards objectives and program elements which form the base of the present system and which will be used in developing the future system are presented in Section 7.4.2.

The inclination of individuals or groups to attempt diversion or sabotage is not readily subject to quantitative determination. Nevertheless, qualitative evaluation of potential threats is possible. The nature of these threats is discussed in Section 7.4.3. The related problems of facility vulnerability to acts of war and sub-national diversion in other countries are discussed in Section 7.4.4.

A complete review of the safeguards problem must include consideration of the potential consequences of safeguards failures. A successful theft could lead to the use of explosive or radiological weapons. These potential consequences and those arising from facility or transport sabotage are discussed in Section 7.4.5.

A description of the safeguards aspects of the LMFBR and comparisons with the safeguards aspects of other fuel cycles are presented in Section 7.4.6.

The current safeguards program and the requirements imposed on the commercial nuclear power industry are described in Section 7.4.7. The adequacy of the current system is discussed in Section 7.4.7.6.

The structure and content of the future AEC safeguards program, as currently visualized, are defined in Section 7.4.8. Section 7.4.9 indicates in a substantive way the general configuration and cost of the increased physical protection which can be expected in the future safeguards system, with emphasis on the LMFBR but with comparative information on other fuel cycles.

The conclusions presented in Section 7.4.10 are based upon consideration of all information in Section 7.4 and the safeguards-related information in Section 5.

^{*}Plutonium, uranium-233, or uranium enriched to greater than 20% in the isotope 235 (materials from which a nuclear explosive can be fabricated).

7.4.2 Safeguards Objectives and Program Elements

Safeguards measures are designed to deter, prevent, or respond to (1) the unauthorized possession or use of significant quantities of nuclear materials through theft or diversion and (2) sabotage of nuclear facilities. The safeguards program has as its objective achieving a level of protection against such acts to ensure against significant increase in the overall risk of death, injury, or property damage to the public from other causes beyond the control of the individual. The program includes the following functional elements:

- (1) definition of the nature and dimensions of the threat;
- (2) development and imposition on the nuclear industry of safeguards requirements directed toward countering the threat;
- (3) licensing activities, including review of safeguards procedures proposed by nuclear industry applicants, as required by regulations;
- (4) inspection of safeguards implementation to ensure adequacy;
- (5) enforcement of requirements through administrative, civil, or criminal penalties;
- (6) administrative and technical support for response and recovery;
- (7) development and testing of methods, techniques, and equipment necessary to the effective implementation of safeguards;
- (8) continuous program review in the light of industrial/technical or social/political changes to assure that any needed changes are made in the program elements above.

The present approach to definition of threat involves consideration of two basic factors:

- (1) adversary characteristics (i.e., number of people, number and position of employees involved, level of motivation, skills and resources, armament, and other characteristics);
- (2) adversary action sequences (i.e., the series of actions that the adversary must successfully accomplish in order to achieve his purpose).

The approach to development of safeguards requirements is to provide "protection in depth," that is, to provide multiple opportunities to interrupt adversary action sequences. Other requirements are directed at minimizing the consequences of a completed sequence.

The program review and inspection elements provide a mechanism for evaluation of safeguards adequacy.

To take into account international developments, the AEC provides technical support to U.S. participation in safeguards activities of the International Atomic Energy Agency (IAEA). This participation provides a means of encouraging other nations to establish safeguards that are equivalent to those in the United States. The U.S. safeguards system has served as a model for many nations with developing atomic energy programs. Through participation in activities associated with the Non-Proliferation Treaty, the United States seeks to maintain a leading role in international safeguards. The impact of LMFB on proliferation is discussed in Section 5.4.3.1.

In carrying out its program, the Commission seeks to be responsive to the views of the public and the industry, consistent with its charter to assure protection of public health and safety and of the common defense and security. This is done through public and professional meetings, through broad-based studies conducted in-house or with other government agencies, and through consideration of public comments on proposed regulations.

7.4.3 The Nature of the Threat

Threats of violent activity may conceivably arise from several sources: psychotics, disgruntled employees, dissidents from labor-management disputes, criminals, or terrorists. Factors which characterize a threat include the motivation and resources of the individual or group, the makeup of any such group and the timing and mechanism chosen for perpetration of the illegal act. Unfortunately, long-range predictions regarding the climate of world political, social, or economic conditions are impossible. The problem of describing the adversary in terms of his characteristics is made even more difficult by the fact that decisions to attack a particular target are based upon the individual's assessment of what he can gain, what he can lose, what resources he needs, and how competent he thinks he is. This assessment not only results in a decision to act or not, but may also result (if he decides to proceed) in changes of his characteristics in terms of group size, resources, technical knowledge, and equipment.

Many comments were received expressing concern about threats which could be made against facilities and materials involved in the LMFBR program.* Representative comments were:

Recent violent crimes and terrorist atrocities suggest very strongly that a few persons will commit the most heinous deeds within their power. Their eventual employment of radioactive materials appears virtually certain.

...if a virtuous but unstable employee came to believe that the perils of nuclear energy had to be demonstrated to the public by a dramatic occurrence he might become motivated to create that occurrence.**

I believe that the hazards of theft and sabotage are very great; far greater than the Draft Environmental Statement admits. We live in an era of war and violence. Sabotage of an intact nuclear power plant may be difficult to carry out, but bold and determined fanatics, who are willing to sacrifice their lives, can accomplish destruction under circumstances that would seem inconceivable to most rational people. The Arab terrorists who recently killed 18 people in a northern Israeli town, and knowingly sacrificed their own lives in doing so, are I believe forerunners of many other similar people, some of whom will direct their hostility against the United States. Furthermore some of them will have the ability and determination to train themselves highly in the necessary technical skills that will enable them to deal with the special problems involved in attacking nuclear power plants. The dangers of theft of plutonium during shipment will also be extremely serious.†

Given then that SNM exists in large quantities in the LMFBR fuel cycle, that were it diverted it could form the basis for the fabrication of either an atomic bomb or a radiation weapon, what does the Draft Environmental Statement have to say about those who might wish to utilize the potential for this "new form of anti-social behavior?"††

The questions of sabotage, terrorism and safeguards are not fully, honestly and openly dealt with. ... It is stated that: "The possibility of sabotage of facilities resulting in radiological incidents must also be considered." Yet this is not done consistently throughout the report.§

Our society has to look at what the implications are of plutonium dispersion devices and a number of atomic bombs in the hands of criminals and terrorists. We have to remember that today we live in a world where Patty Hearst holds up a bank in San Francisco, where Palestinian guerrillas throw babies out of fourth-story windows, where Japanese terrorists indiscriminately slaughter tourists on airlines and where Irish terrorists bomb women and children on escalators.§§

*(1) Comment Letters 8, pp. 4, 5 (Attachment 2); 10, p. 1; 12, pp. 16, 17 (Attachment 2); 16, p. 2; 20, p. 7; 22, pp. 2, 9; 24, p. 2; 37, p. 6; 40, pp. 2-3; 51, p. 46. (2) Pre-Draft Letters 15 (T. B. Taylor Enclosure), p. 4; 1, p. 11; 6, p. 2. (3) Hearings Transcript, p. 64, p. 1 (SIPI Addendum to Hearings). (4) Hearings Record Material 18, p. III-5.

**Comment Letter 12, p. 16 (Attachment 2) from Zero Population Growth.

†Comment Letter 16, p. 2 from John T. Edsall.

††Comment Letter 20, p. 7 from Natural Resources Defense Council (NRDC).

§Comment Letter 22, pp. 2, 9 from Mid-America Coalition for Energy Alternatives.

§§Hearings Transcript, p. 64, Testimony of Dr. Arthur Tamplin, NRDC.

It is noted that many of the comments go beyond the immediate issue of threat into areas of safeguards approaches and credibility, specific fuel cycle vulnerabilities, and the consequences to the public of successfully accomplished threats. These areas are addressed more specifically in other subsections of Section 7.4. In the text that follows, generalizations regarding the threat are reviewed and the implications for the LMFBR fuel cycle are discussed.

7.4.3.1 Description of the Threat

Of the threats to public health and safety, perhaps the terrorist attack is the most difficult to deal with because, to some degree, it may embody all the attributes of the other threats. Technical capability and force size may exceed those of professional criminals. Determination to succeed may be as strong as in the case of mentally unbalanced individuals. Organization and discipline may exceed that of all other threats. Use of the terrorist threat as the basis for this discussion is considered to cover all relevant aspects of the problem, including the assumption that terrorist groups may include employees of nuclear facilities.

Since the mid-1960's, the United States, as well as the rest of the world, has been experiencing an apparent upsurge in terrorist-inspired violence, and there is little reason to believe that the level of such violence will decline. Although terrorism is by no means a new phenomenon, and the same kinds of violent acts that have been committed for centuries are still being committed, the current aggregation of incidents exhibits characteristics that differ in degree or type from those that occurred in earlier years. They also suggest a growing threat to the security of nuclear installations and programs.

7.4.3.1.1 Number of Incidents

The extent of the recent increase in terrorist incidents is difficult to measure. There is a greater consciousness of terrorism, heightened by the increased dissemination of information on terrorist activities. The number of incidents recorded so far for the 1970's is much larger than that of the early 1960's and the stretch of years before; however, it is difficult to separate the actual increase from the apparent increase. Although determination of the statistical amount of increase is impossible, reports of police commissioners and similar authorities in various areas indicate that there is in fact more violence being committed.

7.4.3.1.2 Growth of Terrorist Groups

Although terrorists by nature operate clandestinely, and even the existence, let alone the objectives and operations, of groups and movements frequently remains unknown for years, the number of groups known to be active at the present time is considerably greater than that of any earlier period. Terrorist incidents increasingly involve interests of more than one country. This characteristic is particularly true of airplane hijacking and kidnapping of diplomats and business executives.

7.4.3.1.3 Level of Sophistication

Whether it be means of transportation, including airplanes and helicopters, electronic equipment such as walkie-talkies and listening devices, or remote control devices to deliver or detonate explosives from a concealed place at a distance from the target, modern devices of increasing sophistication are available to and being used by terrorists. Many weapons in the military arsenals of the world have turned up in terrorists' possession, and terrorists have been trained to use them, some in previous military service, many in training camps organized for that purpose. The danger that they might wish to add nuclear weapons to their equipment must be considered.

7.4.3.1.4 Targets

Terrorists strike at targets that yield the most valuable results in relation to their purpose. They have on occasion attacked targets of little strategic or economic value but considerable ideological importance. On other occasions they have selected targets on which a successful assault had a significant strategic or economic impact. The increase in complexity of available targets (i.e., aircraft, large commercial centers, urban concentrations of people, business enterprises, oil pipelines, communications networks, and power lines) presents to the terrorists highly vulnerable targets to which attack can yield a high degree of disruption of operational activity and a major amount of destruction, whether of human life or of property.

7.4.3.1.5 Effect of Publicity

Terrorists increasingly capitalize on the ready availability of publicity. The technological advances in news dissemination and, particularly in the United States, the expansion of news coverage given the terrorists provide them with ready access to a very large audience to publicize their views and their demands. One result of this is the imitation by one individual or group of an incident that was successful for another, creating a wave of kidnappings for ransom, for example. Even in

nations with a highly controlled press, however, terrorist incidents continue, and the attempts to reduce the effectiveness of terrorists by forbidding publication of anything concerning their activities has not been demonstrably effective.

7.4.3.2 Implication for LMFB

The characteristics of the LMFB fuel cycle in comparison to other fuel cycles are discussed in Section 7.4.6. The adversary views these characteristics in terms of their possible payoff. The professional criminal is interested primarily in theft of material that he may sell to interested buyers. The terrorist may be interested in theft of nuclear material for subsequent use in nuclear explosives, for use in radiological weapons, or even for subsequent sale as a means of financing other operations. He may be interested in sabotage to terrorize the public and discredit the government or the "establishment" or simply interested in the threat of sabotage for extortion or to gain some concession (freeing prisoners, for example). In short, the terrorist is interested in those aspects that may directly or indirectly cause either harm to the public or otherwise undermine government control or the public's confidence in the government's ability to control.

Recognition of these characteristics with respect to the objectives of the potential aggressor is important to the establishment of requirements for a new safeguards program and the evaluation of established programs. While attacks may be possible, they are not likely to be attempted unless they are consistent with aggressors' objectives. Terrorist acts may be considered by some to be irrational but actually may be consistent with long-range objectives motivated by social or political situations. Thus, while some terrorist activities inflict mass casualties or disruption, their basic motivation may have been, for example, to call attention to a social or political situation or to attack a symbol of society that relates to their interpretation of social or political ills. Irrational acts have, of course, been committed by mentally unbalanced individuals (perhaps to fulfill some psychological need) and therefore must be included in threat analysis.

The conclusion reached from this analysis is that any vulnerability in the fuel cycle might conceivably be exploited if it could be used for financial return or in some way cause harm to the public, or at least threaten such harm in a way that concessions would have to be made. There is no way to predict from historical data what form the threat would take or what means would be used by the adversary. The safeguards system must be based on an assumption that the possibility of a serious

threat exists and must be designed to make its effectiveness as independent as practicable of the nature of the threat. ●

7.4.4 Related Problem Areas

While not directly related to the domestic safeguards problems, similarity of the considerations involved render appropriate the inclusion under this topic of discussions concerning vulnerability to acts of war and sub-national diversion. Another such area, nuclear proliferation, is discussed in Section 5.4.3.1.

7.4.4.1 Vulnerability to Acts of War

Several comments expressed concern about the consequences of acts of war against nuclear fuel cycle facilities.* Representative comments were:

Any plutonium facility, whether it is a fast breeder, reprocessing plant, fabrication plant, or even a regular nuclear reactor is such a sitting duck in time of war....**

Nuclear power plants are the most vulnerable military targets in any country that uses nuclear energy. Actions against such installations would be consistent with belligerent aims to inflict casualties, deprive an enemy of electric power and deprive an enemy territory. In the next war involving a nuclear power, military actions are likely to cause major releases of radioactivity.†

[Nuclear facilities] offer an enemy a number of advantages for attack ... fewer bombs to knockout more energy sources....††

When discussing the vulnerability to acts of war of reactors and other nuclear fuel cycle facilities, two issues must be treated: first, the likelihood of the facility being targeted in wartime, and, second, the consequences of a successful attack. Both of these issues are covered below in discussions of the implications and consequences of attacks.

To frame the discussion, three terms of reference are cited:

*Comment Letters 8, p. 5 (Attachment 2); 12, p. 17 (Attachment 2); 22, p. 13; 25, p. 26; 38 (Sociopolitical Impacts) p. 9; 51, pp. 59-60. Pre-Draft Letters 6, p. 2; 17, p. 1.

**Comment Letter 8, p. 5 (Attachment 2) from Ilene and Gaylord Younghein.

†Comment Letter 12, p. 17 (Attachment 2) from Zero Population Growth.

††Comment Letter 25, p. 26 from Chauncey Kepford.

- (1) The examination of vulnerability is made in terms of overt war between the U.S. and a potential aggressor. Covert operations can be likened more to sabotage as discussed in Section 7.4.5.2.
- (2) The examination is made in terms of vulnerability to nuclear weapons and excludes conventional attack. If the war is overt, attacks would likely be of intercontinental nature or from sea-based platforms (i.e., strategic attacks). Under those circumstances, a conventional attack is implausible.
- (3) The strategic attack would be of large scale, of necessity including massive attack on U.S. strategic retaliatory forces. While one may postulate a limited nuclear attack, including attack on U.S. nuclear fuel cycle facilities, such attack would not destroy U.S. retaliatory capability and therefore is considered not credible.

The third point is intended as a response to the following comment, which the AEC interprets as an expression of belief in the credibility of a limited nuclear war:

. . . national governments may very well plan near-miss or low-yield nuclear explosions in the vicinity of nuclear power plants, including breeders. The military advantages of the resultant contamination should be very apparent. It becomes apparent that a fully deployed breeder reactor program partakes of the nature of a "doomsday machine" for the nation which adopts it. It is then unacceptable for the same reasons as apply to the doomsday machine concept: The rational forbearance of all human beings cannot be assumed. If your agency holds a contrary belief, this assumption should be stated explicitly and its underpinnings examined. Relevant to this consideration would be data on the trends of world armament, terrorism, and criminality.*

Any discussion of consequences of a successful attack must look beyond the isolated examination of a single attack on a single facility. The war situation that might give rise to postulated attacks on nuclear power facilities must be looked at as a whole. In the context of a massive attack on the forces and resources of United States, hundreds, if not thousands, of large yield weapons would be used over widely spread areas of the United States, irrespective of the existence of nuclear fuel cycle facilities. Many of these would be surface bursts, maximizing fallout. These attacks would create widespread havoc, and the effects of the weapons would have massive consequences in terms of casualties, facility destruction, and land contamination.

*Pre-Draft Letter 6, p. 2 from Zero Population Growth.

Considering this outcome, the consequences of attacks on the nuclear facilities would clearly be a relatively small increment of the overall consequences. However, because of the concerns expressed in the comments, the discussion below examines the implications and consequences of targeting the LMFBR fuel cycle facilities in war situations.

7.4.4.1.1 Implications and Consequences of Targeting Nuclear Facilities

Two reasons have been postulated by commenters for the possible targeting of facilities in the nuclear fuel cycle. First, a foreign enemy may deliberately wish to produce casualties; second, the enemy may be primarily concerned with resource destruction (e.g., denying the United States power production).

Several studies have examined the effects of successful attacks on nuclear facilities, including the LMFBR. Three of interest are:

- (1) C. V. Chester and R. O. Chester, "Civil Defense Implications of an LMFBR in a Thermonuclear Target Area," Nuclear Technology, 21: 190-200 (March 1974).
- (2) C. V. Chester and R. O. Chester, "Civil Defense Implications of a Pressurized Water Reactor in a Thermonuclear Target Area," Nuclear Applied Technology, 9: 786 (1970).
- (3) C. V. Chester and R. O. Chester, "Power Reactor Vulnerability," Civil Defense Research Project Annual Progress Report, March 1971-1972, Report ORNL-4784, Oak Ridge National Laboratory, 1972.

These studies examined the vulnerability of reactors to nuclear attack. They found in general that the probability of obtaining a militarily useful increase in casualties or fallout by deliberately targeting the reactor for a single ground-burst weapon was too small to make it attractive for the enemy planner. Also multi-weapon attacks to raise the probability of success to an acceptable level would become prohibitively expensive as compared with other potential weapons uses, such as direct attacks on urban areas. These conclusions are sensitive to changes in delivery accuracies, and as accuracies improve there would be a decrease in the numbers of weapons required to add the reactor core contents to weapon fallout.

If the case of an attack on a single LMFBR is isolated and examined, some comparison may be made between weapon effect and additional effect from the reactor contents,

assuming total addition of the contents to weapon fallout. The analysis in study (1) looked at the consequence of the reactor contents being added to the fallout from a 1-megaton fission weapon. With a 20-knot wind, the area of potentially lethal fallout (400-R isodose contour) to persons remaining unsheltered is increased by about 17% for a week's exposure and about 33% for a month's exposure. In terms of inflicting casualties, even if all core products were added to the weapon fallout, the enemy would gain only a marginally increased effect. While the products from the reactor have a much longer radioactive life than products of the weapon, they would not necessarily have the casualty effects that the enemy planner might be seeking. From the standpoint of the enemy planner, targeting of large urban areas can produce far more casualties for far fewer weapons and provide him the bonus of the probable destruction of soft industrial facilities in the area.

The possibility of an enemy attacking nuclear waste storage facilities to inflict casualties can also be examined in isolation. There could be large amounts of high-level and noble gas wastes accumulated in waste storage facilities by early in the 21st century. These would include wastes not only from the LMFBR but also from other reactor fuel cycles as well. The AEC has investigated the vulnerability of radioactive waste storage facilities to nuclear attack using the Savannah River complex as a model. At Savannah River, waste is stored at two tank farms about two miles apart, each containing 12 tanks of steel-lined, concrete construction. While the tanks have up to 10 ft of earth cover, they can be considered as surface targets because they would be cratered by a ground burst. Analysis showed that even with extremely large yields, multi-weapon attacks with reasonable accuracy would be needed for acceptable probabilities of success. A successful attack could release a very high level of long-lived radioactive waste. However, in the sense of near-term infliction of casualties, the radioactivity content of the waste is of the same range of magnitude as to be expected from high-yield weapons. Since waste storage facilities are generally sited in relatively remote areas, much of the immediate fallout would not likely add significantly to casualties. Again, if the goal of the enemy planner is to inflict casualties, a direct attack on urban areas would be likely to produce more casualties. A similar logic would apply in weighing whether to attack fuel fabrication or fuel reprocessing facilities in order to inflict casualties.

The second purpose for enemy targeting of nuclear facilities would be to cripple power production capabilities. To achieve an immediate payoff, the enemy must seek

the destruction of the reactors, since loss of fuel fabrication and reprocessing facilities would not have a near-term effect on power production. To cripple the reactor, he would not need extreme accuracy, given sufficient yield. Study (1) above indicates that a 1-megaton weapon detonated within 2-1/2 miles of a reactor would be capable of breaching the reactor containment and damaging the primary cooling system. Studies (1) and (3) point out that lethal exposures to airborne radioactive material escaping from the damaged reactor would be unlikely outside the area directly affected by the weapon.

The consequences to the United States of any possible attack must be viewed as part of a major nuclear strike. The additional effect from the attack on the nuclear facilities would be masked by the overall consequences of a massive strategic attack. Given direct hits on the facilities, casualties would at worst be of the same range of magnitudes as those produced by the weapons themselves. When viewed in the context of large-scale strategic war, the additional fallout from the attacked facilities are unlikely to greatly increase casualties.

7.4.4.2 Sub-National Diversion in Other Countries

The threat of sabotage and nuclear materials diversion will no doubt exist in other countries. The nature of the possible threat will vary considerably from country to country depending upon the size of the nuclear program and the type of nuclear facilities involved.

Several comments expressed concern about effects of the U.S. LMFBR program upon safeguards problems in other countries.* Key comments were:

Will our nuclear energy economy be abandoned if "international agreements and institutions to assure that the common good, is indeed, protected," do not come to pass? Can there ever be such a guarantee? Willrich and Taylor's book should be referenced and discussed.**

...one of the most critical tasks now facing the world...is to set up, within a very few years, a worldwide system of controls for reducing to an acceptable level the threat of destructive use of nuclear materials diverted or stolen outright from parts of the nuclear industry.†

* (1) Comment Letter 20, p. 7; 22, p. 8; 24, p. 2. (2) Pre-Draft Letter 15 (T. B. Taylor Enclosure), p. 1.

**Comment Letter 22, p. 8 from Mid-America Coalition for Energy Alternatives.

†Pre-Draft Letter 15 (T. B. Taylor Enclosure), p. 1.

Nuclear materials and equipment supplied to other countries by the United States are provided under terms and conditions of agreements for cooperation which include safeguards procedures. The recipient governments provide written assurance to the USAEC, with regard to each import, that items will be subject to all the terms of the agreement including safeguards to assure the items are not diverted.

The various foreign countries engaged in nuclear programs have been made aware of U.S. concern about safeguarding nuclear materials to preclude diversion and the preventive steps that have been taken in the United States. The U.S. is prepared to collaborate closely in exchanging information, data, and experience in the area of physical security with a view to arriving at commonly agreed procedures to preclude diversion. As the breeder reactor is developed and placed into foreign commercial operation, the U.S. will use all available means to assure that security measures are significantly expanded and modified to accommodate the future material commitments. Thus, these security measures will be revised as the magnitude of the problem increases. While the protection of nuclear facilities and materials is a sovereign national responsibility that only the countries themselves have the authority and responsibility to dictate, other governments can influence the security measures to be employed with respect to materials and facilities that they supply.

The International Atomic Energy Agency (IAEA) has published a series of recommendations for physical protection of nuclear facilities to assist the various countries in establishing the programs. The IAEA also administers an international safeguards and control system (involving records, reports, and inspections of nuclear material) to verify the Non-Proliferation Treaty and has been looked to by the U.S. to apply its safeguards to U.S. supplied materials and equipment.

The United States has urged and will continue to press for the expansion and modification of foreign nation security measures through our bilateral contacts and through the IAEA, including physical security to preclude diversion. The U.S. will give particular attention to future requests for supplies of highly enriched uranium and plutonium for power reactor use to assure that adequate safeguards including physical protection are in effect. The U.S. will continue to propose the adoption of international standards to be observed by all nations engaged in nuclear activities.

Several foreign countries also have indigenous breeder reactor programs and the number is expected to grow. The control of the equipment and materials associated with these programs is wholly a national responsibility, and these projects may not

be included under the provisions of the agreements for cooperation concluded with the United States in the absence of U.S. assistance to the project.

7.4.5 Consequences of Successful Acts

A failure of safeguards may lead to public risk arising from acts of material theft or diversion (nuclear explosion or radioactive material dispersal) or from acts of sabotage (radioactive material release). The potential consequences of these actions--theft, diversion, and sabotage--are discussed in this section. The second order, but nonetheless potentially serious, sociopolitical consequences attendant to or following a successful terrorist or criminal act are discussed in Section 5.4.2.1. The potential effects of LMFBR on nuclear proliferation matters are discussed in Section 5.4.3.1.

7.4.5.1 Consequences of Successful Theft or Diversion

A number of comments were received on the consequences of explosion or dispersal of stolen or diverted plutonium.* A representative comment is:

...the Statement contains a comment on the ease in constructing a nuclear explosive: "The construction of a workable nuclear explosive device is a complex and difficult task requiring specialized skills and considerable resources. Without testing, there is a substantial possibility that there would be no nuclear yield at all." This statement is unsupported either by material included in the Draft Environmental Statement or included by reference. The statement is also in direct contradiction to conclusions reached and supported by exhaustively detailed reports by persons acknowledged to be expert in the design of fission bombs....Are we to believe that the AEC is incapable of imagining the circumstances at the time and place of the detonation of an illegal nuclear weapon in the hands of an individual or group bent on "anti-social behavior?" Are we to believe that the AEC is incapable of specifying the effects--in terms of property loss, deaths and injuries, and of political and social responses--for an array of "circumstances at the time and place" which would bracket the possibilities in sufficient detail for policy considerations.**

The general thrust of the comments is that the AEC, in the Draft Statement (Appendix III-A), has overestimated the difficulty of successful bomb fabrication and of yield prediction and has failed to consider, or attempt prediction of, the potential

*⁽¹⁾ Comment Letters 8, p. 5 (Attachment 2); 12, Summary (Attachment 1); 20, pp. 3, 17-19, 20; 22, p. 12; 27, p. 19 (Comment #3); 51, pp. 48-49; 54, p. 7. ⁽²⁾ Pre-Draft Letters 15 (T. B. Taylor Enclosure), p. 2; 1, p. 9; 6, p. 1; 24, p. 1.
(3) Hearings Record Material 18, pp. III-2, -5, -8, -10.

**Comment Letter 20, pp. 17-19, 20 from Natural Resources Defense Council.

consequences of diversion-related nuclear calamities. The following discussion amplifies the AEC views on this subject.

7.4.5.1.1 Nuclear Explosion

The debate on whether or not construction of a nuclear explosive device is easy revolves around matters of degree. There appears to be general agreement that, given the availability of the requisite nuclear material, the construction of an illicit explosive device requires a certain level and range of skills and resources. Disagreement arises with respect to the way the level of required skills and resources are characterized. This is important because if the task is made to appear too difficult, the safeguards problem might not be seen in its true dimension; if the task is made to appear too easy, those who might be encouraged to attempt such acts could feel overconfident. Clearly, what would be easy for one man or group might be difficult for another. The design and implementation of the AEC's safeguards system is based on the premise that making an illicit nuclear explosive is within the range of skills and resources available to persons or groups operating outside the law.

The destructiveness of any illicit nuclear explosion depends on the circumstances at the time and place of its detonation and on its yield. The circumstances are a matter of choice for the adversary, as affected by constraints such as logistics and target accessibility, and will depend on his perception of how best to serve his purposes. The yield will depend on the characteristics of the nuclear material and the skills and resources of the adversary.

LMFBR fuel-cycle materials are far from ideal for weapons purposes. Chemical conversion of these materials to more efficient forms, while technically feasible, requires a sequence of time-consuming, careful operations; severe penalties (e.g., accidental criticality, plutonium ingestion) await the uninformed or inexperienced adversary. The fabrication and assembly of a workable weapon is complex and laden with many obstacles, any one of which could prevent the accomplishment of the adversary's first goal--the availability of a workable explosive device. The attempted detonation of even high-grade material is more likely to result in a low tonnage yield or a disassembling, non-nuclear explosion than a substantial yield explosion unless the fabrication and assembly have been carried out by highly trained and experienced technicians. A weapon fabricated directly from raw LMFBR fuel-cycle material will be less likely to operate successfully. Considering the sequence of goals that must be attained by the adversary, the overall probability

of any successful explosion of an illicit weapon is extremely low. That such a weapon would be in the multi-kiloton range is doubtful.

The physical effects of a nuclear blast can be determined from the published literature.¹³ A summary of these physical effects is given by Willrich and Taylor.¹⁴ The damage radii for various effects of nuclear explosions as functions of yield are shown in Table 7.4-1, reproduced from Table 2-1 in that report.

Examples are given by Willrich and Taylor¹⁴ to illustrate the effects of nuclear explosions in a football stadium, a residential area, or a basement parking lot. For example, "A (10 ton) explosion in the center of a football stadium during a major game could lethally irradiate as many as 100,000 spectators." While the examples given are speculative and are based on an assumption of complete success by the adversary, they do illustrate the extremely severe consequences of a nuclear explosion. For reasons stated earlier, the probability that any of these events would actually take place, while not specifically quantifiable, is considered to be extremely low. It should be further noted that the adversary who has succeeded in fabricating a workable weapon, despite the obstacles cited above, faces further serious obstacles if his goal is to cause a high number of casualties and great damage. The selection of appropriate emplacement areas is finite; the safeguards response capability, alerted by the theft or diversion, would have brought its search and detection techniques to bear; and law enforcement agencies would be watchful for suspicious actions, especially in congested urban areas, at public gatherings, at key governmental facilities, and in areas of technological vulnerability. Clearly, however, if a workable illicit device of even modest yield were cleverly placed and detonated, thousands of people could be killed and millions of dollars worth of property could be destroyed.

7.4.5.1.2 Radiological Weapons

The treatment of the consequences of radiological weapons is more speculative than that for nuclear explosions because of the greater extent of uncertainty involved. For example, if the purpose is to deny access to a facility with minimal injury to persons, plutonium might be dispersed by one of several means when the building or facility was empty and the authorities so notified.

The critical path for exposure resulting from a plutonium dispersal device would be inhalation and dose to the lung. There are some uncertainties connected with the specific dose-effect relationship, but the order of magnitude of the amount in the lung usually associated with short-term death is 10^{-3} to 10^{-2} grams and with long-

Table 7.4-1

DAMAGE RADII FOR VARIOUS EFFECTS OF NUCLEAR EXPLOSIONS AS FUNCTIONS OF YIELD^a

Yield (high explosive equivalent)	Radius for Indicated Effect (Meters)						Crater Radius (underground burst)
	500-rem Prompt Gamma Radiation	500-rem Neutrons	Fallout (500-rem Total Dose) ^b	Severe Blast Damage (10 psi)	Moderate Blast Damage (3 psi)	Crater Radius (surface burst)	
1 ton	45	120	30-100	33	65	3.4	6.7
10 tons	100	230	100-300	71	140	6.8	13.3
100 tons	300	450	300-1,000	150	300	13.6	26.5
1 kiloton	680	730	1,000-3,000	330	650	27	53
10 kilotons	1,150	1,050	3,000-10,000	710	1,400	54	104
100 kilotons	1,600	1,450	10,000-30,000	1,500	3,000	108	208
1 megaton	2,400	2,000	30,000-100,000	3,250	6,500	216	416

^aM. Willrich and T. B. Taylor, Nuclear Theft: Risks and Safeguards, Ballinger Pub. Co., Cambridge, Mass., 1974.

^bAssuming 1-hr exposure to fallout region, for yields less than 1 kiloton, increasing to 12 hr for 1 megaton.

term death (from cancer) is 10^{-5} to 10^{-4} grams. The dose received will be a function of concentration suspended in air, respiration rate, retention rate, and residence time. Other factors such as solubility will also have an effect but are not considered in this discussion of gross effects.

The area to be contaminated, the concentration in air, the particle size (affecting settling and resuspension rates and respiratory retention rates), and the residence time of the victims are more or less subject to the control of the adversary within the level of his skills and resources and within such constraints as logistics and target accessibility. Depending on the attacker's ability to transform the physical or chemical form of the material, plutonium could be prepared in liquid or solid form with coarse or fine particle size. It might be dispersed in corridors or ventilation systems, from moving vehicles, or by explosion or fire.

As an example, a large office building or roofed stadium 200 m long by 100 m wide by 50 m high will have an enclosed volume of $1,000,000 \text{ m}^3$. Assuming a respiration rate of 20 liters/min and a retention rate of 10%, the plutonium concentration in air necessary to produce short-term death after a 5-min exposure would be 0.1 to 1 g/m^3 or 100 to 1000 kg suspended in air. Since only a fraction of the total released is likely to be suspended, the total amount required would be several times that amount. The corresponding amount for long-term death would be 1 to 10 kg in suspension. For residence times longer than 5 min, the quantity required would be proportionately smaller. If the purpose is to force evacuation of the building or costly decontamination with minimal injury to personnel, 1 g uniformly scattered on the 20,000 to 100,000 m^2 of floor area would be sufficient.

As in the case of nuclear explosion, the number of scenarios by which the potential effects can be illustrated is unlimited. Willrich and Taylor¹⁴ offer a qualitative discussion of some possibilities. They also indicate that the use of radiological weapons does not appear to be consistent with observed behavior of terrorists or extortionists.

7.4.5.2 Consequences of Successful Sabotage

A number of comments were received on the subject dealt with in this section, that is, the consequences of successful sabotage of nuclear facilities or transportation elements.*

* (1) Comment Letters 16, p. 2; 22, pp. 2, 5, 6, 9; 27, p. 3; 38, pp. 8-10 (Sociopolitical Impacts). (2) Pre-Draft Letters 1, p. 9; 6, p. 1; 17, p. 1; 24, p. 1. (3) Hearings Record Material 18, p. III-2.

7.4.5.2.1 Facility Sabotage

As an introduction to the discussion of the consequences of sabotage of future LMFBR facilities, an examination of the inherent sabotage resistance that these facilities can be expected to possess is pertinent. Although information on the specific requirements that will apply to future facilities is not available and detailed design information is lacking, currently available information related to existing and near-term nuclear facilities is useful in indicating the inherent sabotage resistance probable in future facilities.

The safety features required in the design of nuclear fuel-cycle facilities, including reactors, which provide protection from internal accidents and resistance to natural phenomena, also provide protection against forced entry from the outside and against the effects of internally generated acts of sabotage.

In fulfilling the requirements of 10 CFR 50 ("Licensing of Production and Utilization Facilities"), applicants for reactor and reprocessing facilities must provide to the AEC, for approval, construction and operating license applications with evidence of meeting strict design criteria. The portions of the plants used for storing or processing plutonium must be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, and floods without impairing their capability to perform safety functions. Such design requirements result in massive structures that provide containment for reactors and confinement for processing and storage facilities.

In fulfilling the requirements of 10 CFR 70 ("Licensing of Special Nuclear Material"), applicants for mixed-oxide fuel fabrication and associated storage facilities must also provide to the AEC, for approval, construction and operating license applications with evidence of meeting strict design criteria.

The AEC will approve construction of the principal structures, systems, and components of such facilities after the AEC staff has determined that the design bases provide a reasonable assurance of protection against natural phenomena and the consequences of potential accidents. These criteria require rigid structures designed to resist a tornado or tornado-generated missiles and forces due to high-intensity seismic shock. The structures enclosing the areas where plutonium is being processed into fuel and assembled into rods are designed as confinement structures and as secondary-protection intrusion barriers.

Natural phenomena criteria include:

- (1) Provisions in the facility design to prevent, for example, a tornado-generated (300-mph wind) missile, which consists of a 4-in. x 12-in. x 12-ft long plank, from penetrating the containment and confinement structures. All entrances into these structures must also be provided with labyrinth shields to block direct openings to the outside.
- (2) Structures that are designed to withstand an internal overpressure of 3 psi when encircled by a tornado, during which the outside pressure drops in 3 sec, holds for 3 sec, and then returns to normal atmospheric pressure in 3 sec.
- (3) Provisions in the critical building designs to resist damage to the containment or confinement structures by establishing two forms of seismic data input (i.e., ground-surface-response spectra and floor-response spectra.) The seismic forces imposed on the external structure and internal components, including building and process equipment, are then analyzed and evaluated using site-history design-basis earthquake (DBE) and operating-basis earthquake (OBE) accelerations. A typical site condition might require analysis for a DBE of 0.25 g* and an OBE of 0.125 g. For the OBE, meeting the requirement means that after a system or structure has been subjected to forces equivalent to 0.125 g, the facility can continue to operate and, if necessary, can be shut down in a predetermined, safe sequence.
- (4) Designs that provide for flood protection to ensure that storage or process areas containing plutonium are adequately protected against "the worst possible flood." In some cases, such designs result in heavy-base slabs, up to a thickness of approximately 7 ft, to prevent uplift of the structure during an extreme flooding condition. In addition, the foundation and lower walls are heavily reinforced and waterproofed to resist a high, external water pressure under such conditions.

The use of the criteria for plant protection against natural phenomena results in well-protected, blast-resistant structures resistant to penetration and provides inherent resistance to external sabotage from implanted explosives or deliberate-impact mechanisms. The following are examples of such safety features:

*Note: g = the gravitational acceleration constant, which is approximately 32 ft/sec²

- (1) Reprocessing Plants. Reprocessing plants normally require massive structures for radiological protection. In addition, the portions of the structure where plutonium is being processed, separated, or stored are designed for protection against natural phenomena by providing confinement structures which include walls and decks as much as 2 ft thick consisting of a reinforced, concrete-slab construction suitably ribbed or braced to prevent penetration or to deter damage caused by external forces.
- (2) Plutonium Fuels Fabrication and Storage Facilities. In addition to the external structure, special features are incorporated in the internal designs. For any portion of the building where processing of plutonium is being conducted in glove boxes, the glove box construction, foundations, and building utilities must be provided with special support features to ensure the integrity of the glove-box confinement. An example of this is the special bracing for light fixtures, which are over the glove box, to prevent possible penetration of the confinement by a falling fixture dislodged by a seismic force or a force caused by an act of sabotage.

In addition to the protection provided by the features included in the designs to meet the criteria for natural phenomena, the biological shielding included in reactor containment structures and fuel-cycle facilities offer protection against forced entry from outside forces and internal forces generated by acts of sabotage:

- (1) The biological shield around a reactor is a heavily-reinforced, combined support and protective shield. The outer-containment concrete structure provides a secondary shield in case of reactor or primary system failure. The shielding characteristics required to meet the safety standards for radiation protection, as stated in 10 CFR 20, dictate the wall thickness necessary to meet allowable dose limits outside the containment.
- (2) The shielding requirements in and around reprocessing plants must protect plant personnel and the public from radiation. This type of massive construction is labeled "hot cell construction" and results in heavy walls and deck coverings of as much as 6 ft of reinforced concrete or an equivalent thickness of other high-density materials such as steel. Such shielding is needed for protection against the gamma radiation from the fission products which are at high concentrations in the process streams. Normally, these facilities are partially located below ground level,

which offers additional radiation protection. For the above-ground structure, where confinement is a requirement for operations maintenance and product handling, the housing-structure walls, roofs, and decks are of heavy-reinforced concrete construction. The high-level wastes leaving the plant are stored in special underground tanks which are normally located in concrete vaults that are designed for containment of any spills and fitted with instrumentation for tank levels, content temperature, radiation, and other data. The tops of the tanks and vaults are normally 8 to 10 ft below ground, and the area is protected against intrusion.

- (3) The plutonium confinement enclosures at fuel fabrication plants require neutron and gamma shielding for the protection of operating personnel. Where bulk plutonium is handled, the glove-box enclosure is provided with a neutron barrier that could have a shielding capability equal to that of 8 to 10 in. of concrete. This shielding could be in the form of neutron absorbing material enclosed in metal. In other portions of the process, such as pellet conveying or tube sealing, this shielding is reduced, but individual pieces of equipment are provided with local shielding enclosures to reduce exposures to allowable levels.

These inherent design features will supplement safeguards in protecting against sabotage. However, the consequences of potential acts of sabotage require discussion.

The use of a nuclear bomb for sabotage of a nuclear facility has been postulated.

... a terrorist attack on a nuclear facility with a clandestine nuclear bomb is a credible event.*

To assess the consequences of nuclear bomb sabotage, analysis taking into account factors such as facility design details and explosive device location and yield would be required. In determining the need for such analysis and in judging its priority, the probability that successful nuclear bomb sabotage would actually occur must be considered.

*Comment Letter 38 (Sociopolitical Impacts), pp. 8-10 from Natural Resources Defense Council, attaching an analysis by John W. Gofman of the consequences of such terrorists activity relative to the Barnwell Nuclear Fuel Reprocessing Plant in testimony before the South Carolina State Legislature.

The probability of occurrence of nuclear bomb sabotage is not known in a quantitative sense but is believed to be extremely low, because it would be the product of an extended series of what are judged to be very low probability events. Some of these are: the successful theft of fissile material from the safeguarded fuel cycle; the successful acquisition and application of the knowledge, skills, and resources necessary for safe processing and fabrication of an explosion device; the successful evasion of recovery activities mounted by Federal and other authorities; the successful placement of the device in a safeguarded area; and detonation of the device. It is also considered highly improbable that the individual or group having such a device would choose to attempt sabotage of a nuclear facility, which will be locally protected and physically hardened, in preference to using the device as a threat against relatively unprotected targets such as urban areas. For these reasons, the probability that a nuclear bomb would be successfully used to sabotage a nuclear facility is considered to be so low that the event must be judged incredible.

Considering the above, the AEC does not believe that it would be useful at this time to undertake analysis leading to quantitative estimates of nuclear bomb sabotage consequences or to review and comment upon consequence analyses prepared by others. In taking this position, the AEC recognizes an obligation to continue to examine the factors which enter into a judgment of credibility. This examination will be carried out as part of the activities described in Section 7.4.8 for the development of future safeguards.

In contrast with nuclear bomb sabotage, sabotage attempts involving less potent damage initiators are considered credible. These would include relatively small quantities of chemical explosives or other devices that might be used to cause physical damage to key safety systems and equipment either inside or outside facility buildings and flammable or pyrophoric materials that might be used to initiate fires inside facility buildings. An additional possibility is that, without any devices except readily available hand tools, an individual or small group might attempt to put an operating nuclear facility into an increasingly unsafe condition by maladjustment of control systems and protective interlocks.

The consequences of successful sabotage of LMFBR facilities cannot be quantitatively estimated with certainty at this time, primarily because designs and operating procedures have not yet been developed in sufficient detail to permit meaningful analysis. However, available preliminary analyses of serious accidents in future LMFBR facilities are believed useful in indicating the general magnitude of the

consequences of the "biased-accident" class of sabotage. Discussions of accidents in future LMFBR facilities, as well as in facilities such as the retrievable surface storage facility that would serve LMFBR and other fuel cycles, are presented elsewhere in this Statement.* Preliminary quantitative estimates of the consequences to the public are provided. For example, Table 4.3-21, which presents data on accidents in an LMFBR fuel fabrication plant, indicates that a general facility fire (which might be caused by a saboteur) would release about 0.013 grams of mixed uranium-plutonium oxide to the environment. Table 4.3-26 shows that an individual near the plant would receive a dose of about 0.0042 rem, and Table 4.3-27 indicates a 50-mile population dose of about 0.51 man-rem, as the result of this release. As another example, Table 4.4-15 presents estimates of the releases associated with a serious leak of highly radioactive liquid within the reprocessing plant. The leak was assumed to occur in a vessel or pipe containing dissolver product, one of the most radioactive streams of the plant, and all materials associated with 1 kg of heavy metal are assumed to be dispersed to the cell atmosphere, for release through normal or degraded filters to the environment. For this accident (which also might be imagined as sabotage-initiated), Table 4.4-21 shows that an individual near the plant could receive a total body dose of 8×10^{-5} rem, and Table 4.4-22 shows a 50-mile population dose of 0.12 man-rem.

These consequences are well within limits currently considered acceptable for credible accidental events. Significant analytical effort utilizing detailed plant design information would be required to confirm them. Additional analytical effort would be needed to estimate consequences of sabotage other than the "biased-accident" class. Section 7.4.8 provides information on the basic considerations and guidelines for future work related to sabotage of facilities.

7.4.5.2.2 Transport Sabotage

Radioactive materials in transport are inherently more vulnerable to sabotage attack than nuclear facilities. Future LMFBR transport (packages, vehicles, and other factors) will be designed to limit credible sabotage consequences to acceptable levels. The information on consequences presented herein is intended not as a prediction for the future LMFBR situation, but rather as an interim assessment to

*For information on LMFBR power plant accidents, see Section 4.2.7; fuel fabrication plant accidents, Sections 4.3.8 and 4.3.9; fuel reprocessing plant accidents, Sections 4.4.8 and 4.4.9; retrievable surface storage facility accidents, Section 4.6.3.1.5; noble gas storage facility accidents, Section 4.6.3.2.3; alpha waste storage facility accidents, Section 4.6.3.2.2.

provide early guidance toward timely development and implementation of consequence-minimizing methods.

The packages currently approved or projected for shipping the various kinds of radioactive materials found in the LMFBR fuel cycle are described in Section 4.5. Information on the radioactive inventory and mode of transport of each shipment is also presented in that section (see Table 4.5-1). Through qualitative consideration of the hardness of the packages, the physical form of the products contained, and the general characteristics of the vehicle, rough judgments can be made on the percentages of radioactive inventories that might escape to the environment (outside the vehicle enclosure) as the result of sabotage attack with various kinds of damage-producing devices, assuming that the contained products are unprotected (i.e., assuming no physical protection other than that provided by the current-design package and the non-hardened vehicle). Table 7.4-2 presents a set of estimates made on this basis.

The percent release numbers given in the table are believed to be conservative (high) estimates of the amounts of material that might escape from the package and the vehicle. Where the possible release is estimated to range from zero to an upper value (e.g., 0-10%), this is meant to indicate that there is a substantial probability that there will be no material released in an attack, because of factors such as:

- (1) package design (e.g., the outer container of the PuO_2 package may be penetrated, but the central pipe containing the PuO_2 may be unaffected),
- (2) physical characteristics of the contained item (e.g., the fresh fuel outer and inner containers may be ruptured, but the fuel cladding may remain intact),
- (3) lack of knowledge and skill of the saboteur.

Most of the materials in transport are non-volatile solids, which, should they escape to the environment, would be likely to produce localized contamination only. The exceptions are UF_6 , which reacts with moisture to produce gaseous HF; spent fuel, which contains gaseous and volatile fission products; and the noble gases.

For purposes of further evaluation of the potential consequences of transport sabotage, each of the following examples assumes that the release is the maximum shown in Table 7.4-2.

Table 7.4-2

ESTIMATED RADIOACTIVITY RELEASES TO ENVIRONMENT RESULTING FROM
HYPOTHETICAL SABOTAGE OF UNPROTECTED LMFBR PACKAGES (CURRENT DESIGN)

Material In Package	Mode of Transport ^a	Inventory of Shipment (Ci) ^a	Possible Radioactivity Release (% of Inventory)				Maximum Release (Ci)
			Device A	Device B	Device C	Device D	
UF ₆	Truck	3	0-1	10-50	10-50	10-50	1.5
UO ₂	Truck	102	0-1	0-5	0-5	0-2	5
PuO ₂	Truck	67 x 10 ⁵	0	0	0-1	0-1	0.7 x 10 ⁵
Fresh Fuel	Truck	11 x 10 ^{5b}	0-1	0-2	0-5	0-1	0.6 x 10 ⁵
Spent Fuel	Rail	33 x 10 ^{6c}	0	0	0	0-1	0.3 x 10 ⁵
Alpha Waste	Rail	2.8 x 10 ⁴	0-1	0-1	0	0-1	280
Low Level Beta-Gamma Waste	Truck	475	0-2	0-10	0-10	0-5	48
Tritium	Truck	3.2 x 10 ⁴	0-1	0-5	0-5	0-2	1600
Alpha-Beta Gamma Waste	Rail	500	0	0	0	0-1	5
Cladding Hulls	Rail	1.5 x 10 ⁶	0	0	0	0-1	0.2 x 10 ⁵
High-Level Waste	Rail	7.8 x 10 ⁶	0	0	0	0-1	0.8 x 10 ⁵
Noble Gases	Truck	9 x 10 ⁵	0	0	0	0-20	1.8 x 10 ⁵
Iodine	Truck	1	0-1	0-5	0-5	0-2	0.05

^aData derived from Table 4.5-1.

^bFor core and axial blanket. For radial blanket, inventory is 15 Ci.

^cFor core and axial blanket. For radial blanket, inventory is 4.5 x 10⁵ Ci.

Plutonium Dioxide

Table 7.4-2 indicates a maximum release to the environment of 0.7×10^5 Ci. The amount of material involved would be about 6000 g. This would cause a serious contamination problem in the immediate vicinity. In addition, some of the material would become airborne. In order to estimate the effect of the airborne material, additional assumptions are necessary on area of contamination, wind velocity, and particle pickup. For this analysis, the contaminated area is assumed to be 30 m^2 and wind velocity is assumed to be 3 m/sec. For PuO_2 (assumed to be in the form of powder), respirable size particles would exist in a concentration of about $1 \text{ } \mu\text{g}/\text{m}^3$ in the air immediately above the contaminated area. For these conditions, there would be a downwind release of 0.3 g/hr, or about 3.5 Ci/hr.

The doses to man associated with this release can be estimated by extrapolating from the alpha waste transportation accident doses given in section 4.5.6.2. For an assumed 1-hr release from the sabotage site, the maximum dose to an individual (50 m from the site) would be about 12 rems (whole body) and about 520 rems to the critical organ (bone). The corresponding 50-mile population doses would be about 10 man-rems (whole body) and 440 man-rems (bone).

Spent Fuel

Table 7.4-2, indicates a maximum sabotage-related release of 0.3×10^5 Ci. A sabotage device was assumed to rupture all fuel assemblies and produce an opening in the cask large enough to permit all available gaseous and volatile fission products to escape quickly. If a fire accompanied the sabotage, additional volatilized fission products would escape until the fire was extinguished. Solid and non-volatile radioactive materials ejected from the damaged cask would make up the remainder of the release.

A spent fuel cask accident involving release of gaseous and volatile fission products has been analyzed. Table 4.5-19 indicates releases of about 2120 Ci without a fire and 3080 Ci assuming a 2-hr fire. Table 4.5-35 presents estimated individual and population doses for several variations of the accident. The highest individual dose is 4.3 rems (short-time ground level release, no fire, individual 50 m from site). The highest population dose is 6.8 man-rems (2-hr elevated release, fire). The data in Table 4.5-35 are believed to provide a reasonable estimate of that portion of the radiological consequences of spent fuel-cask sabotage which can be attributed to the escape of gaseous and volatile fission products.

In terms of curies, the major portion (about 90%) of the postulated sabotage release would be solid and non-volatile radioactive material. The ejection of this material from the damaged cask would seriously contaminate the rail car and nearby ground or facilities. The area contaminated would probably be greater if the car were moving at the time of the attack. Individuals near the car might suffer severe exposure, particularly if they remained in the area.

Noble Gases

Section 4.5.5.13 states that a very severe accident could result in complete inventory release (9×10^5 Ci). For a successful sabotage, only one of the six cylinders in the shipment was judged to be damaged, resulting in a loss of approximately 20% of the total inventory.

Section 4.5.6.2 describes the methodology and assumptions used in accident analyses. For the noble gas accidents as well as accidents to certain other shipments, an important assumption is that a fire would accompany the accident, resulting in an elevated rather than a ground level release. Table 4.5-33 indicates that the highest potential dose to an individual would be about 3.5×10^{-5} rem, at about 1250 m from the site of the accident. Table 4.5-34 indicates a 50-mile population dose of 0.4 man-rem as the result of the noble gas accident. If a fire accompanied the sabotage event, the doses would be a factor of five lower than for the accident case. If no fire is assumed, and the conversion factors in Table 4.5-36 are used, the maximum potential dose to an individual 50 m from the site would be about 0.06 rem, and the 50-mile population dose would be about 0.2 man-rem for the sabotage case.

7.4.5.2.3 Advanced Fuels

One commenter requested that the Final Statement discuss the consequences of sabotage with respect to carbide as well as oxide reactor fuel.

... it is essential that the consequences of deliberate acts of sabotage or terrorism that would result in plutonium dispersion should be fully discussed at each stage in the fuel cycle for both oxide and carbide fuels....*

Apparently this request is based on the understanding that the AEC believes the relatively early introduction of carbide fuel is necessary to economic justification

*Comment Letter 38, p. 12 (Plutonium Toxicity) from Natural Resources Defense Council.

of the LMFBR program. This is not the case. The discussion of advanced fuels in Section 11 is intended to illustrate the economic and resource incentives for advanced fuel development, but does not change the selection of oxide as the reference fuel, for which substantial economic benefits are estimated. Advanced fuels such as plutonium carbides or nitrides would not be committed to commercial use without a thorough investigation of their safety, environmental, and safeguards implications.

7.4.6 Safeguards Aspects of LMFBR and Other Fuel Cycles

The nature of the safeguards problem is substantially dependent on the characteristics of the nuclear materials present in a fuel cycle and of the forms and locations in which they appear. Some elements of the fuel cycle are less vulnerable, or contain materials of less value, than others to a person or group intent upon acts against society. A number of comments were received requesting information on the safeguards aspects of the LMFBR and comparisons with alternative nuclear fuel systems.* This section provides information on the LMFBR and other fuel cycles from a safeguards point of view. Regarding the other fuel cycles, emphasis is placed on the LWR and HTGR which have been demonstrated and are in commercial use for electric power generation. Less extensive consideration is given to proposed but less well developed nuclear cycles: GCFBR, LWBR, MSBR, and CTR.

7.4.6.1 The LMFBR Fuel Cycle

A breeding reactor cycle produces fissile fuel from fertile fuel at a rate higher than the original fissile fuel is expended in the production of energy. The fissile fuel thus produced is separated from the spent fuel by reprocessing. The new fuel can then be recycled to the reactor.

Figure 7.4-1 presents a simplified schematic of the LMFBR fuel cycle. The reactor is fueled with blended mixed oxides of plutonium and uranium. The PuO_2 makes up approximately 20% of the fuel and provides the fissile material for power generation. The UO_2 is either depleted or normal U-235 concentration. Because the reactor is cooled by liquid sodium, the neutron spectrum is fast. Under these conditions, more plutonium is produced from neutron captures in U-238 than is destroyed in the process of plutonium fission. The fission process also results in the formation of intensely radioactive fission products.

* (1) Comment Letters 8, p. 4 (Attachment 2); 9, p. 1; 20, pp. 3, 5; 34, p. 11; 37, pp. 3, 5; 51, pp. 38, 43; 53, p. 84. (2) Pre-Draft Letter 1, pp. 10-11. (3) Hearings Transcript, p. 65, p. 107, p. 229. (4) Hearings Record Material 18, pp. 1-4, III-1.

LMFBR FUEL CYCLE

Figure 7.4-1

After its period of use in a reactor, the fuel is depleted and poisoned with fission products and must be replaced with fresh fuel. The spent fuel elements are transported in massive shielded casks to a reprocessing plant. The fission products are separated, solidified, and transported to high-level waste storage. The unexpended plutonium and the produced plutonium are transported to storage (or directly to the fuel fabrication facility for recycle) as PuO_2 . (For startup of early LMFBRs, the PuO_2 will be supplied by the reprocessing of LWR fuel.) The unused uranium is separated as uranyl nitrate, uranium oxide, or uranium hexafluoride and is transported to storage or recycled directly to the fuel fabrication facility.

At the fuel fabrication facility, plutonium and uranium oxides are blended to form the bulk mixed oxide feed which is then pressed into pellets. The pellets are loaded into fuel pins which in turn are assembled into complete fuel elements. The elements are then transported to the reactor for refueling.

The attractiveness of a material as a target for theft will depend on the degree of processing necessary to transform the material into a useful form. Table 7.4-3 lists several of the material forms found within the LMFBR fuel cycle and shows the processing necessary to produce a quantity of material that could be used in a nuclear explosive.

Of the materials listed in Table 7.4-3, PuO_2 is the most suitable for use as a nuclear explosive. While $\text{Pu}(\text{NO}_3)_4$ can sustain a fission reaction, it is not directly suitable for use in a nuclear explosive and would require chemical conversion to the oxide or metal (see Section 4.4.4.1.6). The mixed plutonium-uranium oxide fuel (bulk feed, pellets, pins, or elements) can also sustain a fission reaction. However, the amount of contained plutonium and the technical sophistication necessary to produce an explosion without separation, would be much greater than if the plutonium were separated. Therefore, diverted mixed oxide materials would have to be processed to separate the plutonium. This processing (see Section 4.4.4.1.5) is more complex than that required to convert the nitrate to the oxide.

The intensely radioactive spent-fuel elements from a reactor are remotely handled and shipped to reprocessing plants in massive shielded casks. An attempt to divert the spent fuel is not likely, although sabotage might be attempted to bring about a dispersal of radioactive material (see Section 7.4.5.2). The spent-fuel elements are treated at a reprocessing plant to separate the plutonium and uranium from the high-level wastes. The relative attractiveness of the plutonium, produced as

Table 7.4-3

MATERIALS PRESENT IN LMFBR FUEL CYCLE

Material	Location in Fuel Cycle	Processing Necessary	Approximate Mass Needed for 10 kg of Contained Pu	Other Difficulties
PuO_2	Reprocessing output Plutonium storage Fuel fabrication input	None	12 kg	Toxicity
$\text{Pu}(\text{NO}_3)_4$	Reprocessing	Conversion to oxide or metal	17 kg	Toxicity
$(\text{Pu}+\text{U})\text{O}_2$	Fuel fabrication	Dissolution and separation	60 kg	Toxicity
Fuel element (prior to irradiation)	Fuel fabrication output Reactor input	Mechanical and chemical separation	1 complete assembly (150 kg)	Toxicity
Irradiated element	Reactor output Reprocessing input	Mechanical and chemical separation	1 complete assembly (150 kg)	Intense radioactivity, massive shielding

either a nitrate or oxide, has been discussed above. The uranium is also produced as a nitrate or oxide; however, since it is, at most, of natural U-235 concentration, it is not a target for diversion. The high-level waste contains an extremely low concentration of plutonium and uranium and would not be a likely target for diversion to produce a nuclear explosive. Here again, dispersal of radioactive material might be attempted via sabotage.

The LMFBR fuel cycle involves no enriched uranium. The plutonium isotopes are stronger gamma-ray sources than enriched uranium. This property significantly increases the likelihood of detection in the case of attempted surreptitious removal of plutonium. Portal monitors can easily detect the passage of one gram of unshielded plutonium, in any of the forms in which it would be found in the LMFBR fuel cycle. Shielding sufficient to prevent detection by the doorway monitor would be very heavy and bulky.

Although recycled plutonium fuel for LMFBR* will require shielding to keep the radiation exposure of workers below occupational standards, the radioactivity of LMFBR plutonium is unlikely to have a seriously deterring effect on potential diversion. The neutron output of recycled plutonium is over 10 times greater than that of an equal mass of weapons-grade plutonium. This increase arises from the greater Pu-240 content of reactor recycle plutonium and its spontaneous fission neutrons as well as (α, n) neutrons from the oxygen in the oxide fuel material. This neutron output can cause premature initiation of an intended explosive reaction in a weapon made of such material. However, this situation does not preclude use of recycled plutonium for explosives.

7.4.6.2 The LWR and HTGR Fuel Cycles

The LWR and HTGR offer the only near-term source of nuclear power. Both of these cycles are described elsewhere in this Statement (LWR, Section 6A.1.1 and HTGR, Section 6A.1.2). Neither the LWR nor HTGR offers the possibility of a closed fuel cycle, since each requires mining, milling, and isotopic enrichment of uranium.

The LWR fuel cycle, including plutonium recycle, is illustrated in Figure 7.4-2. Table 7.4-4 summarizes the material forms found in the LWR fuel cycle in the approximate order of their potential use to a diverter. The present LWR fuel is uranium oxide enriched to about 3% in U-235. This material is not useable as a

*The isotopic composition of plutonium in recycled LMFBR fuel is expected to fall into the following ranges (percentage by weight): 238--1%; 239--60 to 70%; 240--22 to 25%; 241--3 to 13%; and 242--1 to 4%.

LWR FUEL CYCLE

Figure 7.4-2

Table 7.4-4

MATERIALS PRESENT IN LWR FUEL CYCLE (with Pu recycle)

Material	Location in Fuel Cycle	Processing Necessary	Approximate Mass Needed for 10 kg of Contained Pu	Other Difficulties
PuO_2	Reprocessing output Plutonium storage Recycle fuel fabrication	None	12 kg	Toxicity
$\text{Pu}(\text{NO}_3)_4$	Reprocessing	Conversion to oxide	17 kg	Toxicity
$(\text{Pu}+\text{U})\text{O}_2$	Recycle fuel fabrication	Dissolution and separation	350 to 1000 kg	Toxicity
Fuel element (prior to irradiation)	Recycle fuel fabrication Reactor input	Mechanical and chemical separation	1 PWR, 2 BWR assemblies (~400 to 1000 kg)	Toxicity
Irradiated element	Reactor output Reprocessing input	Mechanical and chemical separation	1 PWR, 2 BWR assemblies (~400 to 1000 kg)	Intense radioactivity, massive shielding

nuclear explosive nor does it constitute a serious radiological hazard. As in the LMFBR, the LWR spent fuel is highly radioactive. The reprocessing of LWR fuel is similar to that of LMFBR fuel. The high-level wastes must be heavily shielded and may be of concern from a radioactivity dispersal viewpoint. The recovered uranium is too low in enrichment to be of concern. As in the LMFBR, the LWR produces plutonium via neutron capture in the fertile uranium. The plutonium is separated from the reprocessed fuel as with LMFBR. At present, the separated plutonium is in storage. In the future, the plutonium may be recycled into the LWR fuel cycle in order to reduce the need for uranium isotopic enrichment. This process is similar to that planned for the LMFBR. In the LMFBR, plutonium will make up about 20% of the fuel, while in the LWR, plutonium will make up no more than 2 to 4% of the recycled fuel. However, the plutonium can be separated from the uranium in the fuel by chemical techniques.

A simplified diagram of the uranium-thorium fuel cycle used by the HTGR is given in Figure 7.4-3. The HTGR is fueled with coated fuel particles of fissile U-235 and fertile Th-232 in a graphite moderator. Cooling for this thermal reactor is provided by helium gas. The HTGR is not a breeder reactor, but it does convert an appreciable amount of fertile Th-232 to fissile U-233.

Referring to the fuel cycle diagram in Figure 7.4-3, the mining, milling, and conversion of uranium is the same as for the present LWR cycle. Safeguards problems in these steps are minimal. Important from the safeguards viewpoint is the enrichment step because 93% enriched U-235 is used in the HTGR. The highly enriched UC_2 present at the conversion plant output and the fuel fabrication plant input and in transit between these facilities could be used directly in weapons without further processing.

As the enriched UC_2 moves through the fuel fabrication plant, it becomes increasingly diluted. First, the fissile $^{235}UC_2$ is coated with three layers (two of pyrolytic carbon and one of SiC) to retain the fission products. The ThO_2 is coated with two pyrolytic carbon layers. When U-233 is recycled in the HTGR, it will be coated in the same way as $^{235}UC_2$. The different particle coatings and sizes aid in separating the U-233 from the U-235 and U-236 during the fuel reprocessing. Holes in the graphite fuel assemblies are filled with rods of compacted coated particles.

The shipment of the fabricated fuel to the reactor and spent fuel from the reactor to the reprocessing plant will likely utilize the same massive shielded casks for

HTGR FUEL CYCLE
Figure 7.4-3

both operations, because with the U-233 recycle the daughter products of the U-232 in the fresh fuel are very radioactive and all handling operations must be accomplished remotely. This radioactivity would serve as a deterrent against unauthorized diversion. The $^{233}\text{UC}_2$ is similar to PuO_2 and $^{235}\text{UC}_2$ in that it could be directly utilized in a nuclear explosive without further processing. It is also radiotoxic, but less so than PuO_2 . Only a small amount of fissile plutonium is produced in the HTGR (about 1 kg/year for each 1000 MWe).

Table 7.4-5 lists the materials found in the HTGR fuel cycle that are of interest from a safeguards viewpoint. The materials are roughly ordered as to the degree of processing required to produce a nuclear explosive device.

7.4.6.3 Other Reactor Concepts

Several other reactor types may be utilized in meeting the long-term power needs of the United States. These are discussed in Section 6 under Alternative Technology Options (Gas Cooled Fast Breeder Reactor, Section 6A.1.4; Light Water Breeder Reactor, Section 6A.1.3; Molten Salt Breeder Reactor, Section 6A.1.5; and Controlled Thermonuclear Reactor, Section 6A.1.6). General comparisons with the fuel cycles already discussed can yield insight into the types of safeguards problems that might be encountered if any of these concepts attain widespread commercial use.

7.4.6.3.1 Gas Cooled Fast Reactor

This reactor is an alternative breeder option to the LMFBR. It is a fast reactor that uses high pressure helium as a coolant. The fuel consists of mixed $(\text{Pu-U})\text{O}_2$ pellets in the core region with depleted UO_2 pellets in the blanket. In this respect it is essentially identical to the LMFBR. The GCFR will operate on the same fuel cycle as the LMFBR and should have similar safeguards problems with respect to the types of material present.

7.4.6.3.2 Light Water Breeder Reactor

The LWBR is a water moderated and cooled thermal reactor that uses the U-233 thorium breeding cycle. For the initial startup, U-233, U-235, or plutonium may be used. Use of any of these fissile materials has attendant material safeguards considerations. Once a breeding cycle is attained, no U-235 or plutonium would be used. With respect to use of U-233 and thorium, the safeguards problems for this fuel cycle are similar to those for the HTGR as described in Section 7.4.6.2.

Table 7.4-5

MATERIALS PRESENT IN HTGR FUEL CYCLE

Material	Location in Fuel Cycle	Processing Necessary	Approximate Mass Needed for 10 kg Uranium	Other Difficulties
UC ₂ (93% U-235)	Conversion output Fuel fabrication input	None	12 kg	None
UF ₆ (93% U-235)	Enrichment output Conversion input	Conversion to oxide	15 kg	None
Recycle ²³³ UC ₂	Reprocessing output U-233 storage Fuel fabrication input	Conversion to oxide	~12 kg	Radiotoxic
Mixed U-235 and Th Fuel (oxide or carbide)	Fuel fabrication	Chemical or physical separation	~250 kg	None
Mixed ²³³ U + ThO ₂	Fuel fabrication	Chemical separation	~250 kg	Radiotoxic
Fresh Fuel (U-235)	Fuel fabrication output Reactor input	Mechanical and chem- ical separation	~2100 kg (15 assemblies)	None
Fresh Fuel (U-233)	Fuel fabrication output Reactor input	Mechanical and chem- ical separation	~2100 kg (15 assemblies)	Radiotoxic
Irradiated Element	Reactor output Reprocessing input	Mechanical and chem- ical separation	~4200 kg (30 assemblies)	Intense radio- activity, mass shielding

7.4-40

7.4.6.3.3 Molten Salt Breeder Reactor

This reactor type differs from the above concepts in that it uses a fluid fuel circulating through the core coupled with on-line continuous fuel reprocessing. The MSBR operates on the ^{233}U -Th breeding cycle and, in that sense, is similar to the LWBR and the HTGR. The use of a molten salt fuel with on-line chemical reprocessing results in significant differences between the MSBR fuel cycle and others. There is no solid fuel fabrication. No shipping and reprocessing of spent fuel elements is under consideration since the fuel reprocessing is done on-line and on-site. Safeguards problems would center on the critical core loading, which could contain U-235, its manufacture (a different chemical form than the currently used oxides), and its shipment to the reactor site. In the "equilibrium" cycle, safeguards problems would be minimized by having all activities confined to the reactor complex, similar to the nuclear park concept. The storage and shipping problems associated with fresh fuel fabrication and spent fuel reprocessing would be eliminated. There could be some shipment from the reactor of bred U-233, a potential diversion target. The problems for the diverter arising out of the toxicity and radiation levels associated with U-233 have been mentioned.

7.4.6.3.4 Controlled Thermonuclear Reactor

The CTR program is in its early development stages (see Section 6A.1.6). The program is not anticipated to use any strategic special nuclear materials. Safeguards problems should not be present as they are in the fission reactor fuel cycles. The successful development of laser fusion for weapons applications, if possible, would require extensive technology and would likely be outside the capability of a small terrorist group. Additional discussion of these possibilities is premature and beyond the scope of this report.

7.4.7 Description of the Current AEC Safeguards Program

Section 7.4.2 describes the AEC safeguards objectives and program elements in general terms. The current AEC program is directed at protecting against theft or diversion of types and quantities of nuclear materials that could be used for nuclear explosives and to protect against sabotage of nuclear facilities containing such materials. The requirements are designed to protect against theft, diversion, or sabotage by one or two employees with access to the plant and material, a small armed force attacking a plant or vehicle, or both acting in combination.

7.4.7.1 Licensing Activities

Title 10 of the Code of Federal Regulations (10 CFR) provides that no person may receive title to, own, acquire, deliver, receive, possess, use, transport, import, or export SNM without a license. The AEC publishes specific safeguards requirements for materials and plant protection in 10 CFR and carries out the following activities to assure effective compliance with the requirements: (1) pre-licensing evaluation of a license applicant's proposed nuclear activities including safeguards procedures; (2) issuance of a license to authorize approved activities subject to specific safeguards requirements; and (3) inspection and enforcement to assure that applicable safeguards requirements are met by implementation of approved procedures.

The pre-licensing review addresses information submitted by the applicant to the AEC for approval--including the applicant's technical qualifications; a description of the process, equipment, and facilities to be used; the material control and accounting program, including measurement performance capability; and a physical security plan. The details of the material control and accounting program and the physical security plan are withheld from public disclosure as provided in 10 CFR Part 2 (10 CFR 2).

The pre-licensing review includes consideration of other regulatory aspects of the facility design and operation. Full account is taken of the interrelated effects of safety requirements and of the inherent features of the facility that contribute to the protection afforded by the safeguards system. For example, the requirements that SNM be safely contained during normal operation, operational accidents, and earthquakes and tornadoes, as well as requirements for shielding and safe shutdown in the event of maloperation, result in the incorporation of substantial physical containment structures, shutdown systems, and personnel access limitations that in themselves enhance safeguards.

Each licensee must confine possession and use of SNM to the purposes and locations authorized in the license and may transfer nuclear materials only to an authorized recipient. The licensee must also comply with the detailed accountability and physical protection requirements incorporated into the license pursuant to the regulations. The licensee is required to afford the AEC opportunity at all reasonable times to inspect SNM and the premises and facilities where SNM is used, produced, or stored. In addition, each licensee is required to make available for inspection any relevant records and to perform or to permit the AEC to perform any tests deemed necessary for the administration of AEC regulations.

7.4.7.2 Safeguards Requirements for Fixed Facilities

7.4.7.2.1 Physical Protection

In recognition of the potential threat of diversion of SNM or intentional damage to nuclear facilities, the AEC has promulgated regulations for the protection of licensed facilities against such acts. These regulations (10 CFR 50, 70, and 73) apply to licensees authorized to possess or use 5 kg of U-235 (contained in uranium enriched to 20% or more), 2 kg of U-233, 2 kg of plutonium, or a weighted combination of these.*

With regard to protection of reactor facilities, the procedures to be employed at LMFBRs will be an outgrowth of procedures currently used at commercial light-water reactors. Protection of LMFBRs can build on a base of more than 15 years of experience before commercial LMFBRs go into operation in the 1980s. Current AEC regulations provide for a sabotage protection program to be designed by the reactor licensee and approved by the Commission. The AEC has published a Regulatory Guide¹⁵ to assist the licensee in the development of an adequate program. The guide includes recommendations on control of material and personnel access to the plant site, selection and training of plant operating personnel, monitoring of plant equipment, and design and arrangement of plant features. Some of the specific criteria it includes are: on-site armed guards; two continuously manned alarm stations; two independent communication links with law enforcement authorities; specifications for intrusion alarms, emergency exit alarms, and line supervisory systems; equipment testing; and protection of vital equipment through design features including automatic indication of inoperability.

Nuclear power plants possess several inherent structural characteristics that would make intentional damage extremely difficult. Examples are the steel-lined, reinforced or prestressed concrete containment shells, which are capable of withstanding the effects of such events as large jet aircraft impact, and the massive steel pressure vessels containing the nuclear fuel, which in turn are surrounded by heavy concrete shielding up to 8 ft or more in thickness. Much of the primary system is also in the below-grade regions of the containment building and is afforded additional protection by the surrounding earth. Additional features that provide protection against acts of sabotage, incorporated into typical plant designs for normal safety reasons, include missile shields, physical separation of vital engineering safety

*The regulations apply to a weighted combination of 5000 g or more computed by the formula: $\text{grams} = (\text{grams contained U-235}) + 2.5 (\text{grams U-233} + \text{grams plutonium})$.

features, and duplication of essential electrical and mechanical systems. These features, together with conventional industrial security measures such as fencing and guards, collectively provide a significant measure of protection against the occurrence or the effects of sabotage.

The requirements for facilities other than reactors specify that vital equipment or SNM be located within areas protected by barriers, which, in turn, are within a fenced or walled protected area. The space between the protected area fence and the inner barrier must be monitored to detect abnormal presence or activities. Guards and watchmen must be trained and equipped; access to protected and vital areas must be restricted; individuals authorized to enter such areas without escort must wear coded picture badges; vehicles inside the protected area must be escorted. Persons and packages entering protected areas are searched (employees having AEC security clearance and packages other than hand-carried are searched at random). Prior to entry into a material access area, all packages are searched, and all persons, packages, and vehicles are searched upon leaving. A Regulatory Guide¹⁶ has been issued on control of personnel access.

7.4.7.2.2 Material Control and Accountability

Accountability is one of the fundamental measures used in the safeguarding of nuclear materials and is applicable to all types of nuclear facilities. It includes preparation of detailed and current records on the form, quantity, and location of SNM and the completion of material balances based on physical inventories. In its general application, it includes various administrative and operational procedures directed at maintaining current knowledge of nuclear material quantity and location and detecting any removal of such material from authorized locations. Methods include documented transfer of custodial responsibility, regular and frequent piece count by operating personnel, and analysis of correlated process information.

A specialized aspect of material accountability is "material balance" accounting in which statistical information is generated by which the accounting data can be evaluated. The sensitivity of this technique is limited by the accuracy of the measurements, and the timeliness is limited by the interval between physical inventory measurements.

Licensees authorized to possess at any one time more than one effective kilogram* in unsealed form are required to establish a measurement system and physical inventory procedures adequate (1) to assure that the uncertainty of the material balance is within prescribed limits and (2) to calculate material balances based on physical inventories at bimonthly intervals for plutonium (except for plutonium containing 80% or more by weight of Pu-238), for U-233, and for uranium enriched to 20% or more in the isotope U-235 and at semiannual intervals for uranium enriched to less than 20% in the isotope U-235; for plutonium, U-233, and highly enriched uranium in that portion of an irradiated fuel reprocessing plant from the dissolver to the first vessel outside the shielded portion of the process; and for plutonium containing 80% or more by weight of the isotope Pu-238. Minimum standards have been stipulated for the quality of these material balances. Licensees authorized to possess from 350 g up to one effective kilogram of contained U-235, U-233, plutonium, or any combination thereof are required to conduct physical inventories at least annually.

7.4.7.3 Safeguards Requirements for SNM in Transit

In addition to protecting SNM at specific facilities in the LMFBR fuel cycle, AEC safeguards are directed toward protection of material being moved between sites. At the present time, about 500 licensee shipments of SNM each year are protected against theft or diversion because the quantity and/or isotopic enrichment is of sufficient magnitude to be considered strategically important. The provisions of 10 CFR 73 include specific physical protection requirements that apply to licensees who ship 5 kg of U-235 (contained in uranium enriched to more than 20%), 2 kg of plutonium or U-233, or a weighted combination of these (see Section 7.4.7.2).

Truck shipments involving these quantities of material must be escorted by two armed guards in a separate vehicle unless the licensee uses a truck or trailer specially designed to protect against theft or diversion. Truck shipments must be made directly from the shipper to the consignee with no loading or unloading of other cargo between these points. Additional measures include: (1) communication every 2 hr by radiotelephone on board the truck (where radiotelephone coverage is not available, conventional telephone calls must be made when there has been no communication for more than 5 hr); (2) marking of the top and sides of the truck with

*"Effective kilograms of special nuclear material" means: (1) for plutonium and U-233 their weight in kilograms; (2) for uranium with an enrichment in the isotope U-235 of 0.01 (1%) and above, its element weight in kilograms multiplied by the square of its enrichment expressed as a decimal weight fraction; and (3) for uranium with an enrichment in the isotope U-235 below 0.01 (1%), by its element weight in kilograms multiplied by 0.0001.

identifying letters or numbers; (3) use of preferential routing to avoid trouble areas; (4) continuous surveillance of truck transport, including the use of two persons on board; (5) preplanning shipments to assure delivery at a time when the receiver is available to accept the material; and (6) the use of locks and seals on vehicles and containers.

When rail transportation is used, the shipment must be escorted by two armed individuals in the shipment car or in an escort car of the train, to keep the shipment cars under observation and to guard the shipment and check the car or container locks and seals when the train is stopped. Radiotelephone communication must be maintained with a licensee or his agent, backed up as needed by normal telephone communication at scheduled stops. All transfers must be monitored by armed personnel.

Regulation 10 CFR 73 prohibits licensee shipments aboard passenger aircraft of more than 20 g or 20 Ci, whichever is less, of plutonium or U-233 and shipments of more than 50 g of U-235 enriched to more than 20%. When cargo aircraft are used, the number of enroute transfers are to be minimized and are to be observed by armed monitoring personnel.

Shipments by sea must be made on vessels making minimum ports of call; ship-to-shore contact must be made daily. No ship-to-ship transfers are permitted. Transfer to other transport modes must be monitored by armed guards. The shipment must be kept in a sealed compartment that must be monitored during transfer of other cargo.

Importers are required to protect shipments in accordance with the requirements outlined above from the time the shipments arrive in this country. Exports must be accompanied by escorts (unarmed) from the last terminal in the U.S. to the point where the shipment is unloaded at a foreign terminal.

7.4.7.4 Inspection and Enforcement

7.4.7.4.1 Inspection

During operation of a licensed facility, the AEC carries out a program of on-site inspection to assure continued effective implementation of the protection plans. Each licensee is required to afford the AEC opportunity to inspect the nuclear materials and the premises and facilities where the materials are used, produced, or stored; to perform or permit the AEC to perform necessary tests of materials and equipment; and to make available any records pertaining to possession, use, or transfer of nuclear material.

The AEC's inspection strategy is directed at achieving its objectives on a systematic basis, where the scope, frequency, and intensity of inspection are determined primarily by considering: (1) strategic value of the SNM, (2) the accessibility of the SNM and (3) safety significance.

Secondary but important modifying factors are: (1) prior inspection history of the facility and (2) results of AEC monitoring of facility reports, including shipper/receiver differences.

The inspection activities are carried out in a manner intended to achieve one of the following levels of assurance:

- (1) Level A. Assurance that the facility has the capability to safeguard material adequately.
- (2) Level B. Assurance that the facility not only has the inherent capability but is, in fact, employing the capability at a satisfactory level of performance.
- (3) Level C. Assurance that the facility has the capability and is performing at a satisfactory level with independent testing of facility performance. This level of assurance requires the AEC to perform independent measurements and verifications to assure that stated quantities for receipts, shipments, inventories, and discards are credible and that physical protection systems are working properly.

Safeguards inspections consist of one or more of three distinct sets of activities:

- (1) audit of records and review of procedures, programs, and operations,
- (2) verification of inventory by observation and independent measurements, and
- (3) evaluation of physical protection of materials.

The appropriate level of assurance and inspection activities is associated with a facility on the basis of an inspection grouping that is made according to the criteria indicated in Table 7.4-6.

7.4.7.4.2 Enforcement

If items of noncompliance or deficiencies are found in the licensee's implementation of safeguards requirements, the licensee is instructed to take prompt corrective action and to inform the AEC of the results. The AEC has the authority to modify,

TABLE 7.4-6

INSPECTION OF LICENSEES

Inspection Group	Inspections	
<u>Group I</u>		
Fuel Facilities--Material of High Strategic Importance	Fuel processing and fabrication plants--Level C Assurance	
<u>Criteria</u>	<u>Inspection Activity^a</u>	<u>Frequency</u>
Authorization to possess large quantities of strategically important materials (plutonium, U-233, and/or enriched uranium >20% U-235) in unsealed form. Quantities authorized: >5 kg of plutonium and/or U-233; >15 kg of contained U-235.	(1)	3 per year
	(2)	1 per 2 years
	(3)	1 per year
	Irradiated fuel reprocessing plants - Level C Assurance	
	<u>Inspection Activity^a</u>	<u>Frequency</u>
	(1)	6 per year (minimum)
	(2)	1 per year
	(3)	1 per year

<u>Group II</u>		
Reactors--Fuel of High Strategic Importance	Level C Assurance	
<u>Criteria</u>	<u>Inspection Activity^a</u>	<u>Frequency</u>
Authorization to possess large quantities of strategically important materials (plutonium, U-233, and/or enriched uranium >20% U-235) in sealed fuel for reactors or critical assemblies. Quantities authorized: >5 kg of plutonium and/or U-233; >15 kg of contained U-235.	(1)	1 per 2 years
	(2)	1 per 2 years
	(3)	1 per year

^a (1) Audit of records and review of procedures, programs, and operations.		
(2) Verification of inventory by observation and independent measurements.		
(3) Evaluation of physical protection of materials.		

TABLE 7.4-6 (continued)

Inspection Group		Inspections	
<u>Group III</u>			
Fuel Facilities--Material of Moderate Strategic Importance		Level C Assurance	
<u>Criteria</u>		<u>Inspection Activity^a</u>	<u>Frequency</u>
Authorization to possess, in any form, >5000 kg of U-235 contained in uranium enriched to <20% U-235		(1)	1 per year
		(2)	1 per 3 years

<u>Group IV</u>			
Reactors--Fuel of Moderate Strategic Importance		Level C Assurance	
<u>Criteria</u>		<u>Inspection Activity^a</u>	<u>Frequency</u>
Licensees authorized to possess <20% U-235 in sealed fuel.		(1)	1 per 3 years
		(2)	1 per 3 years
		(3)	1 per year

<u>Group V</u>			
Other Licensees Possessing Small Quantities of Material but Greater than 350 g		Level B Assurance	
<u>Criteria</u>		<u>Inspection Activity^a</u>	<u>Frequency</u>
Authorization to possess small quantities of strategically important materials (plutonium, U-233, and/or enriched uranium $\geq$ 20% U-235) in an unsealed or reactor fuel form. Quantities authorized: $\leq$ 5 kg of plutonium or U-233, or $\geq$ 350 g but $\leq$ 15 kg of contained U-235.		(1)	1 per 4 years
		(2)	1 per 4 years
		(3)	1 per 2 years

Authorization to possess >350 g of U-235 but <5000 kg of U-235 contained in uranium enriched to <20% U-235.			

^a (1) Audit of records and review of procedures, programs, and operations.			
(2) Verification of inventory by observation and independent measurements.			
(3) Evaluation of physical protection of materials.			

TABLE 7.4-6 (continued)

Inspection Group	Inspections
<u>Group VI</u>	
Licensees Possessing Less than 350 g of SNM	Level A Assurance
<u>Criteria</u>	<u>Inspection Activity</u>
Authorization to possess uranium of any enrichment in quantities <350 g of contained fissile material.	Certain items checked during health and safety inspections.
<u>Group VII</u>	
Licensees Possessing Source Material	Level A Assurance
<u>Criteria</u>	<u>Inspection Activity</u>
Authorization to possess source material in any quantity.	Same as Group VI

suspend, or revoke licenses and to impose civil penalties on licensees for noncompliance with the terms and conditions of their license. Violators of the Atomic Energy Act or any regulation or order issued by the AEC may be guilty of a crime and, upon conviction, may be punished by fine or imprisonment or both as provided by law.

7.4.7.5 Response to Theft or Sabotage

AEC procedures provide for response to:

- (1) any suspected or actual theft of SNM or other material which could present a radiological hazard;
- (2) any threat of sabotage to a facility containing such materials;
- (3) any threat involving the destructive use of such materials.

Licensees are required to inform the AEC promptly, and will normally inform local law enforcement agencies, in the event of a suspected or actual theft or of a threat of sabotage. If the threat arises outside nuclear facilities, the AEC may be informed by various sources such as local law enforcement agencies, other government agencies, or concerned citizens.

Upon being informed of any of the circumstances listed above, the AEC would promptly inform the FBI, which has statutory responsibility for investigating all such incidents. The AEC would support the FBI with specialized technical assistance, especially in connection with the recovery of stolen material. In addition, the AEC would undertake to determine whether there is a potential hazard of nuclear explosion or radiological danger. If a hazard is determined to exist, the various AEC elements* responsible for implementing the established Radiological Assistance Plan would be alerted or activated. This plan provides for advice and assistance in the areas of emergency evacuation and rescue, radiation monitoring, decontamination, and specialized emergency medical services where personnel are exposed to radiation.

7.4.7.6 Adequacy of the Current AEC Safeguards System

Comments on the current AEC safeguards system included requests for a discussion of the adequacy of the current system.**

*Including, for example, the Headquarters Radiological Incident Center, the Joint Nuclear Accident Coordinating Center, the Aerial Radiological Measuring System, and the appropriate AEC field offices.

** (1) Comment Letters 8, p. 4 (Attachment 2); 20, p. 9; 22, p. 12; 25, p. 14; 37, pp. 6, 7, 8; 51, p. 40, 42; 53, p. 4. (2) Pre-draft Letters 15 (T. B. Taylor Enclosure); p. 5; 20, p. 1. (3) Hearings Record Material 18, p. III-2, -5.

The AEC "considers that safeguards measures presently in place provide adequate protection at this time against this kind of threat, independent of the probability of its occurrence." I cannot understand the basis of the quoted conclusion....Since [the Rosenbaum study] was performed after a new set of special nuclear material safeguards regulations were finalized by the AEC in November 1973, I believe it strongly corroborates my conclusion that the present system of AEC safeguards does not adequately protect the public from the risks of theft of special nuclear materials that could subsequently be used for destructive purposes.*

...we are concerned by the recent findings of the General Accounting Office [that implementation and enforcement of safeguards provisions have been deficient in some cases] which led to the revision of 10 CFR Part 73.**

In addition, a question was raised regarding the protection of small quantities of SNM:

...it is stated that "the AEC seeks to prevent any diversion of nuclear material and does not recognize any quantitative limit on this objective." How can this statement be reconciled with the fact that the AEC regulations for the protection of licensed facilities against the potential threat of diversion of special nuclear materials (SNM) apply only to those licensees authorized to possess 5 kilograms or more of U-235 contained in highly enriched uranium, or 2 kilograms or more of plutonium or U-233? (Volume III, p. 7-70). I am disturbed by this exception of smaller quantities of SNM from any special physical security requirements...†

The current system is designed to protect against theft or diversion of types and quantities of nuclear materials that could be used for nuclear explosives and to protect against sabotage of nuclear facilities containing such materials. To the extent that protection is considered necessary against theft or sabotage of other, non-explosive quantities or types of nuclear material, the current system would have to be changed accordingly. The rationale proposed in Section 7.4.8.1 for the structure of future safeguards does not exempt any quantity of material from concern, but makes clear the relationship between the potential consequences of an adversary's action and the degree of protection required.

The current system is designed to protect against theft or sabotage by one or two trusted employees or a small armed force or both. Although the size of the adversary force is only one of several factors that could influence the nature of the safeguards to be employed, the current system might not be effective against

*Comment Letter 37, pp. 6, 7, from International Research and Technology Corp.

**Comment Letter 53, p. 4, from Environmental Protection Agency.

†Comment Letter 37, p. 7, from International Research and Technology Corporation.

large, heavily armed forces. This lack would be more important in connection with sabotage than in the case of theft where a large group could be a disadvantage to the adversary during pursuit and recovery operations.

With regard to the effectiveness of the system in achieving its objectives, the evaluation is necessarily a matter of judgment. The AEC considers that the current regulations, as implemented by the plant operators and enforced by AEC staff, will adequately achieve the protection objectives for which it is designed. The current regulations include amendments that became effective on March 6, 1974, and represented a significant strengthening of the previous regulations. These amendments resulted from internal AEC review and staff study carried out over several years.

Appendix IV.A discusses three independent reviews of the AEC's safeguards system which were done during recent years. They were:

- (1) Improvements Needed in the Program for the Protection of Special Nuclear Material (U.S. General Accounting Office, Washington, D.C., Nov. 7, 1973);
- (2) Protecting Special Nuclear Material in Transit: Improvements Made and Existing Problems (U.S. General Accounting Office, Washington, D.C., April 12, 1974); and
- (3) D. M. Rosenbaum et al., "Special Safeguards Study," Directorate of Licensing, U.S. Atomic Energy Commission, April 1974.

The two GAO reports identified deficiencies or apparent deficiencies, many of which were due to conditions that would be resolved by the regulatory amendments then under review.

The "Special Safeguards Study" was performed under contract to the AEC and was a "very broad brush view" of the safeguards problem by five knowledgeable people. The qualitative views and conclusions of this group were expected to serve to establish priorities for short-term effort to effect improvements. In the end, the report mainly iterated safeguards options that were already under consideration. The report identifies the limitations of material balance accounting but ignores its value when it recommends the abandonment of material-unaccounted-for ("MUF") evaluation rather than supplementation with additional procedures, as is already being done on a limited basis.

7.4.8 Future AEC Safeguards

7.4.8.1 The Future Structure of AEC Safeguards

More systematic and comprehensive safeguards measures will be required for the future expanding nuclear power system, including the LMFBR fuel cycle. This section describes the approach by which a methodology for future safeguards is being developed. A number of comments received on the Draft Statement were concerned with the future development of safeguards.* Representative comments were:

....several recurring statements in the report, such as "these general factors, coupled with the broadened 'target' for diversion offered by the increased use of plutonium, indicate the need for continuous upgrading and strengthening of the AEC's safeguards program" (p. 1.7-8), strongly suggest that the AEC does not consider the present safeguards program to be adequate for the LMFBR fuel cycle. **

....how does the AEC plan to develop an adequate system of safeguards? Again we suggest that this may well be beyond human capabilities.[†]

Since the potential for possible diversion and the magnitude of possible consequences will increase if breeders are developed and used, this is a major consequence of a decision to develop the breeder reactor program.^{††}

Other commenters were more optimistic:

I believe in the future that the AEC's safeguards program can be strengthened such that adequate assurance will be available that this will not be as serious a problem as it appears at the present time.[§]

....in the area of safeguards, perfection is never achieved and perfection will never be achieved. By "perfection" I mean absolutely zero risk. What must be strived for, and we can't settle for less, is to reduce the risks to an acceptable level. We have evidently done this over the years in the weapons area in that no untoward incident has ever occurred with nuclear weapons. That full experience, of course, is an experience that the Atomic Energy Commission participated in. They participated in it, and that background is available to them and is being used in the attacking of the problem of the civilian nuclear sector.^{§§}

The following discussion is responsive to these comments with respect to the approach by which future safeguards will be developed, implemented, and evaluated.

* (1) Comment Letters 20, pp. 2, 3, 8, 9; 37, p. 2; 38 (Sociopolitical Impacts), p. 6; 48, pp. 22, 24; 51, pp. 38, 39; 62, p. 9. (2) Hearings Transcript, pp. 61, 62, 63, pp. 191-192, pp. 210-211, p. 220, p. 230, p. 19 (SIPI Addendum to Hearings). (3) Hearings Record Material 18, p. III-1.

** Comment Letter 37, p. 2-3, from International Research and Technology Corp.

† Comment Letter 38 (Socio-political Impacts), p. 6, from Natural Resources Defense Council

†† Comment Letter 51, pp. 38, 39, from Environmental Impact Assessment Project.

§ Hearings Transcript, p. 220 by R. Balent.

§§ Hearings Transcript, p. 230 by Carl Walske, Atomic Industrial Forum.

The development of future safeguards will be based on an appreciation of the nature and dimensions of the threat and the establishment of safeguards requirements directed at countering the threat. To date, the studies directed at defining the threat have concluded that there is no way to predict the characteristics of the adversary nor to determine the probability that a particular scenario would be attempted by the adversary. However, an effective safeguards system may be designed using a definition of the threat which is expressed in terms of the events that represent the goals of the adversary and the sequences of action that must be completed for those goals to be achieved. Table 7.4-7 is a summary of events grouped

Table 7.4-7
EVENT TABLE

Category of Consequences	Event	Type of Location	Material Quantity (Large = >1 kg)
I	Nuclear Explosion	Populated	Large
II	Nuclear Explosion	Unpopulated	Large
	Dispersal: Sophisticated	Populated	Large
	Dispersal by Sabotage	Populated	Large
	Criticality Incident	Populated	Large
III	Dispersal: Unsophisticated	Populated	Large
	Dispersal: Sophisticated	Unpopulated	Large
	Dispersal: Sophisticated	Populated	Small
	Dispersal: Unsophisticated	Populated	Small
	Dispersal by Sabotage	Unpopulated	Large
	Criticality Incident	Unpopulated	Large
IV	Dispersal: Sophisticated	Unpopulated	Small
	Dispersal: Unsophisticated	Unpopulated	Large
	Dispersal: Unsophisticated	Unpopulated	Small

by category of consequences listed in the order of decreasing severity for various combinations of events, population density, and material quantity. This ordering of categories permits the priority of action and the degree of protection to be related to the magnitude of the potential consequences. The ordering of events within each category has no significance.

Each of the listed events requires that the adversary complete an action sequence including several of the following activities:

- (1) decision to cause and produce the event;
- (2) organization of perpetrators;
- (3) planning of attempt;
- (4) acquisition of physical resources;
- (5) acquisition of information on material location and protection;
- (6) external penetration of facility or vehicle;
- (7) access to facility;
- (8) control of vehicle;
- (9) access to material;
- (10) destruction and/or manipulation of equipment or material;
- (11) removal of material;
- (12) construction of explosive or dispersal device;
- (13) delivery to event location; and
- (14) event-detonation, critical incident, or dispersal.

Figure 7.4-4 illustrates the relationship of these activities and depicts possible adversary action sequences that could produce the generalized events identified in Table 7.4-7.

The safeguards system consists of the proper mix of safeguards actions to counter all relevant adversary action sequences. The safeguards include interruption activities to reduce the probability of the adversary successfully completing an action sequence and minimization activities to reduce the magnitude of the consequences of a completed sequence. The protective actions for interrupting the sequence of adversary actions or minimizing the consequences within the attack part of the sequence are those that are currently under the direct authority of the AEC. Commission actions in connection with the other parts of the sequence will usually be carried out in association with law enforcement and other government agencies.

7.4.8.1.1 Interruption Activities

The goal of interrupting the action sequence may be accomplished by deterring an attempt or by detecting an adversary action and responding to prevent the completion of the sequence. The general principle to be applied is "protection in depth," that is, to provide multiple opportunities to interrupt any adversary action sequence and to detect an adversary action as early as possible. This approach implies that time

7.4-57

ADVERSARY ACTION SEQUENCES

Figure 7.4-4

will be a critical parameter in establishing goals for the specific safeguards activities.

Specific measures that can be used to interrupt the adversary action sequence include:

- (1) Legal provisions establishing adversary actions as criminal acts punishable by severe penalties.
- (2) Public information that communicates a high probability of adversary failure and apprehension.
- (3) Liaison with police intelligence organizations to detect preparatory adversary activities.
- (4) Legal provision for rewarding informants.
- (5) Physical barriers to impede entry into a transport vehicle or into a facility except through well-defined, authorized portals.
- (6) Sensors and alarms to detect attempts at entry through the physical barriers.
- (7) Access controls to detect attempts at unauthorized entry through normal portals.
- (8) Monitoring systems to detect unauthorized passage of nuclear materials, weapons, high explosives, or other adversary tools through barriers or portals.
- (9) Hardened facilities, containers, storage vaults, or vehicles to deter and delay attempts to remove or disperse nuclear materials.
- (10) Communication systems to assure timely and appropriate response to alarms generated by instruments or personnel.
- (11) Armed security personnel at fixed sites and accompanying shipments of nuclear material to provide an immediate response to alarms at a level that takes into account the ability of reserve law enforcement and military units to provide a timely response force.
- (12) Internal controls and administrative procedures to provide timely detection of diversions that might go undetected by perimeter controls and monitors.
- (13) Police intelligence and detection activities directed at the recovery of stolen material prior to its utilization.

Figure 7.4-5 shows an example of a specific adversary action sequence and related interruption activities.

AN EXAMPLE ADVERSARY ACTION SEQUENCE AND
ASSOCIATED INTERRUPTION ACTIVITIES

Figure 7.4-5

For each sequence of adversary actions, the relevant set of interruption activities should reduce the probability of adversary success to an acceptably low level for a broad range of adversary characteristics. The safeguards effectiveness, expressed as the probability of adversary success, might be sensitive to the characteristics of the adversary for some action sequences and insensitive for others.

For many action sequences, development of methods for quantitatively assessing the probability of adversary success is considered possible. However, a quantitative statement will not be possible for all action sequences; therefore, a qualitative assessment will be necessary, based on a detailed consideration of the relationship of the safeguards actions and the adversary action sequence. A study is currently under way to provide a methodology that will permit these assessments to be made as quantitatively as is possible at this time. The study will be completed in December 1974.

The difficulty of arriving at an objective assessment of effectiveness in the absence of adequate historical data is common to many areas that deal with human behavior. One analogy is the achievement of national security. The defense posture must be "adequate" in relation to the threat, but there is no objective way to assess the national security in quantitative terms. The method of assuring adequacy includes professional judgment by the military and review and appraisal by Congress.

7.4.8.1.2 Minimization Activities

The goal of minimizing the consequences of successful adversary action is effected by reducing the potential hazard inherent in a nuclear facility or material or by responding to an event or a threatened event in a manner that reduces the effect on life and property. The measures relevant to this purpose include:

- (1) Facility siting, design, and operating criteria to limit potential consequences of sabotage.
- (2) Vehicle design and operating criteria to limit potential consequences of sabotage.
- (3) Criteria for physical and chemical form of material at certain points in the fuel cycle to impede its use as an explosive or dispersal weapon.
- (4) Provision for automatic reaction to certain adversary actions which alters drastically the material or facility so as to reduce the hazard of adversary success.

- (5) Prior organization and planning for evacuation and decontamination.

7.4.8.1.3 Future Safeguards Program

The future safeguards program will be based on the approach described above and will include the basic functional elements listed in Section 7.4.2. The implementation of these functions is a continuing, iterative process involving the activities shown in Figure 7.4-6 and described below.

- (1) Improvement of threat definition is the purpose of interdisciplinary threat analyses that are being conducted to establish an understanding of the possible organization, operational methods, and equipment that might be used in future terrorist attacks. Similar studies, including some directed at motivation analysis, will be an ongoing activity to keep abreast of the ability to define the threat and the social changes that determine the threat.
- (2) Improvement of the safeguards system evaluation model will be provided by current and future efforts to provide a methodology for systematic development and evaluation of safeguards. A study directed at such improvement will be completed in December 1974 and will provide an initial capability to quantify goals and evaluate effectiveness for use in defining and revising the safeguards system. Ongoing efforts to improve these capabilities will include adversary simulation gaming analysis, as well as other analytical techniques, to test the strengths and weaknesses of existing safeguards and security systems. The results will be used to improve the systems evaluation models and to identify specific requirements for technological development.
- (3) Improvement of capability for interruption and minimization will involve individual projects and studies aimed at resolving specific problems. This ongoing activity mainly responds to requirements that are identified during program review and system evaluation. Subjects for which studies are under way or planned include the following:
 - (a) Co-location of reprocessing and fabrication facilities to minimize transport of accessible plutonium and provide more effective facility protection by concentration of resources.
 - (b) Use of massive or secure, penetration-resistant containers for shipment--and possibly for storage--of plutonium. This procedure might involve the use of the same casks for shipment of both fresh and irradiated fuel assemblies.

7.4-62

Figure 7.4-6
ITERATIVE PROGRAM FOR SAFEGUARDS IMPROVEMENT

- (c) Use of specialized vehicles for transport of plutonium, incorporating hardened crew and cargo compartments, secure communication and vehicle-tracking systems, and automatic protective and vehicle disabling mechanisms.
 - (d) Armed convoys for transport of plutonium or arrangements for relaying protective responsibility among local law enforcement agencies.
 - (e) Safeguards "drills and maneuvers" similar to those used by other organizations with infrequently exercised functions.
 - (f) Use of automatic protective mechanisms at fixed-site facilities for areas where strategically important types and quantities of SNM are processed or stored.
 - (g) Restrictions on the form of plutonium that could appear at different parts of the fuel cycle (e.g., co-precipitation of PuO_2 and UO_2 at the output of the reprocessing plant to avoid transport of PuO_2).
 - (h) Personnel reliability checks for employees in the nuclear industry.
 - (i) Evaluation of alternative guard force structures including the possibility of a new or existing Federal guard force, a private guard force with support from government law enforcement, or a mixed Federal/private force.
 - (j) Techniques for greatly shortening inventory intervals, including automatic label-reading devices coupled to assay instruments and central computers for inventory control and other such dynamic materials control techniques, to improve the timeliness and sensitivity of materials balance accounting.
 - (k) Expanded use of internal controls to provide early detection of covert theft by employees. Such controls include the evaluation of process data, the use and timely inspection of tamper-indicating seals on process equipment and on containers, and verification of material presence by such indicators as container gross weight and material radiation spectra.
- (4) System Evaluation and recommendations for improvement will be based on the analysis of adversary action sequences for each of the events listed in Table 7.4-7, with priorities established by the magnitude of event consequences. The analysis of adversary action sequences and the safeguards evaluation model will be used to establish criteria, quantitative whenever feasible, for interruption and minimization capabilities. These criteria will constitute or form the basis for recommended modifications of the safeguards requirements. These recommendations will take into account a cost-benefit analysis of environmental, safety, economic,

social, operational, and other impacts as well as the effectiveness of the proposed measures.

- (5) Safeguards policy decisions will be made at appropriate levels of management taking into consideration the technical requirements and the overall national objectives.
- (6) Promulgation of safeguards requirements will emphasize goals rather than means, but system components will be specified when necessary to assure adequate protection. The revision of regulations related to the commercial use of strategic SNM in power generation will be expedited in order to assure that issuance of new requirements will precede any significant growth. Requirements that would affect facility design will be given priority as appropriate.
- (7) AEC operations, including licensing review and inspection activities, will be directed at evaluating the safeguards effectiveness of plant design and operation procedures in providing protection against specified adversary actions. Enforcement activities will emphasize timely correction of safeguards deficiencies.
- (8) The materials and plant protection operations carried out by the plant operator will be based on AEC safeguards requirements and will be directed at achieving an adequate level of protection against all relevant adversary action sequences. Protection plans will be submitted to the AEC for review at the time of license application and will be subject to subsequent review and inspection.
- (9) The U.S. Government interagency operations include AEC liaison and consultation with law enforcement and intelligence agencies at the national and local levels. The AEC will provide technical assistance in the development of plans and procedures for deterrence, interdiction, and pursuit and recovery where nuclear materials are involved. Also, AEC technical capabilities will be established and maintained as required to support interagency emergency preparedness plans covering nuclear sabotage, dispersal, or explosion and to support any search and recovery procedures conducted by other agencies.

7.4.9 Costs of Future Safeguards

This section provides preliminary estimates of the economic impact on LMFBR fuel cycles of safeguards designed to prevent theft or diversion of plutonium or sabotage that could expose the public to dangerous radiation levels. Several comments concerning the costs of providing adequate safeguards and the lack of such information

in the Draft Statement were received.* Key comments were:

Planning for the safeguards program rests on the assumption that whatever measures are deemed necessary can and will be provided within the constraints of program economics. Information in the draft statement does not provide assurance that adequate safeguards can be provided within the constraints that may be imposed by limitation of costs or resources.**

The safeguarding that must be necessary to ensure absence of diversion risk from the plutonium portion of the LMFBR cycle does not appear to be a difficult or expensive task, although it certainly must be addressed in the design of an LMFBR power system.†

The commercial LMFBR fuel cycle is not likely to become routinely operational before the late 1980's, and many of its detailed characteristics have not yet been determined. The safeguards measures described here were therefore chosen only to illustrate possible approaches to achieving a balanced system of effective safeguards for such a fuel cycle, using the present AEC regulatory framework and estimated characteristics of LMFBR fuel cycles as a point of departure. As more detailed cost-benefit analyses of alternative new regulatory policies and ways of implementing them are carried out, and the LMFBR program becomes defined in greater detail, some safeguards options that are significantly different from those described briefly in this section can be expected to be adopted. There does not appear to be any fundamental reason, however, to expect that adoption of such options would involve costs much higher than those that are derived in this analysis. As discussed briefly in the concluding part of this section, there exist some new options that are likely to decrease overall LMFBR fuel cycle costs, while at the same time lowering the risks of theft or sabotage.

The overall conclusions of the analysis are:

- (1) The operating costs of safeguards with a high level of effectiveness will be less than 2% of the total operating costs of a large (80,000-MWe) LMFBR fuel cycle module.
- (2) The capital costs of safeguards equipment will be less than 1% of the LMFBR fuel cycle capital costs.
- (3) Safeguards costs for LWR without plutonium recycle would be about half of LMFBR safeguards costs.

* (1) Comment Letters 10, p. 1; 12, pp. 8, 9; 19 (Attachment No. 2); 20, p. 3; 51, p. 47; 53, pp. 1, 4 (Attachment); 58, p. 1; 59, p. 4. (2) Pre-Draft Letter 15 (T. B. Taylor Enclosure) p. 7. (3) Hearings Transcript, pp. 179-180, p. 271.

**Comment Letter 53, p. 1 (Attachment), from U.S. Environmental Protection Agency.

†Hearings Transcript, p. 271, by M. Levenson, Electric Power Research Institute.

- (4) The costs of safeguarding components of LMFBR fuel cycles will be somewhat greater than the costs of safeguarding components of HTGR, LWR with plutonium recycle, or MSBR and comparable with the costs of safeguarding GCFR fuel cycles.

7.4.9.1 General Framework for Analysis

Preliminary estimates of the cost of applying the safeguards measures discussed in Section 7.4.8.1 to LMFBR fuel cycles have been obtained by proceeding through the following steps:

- (1) Description of a reference LMFBR fuel cycle "module," consisting of twenty 4000-MWe nuclear power stations with an aggregate generating capacity of 80,000 MWe; one reprocessing plant with a capacity for reprocessing all fuel and blanket assemblies discharge from the 20 power stations; one fuel and blanket fabrication plant with a capacity sufficient to meet the refueling requirements of all power stations in the module; a Federal repository for high level radioactive wastes produced at the reprocessing plant; a noble gas storage facility; and the transportation links required among these facilities.
- (2) Identification of those parts of the reference module with relatively high inherent risks of theft or diversion of plutonium and risks of sabotage that might release dangerous amounts of radioactivity.
- (3) Specification of types of safeguards measures to be applied to each major component of the reference module.
- (4) Estimation of the capital and operating costs of the specified safeguards measures and comparison with other costs associated with the module.

In addition, several possible modifications of the module that might improve the effectiveness or decrease the costs of safeguards have been examined in a preliminary way.

7.4.9.2 Description of LMFBR Reference Module and Associated Safeguards

7.4.9.2.1 Overall Characteristics of Fuel Cycle Module

A schematic diagram of an LMFBR reference fuel cycle module is shown in Figure 7.4-7. All the fixed facilities, indicated by boxes, are assumed to be at different locations. Transport links and the directions of flow of materials are indicated by appropriate lines and arrows between the boxes. The safeguards

7.4-67

LMFBR FUEL CYCLE MODULE

Figure 7.4-7

implications of co-locating some of the fixed facilities are discussed in Section 7.4.9.4 below.

Some of the parameters that relate to the need for safeguards at the fixed facilities are listed in Table 7.4-8, and those related to the need for safeguards during transportation are listed in Tables 7.4-9 and 7.4-10. All the indicated parameters are consistent with the characteristics of LMFBR fuel cycles presented in Section 4 of this Statement. It should be emphasized that, throughout this section, the data presented are estimates, which are in some cases rough approximations. The apparent precision of the data results from a desire for internal consistency among commonly derived data.

The parameters listed in Tables 7.4-8 through 7.4-10 correspond to operation of the module in equilibrium, that is, after all components have been operating at rated capacities for several years. During startup phases, the required plutonium would be provided either by excess production from other LMFBR modules or from stockpiles of plutonium produced by LWR power plants and separated at LWR fuel reprocessing facilities.

For subsequent comparisons with the estimated costs of safeguards, the projected capital and operating costs (in 1974 dollars) associated with the module are summarized in Table 7.4-11.

A review of the parameters given in Table 7.4-8 and 7.4-9, and of the discussion in Section 7.4.6, suggests that the inherent likelihood of attempted theft or diversion relates to the desirability of a particular chemical or physical form of plutonium for subsequent use in nuclear weapons, the total weights of items that would have to be removed to obtain a particular mass of contained plutonium, and the basic accessibility of the part of the fuel cycle to unauthorized persons. A tentative ordering of different parts of the module, in terms of decreasing likelihood of attempted theft or diversion of plutonium, is as follows:

- (1) Transportation of plutonium oxide from fuel reprocessing to fuel fabrication plant.
- (2) At fuel fabrication plant, unloading of shipments of input PuO_2 , storage of input PuO_2 , fuel element fabrication steps, storage of mixed oxide fuel elements, and loading of fuel elements for shipment to power plants.

Table 7.4-8

CHARACTERISTICS OF LMFBR REFERENCE FUEL CYCLE MODULE (FIXED FACILITIES)

Power Plants

Total Number of Sites	20
Power Capacity of Each Site	4,000 MWe
Assumed Load Factor	80%
Thermal Efficiency	40%
Assumed Average Breeding Ratio (early oxide)	1.15
Average In-reactor Plutonium Inventory at Each Site, including breeding blankets	~13,000 kg
Number of Fuel Assemblies In-core at each Site	1,100
Plutonium Content of Each Clean Fuel Assembly	10.6 kg
U/Pu Ratio in Clean Fuel	5.4
Total Weight of Each Fuel Assembly, including Axial Blanket Material, Cladding, etc.	~150 kg
Number of Fuel Assemblies Replaced per Year at Each Site (1/2 core each year)	550

Fuel and Blanket Reprocessing Plant

Number of Sites	1
Plant Capacity (300 days/year)	1,500 tonnes/year
Separated Plutonium Output (total)	134,000 kg/year
Rate of Shipment of Plutonium for Recycling through Module	117,000 kg/year
Rate of Shipment of Excess Plutonium to Other Modules	17,000 kg/year
Rate of Production of Solidified, High-level Radioactive Wastes	4,800 ft ³ /year
Av. Inventory of Solid, High-level Wastes (prior to shipment to Federal repository)	48,000 ft ³
Maximum Storage Capacity for Separated Plutonium (~10% of annual throughput)	13,500 kg
Maximum Storage Capacity for Irradiated Fuel Assemblies (~10% of annual throughput)	150 tonnes (1,000 assemblies)
Average (or typical) In-process Inventory of Plutonium Separated from Fission Products	900 kg

Fuel Fabrication Plant

Number of Sites	1
Plant Capacity (300 days/year)	1,500 tonnes/year
Separated Plutonium Input (as PuO ₂)	117,000 kg/year
Rate of Fabrication of Fuel Assemblies	11,000 per year
Maximum Storage Capacity for Plutonium as Input PuO ₂ (10% of throughput)	11,700 kg
Maximum Storage Capacity for Fabricated Fuel Assemblies (10% of throughput)	1,100 assemblies
Average (or typical) In-process Plutonium Inventory	~11,700 kg

Table 7.4-8 (Continued)

Federal Repository for High-Level Radioactive Wastes

Number of Sites (for all modules, until 2000)	1
Rate of Input of Wastes from Module	4,800 ft ³ /year
Total Contribution to Waste Volume from Module's Operation at Equilibrium for 30 years	144,000 ft ³
Rate of Input of Fission Products from Module	~55 tonnes/year
Total Inventory of Fission Products from Module's Operation at Equilibrium for 30 years	1,650 tonnes

Table 7.4-9

CHARACTERISTICS OF LMFBR REFERENCE FUEL
CYCLE MODULE (Transportation Link)

Irradiated Fuel and Blanket From Power Plants to Reprocessing Plant

Method of Shipment	Rail, in shielded, heavy casks
Loaded Weight of Each Shipping Cask	~75 tons
Number of Assemblies per Cask	6
Number of Casks Shipped per Year from Each Power Plant Site	107
Total Number of Casks Shipped per Year from all Power Plants in Module	2140

Plutonium Oxide from Fuel Reprocessing Plant to Fuel Fabrication Plant

Method of Shipment	Truck, 55-gal "bird cages"
PuO ₂ Package Weight	200 lb
PuO ₂ Content of Each Package	10.2 kg
Number of Packages per Vehicle	64
Total PuO ₂ per Vehicle	653 kg
Number of Shipments per Year	204

Excess Plutonium Oxide from Fuel Reprocessing Plant to Other Modules

Method of Shipment	Truck, 55-gal "bird cages"
Number of Shipments per Year	29

Fresh Fuel (Pu-bearing) from Fuel Fabrication Plant to Power Plant Sites

Method of Shipment	Truck-Trailer
Loaded Weight of Each Fuel Package	2500 lb
Number of Fuel Assemblies per Package	2
Total Plutonium in Each Fuel Package	21.2 kg
Fuel Packages per Vehicle	4
Plutonium Weight per Vehicle	84.8 kg
Number of Shipments (vehicles) to Each Power Plant Site per Year	69
Total Number of Shipments per Year to all Power Plant Sites in Module	1380

Table 7.4-10
ANNUAL SHIPMENTS IN 80,000-MWe LMFBR MODULE--SUMMARY

	Annual Number of Shipments in Module
<u>Recycle Plutonium</u>	
PuO ₂ , from Fuel Reprocessing to Fabrication Plant	204
Excess PuO ₂ , from Fuel Reprocessing Plant to Other Modules	29
Fresh Fuel from Fabrication to Power Plants	<u>1380</u>
Subtotal	1613
 Irradiated Fuel from Power Plants to Reprocessing Plant	 2140
 Total Shipments per Year	 3753

Table 7.4-11
LMFBR MODULE COSTS
(excluding safeguards costs)

Type of Cost	Costs (millions of dollars)
<hr/>	
Capital Costs	
Power Plants, @ \$520/kWe	41,600
Fuel Reprocessing Plant	200
Fuel Fabrication Plant	100
Pro-rated Cost of High-level Waste Repository	50
Pro-rated Cost of Low-level Waste Repository	<u>15</u>
	41,965
 Operating Costs	
Total, @ 1.3 ¢/kWhr (80% load factor)	7,330
<hr/>	

- (3) At fuel reprocessing plant, loading of PuO_2 for shipment to fuel fabrication plants, storage of output PuO_2 , and plutonium processing steps after separation from fission products.
- (4) Transportation of fresh fuel from fuel fabrication plants to power plants.
- (5) At power plants, unloading of fresh fuel, storage of fresh fuel prior to refueling, and refueling operations.
- (6) Transportation of irradiated fuel from power plants to reprocessing plant.

The relative likelihood of attempted sabotage of different parts of the LMFBR fuel cycle is much more difficult to assess than that of theft of plutonium. Detailed analyses of conceivable purposeful ways to release dangerous amounts of radioactive material beyond surrounding confinement structures would be required to rank these risks. Such analyses of components of the LMFBR fuel cycle will be used as a partial basis for further specification of regulations, enforcement procedures, and specific safeguards measures designed to prevent acts of sabotage that could pose serious radiation exposure to the public.

7.4.9.2.2 Specific Safeguards Measures Postulated for Module Components

The major categories of postulated physical safeguards components are listed for each part of a reference LMFBR module in Table 7.4-12. Table 7.4-13 indicates the number of protective security personnel associated with each part of the cycle.

For purposes of these preliminary cost analyses, specific safeguards measures are assumed to be applied to all fixed sites that contain potentially dangerous quantities of fission products or other radioactive materials, such as high-level waste repositories, and they are included in the cost estimates. The cost of safeguarding a fixed site that contains only fission product wastes is significantly lower than for a fixed site that has both high-level wastes and plutonium separated from fission products.

All cases also postulate that local and regional arrangements have been made for providing offsite law enforcement and, if necessary, military assistance forces at the scene of an attempted theft or act of sabotage at sufficient levels and in sufficient time to prevent any credible theft or sabotage attempt from being completed. Onsite or in-transit security measures are expected to be capable of obstructing an attempted theft or act of sabotage for at least 2 hours to allow time for reserve protective forces to be used, as needed, for obstructing the theft for longer times and, eventually, to apprehend individuals involved in the incident and to recover any materials removed from authorized places before their location has

Table 7.4-12
CAPITAL COSTS OF LMFBR SAFEGUARDS EQUIPMENT

Equipment	Cost Per Site (millions of dollars)	Costs for Module (millions of dollars)
<u>Fixed Sites</u>		
<u>Power Plants</u>		
Alarmed Reactor Perimeter Fences	0.5	10
Internal Intrusion Alarm Systems	1.0	20
Internal Communications and Monitoring System	1.0	20
SNM and High-explosives Monitors at Personnel Access Control Points	0.1	2
Offsite Communications System	0.2	4
Other, Including Special Design Features to Increase Safeguards Effectiveness	<u>5.0</u>	<u>100</u>
Totals	7.8	156

Fuel Reprocessing and Fuel Fabrication Plant

	Fuel Reprocessing Plant Costs (millions of dollars)	Fuel Fabrication Plant Costs (millions of dollars)
Alarmed Perimeter Fences	1.5	1.5
Structure Hardening Around Fission Product-free Plutonium Process Access Areas	.3	1.5
Plutonium Oxide Storage Vaults	2.0	2.0
Internal Intrusion Alarm Systems	1.0	3.0
Internal Communications and Monitoring System	1.0	3.0
SNM and High-explosives Monitors at Personnel Access Control Points	.2	.5
Offsite Communications Systems	.5	.5
Physical Barriers Surrounding Process Stream	1.0	2.0
Fabricated Fuel Storage Vaults		3.0
SNM Materials Accounting System	3.0	6.0
Other, Including Special Plant Design Features	<u>3.0</u>	<u>5.0</u>
Totals	13.5	28.0

Table 7.4-12 (Continued)

	<u>Costs</u> <u>(millions of dollars)</u>		
High Level Waste Repository			
Alarmed Perimeter Fences			0.5
High-Explosives Monitors at Access Control Points			0.2
Added Costs of Constructing Repository Underground (for protection from sabotage)			<u>50</u>
	Totals		~51
<u>Transportation</u>			
Specially Designed Vehicles and Escort Vehicles	<u>Number of Units</u>	<u>Unit Costs</u>	<u>Total Cost (millions of dollars)</u>
For Fresh Fuel Shipments	75	\$150,000	11.25
For PuO ₂ Shipments	6	200,000	1.2
For Irradiated Fuel Shipments (added costs of security features)	250	35,000	<u>8.75</u>
	Totals		\$ 21.20
Fixed Communications Installations (two vehicle monitoring stations, relays, etc.)		\$5 million times pro-rating fraction (module capacity/ U.S. capacity)	
<u>Federal Data Processing and Monitoring Installation</u>		\$5 million times pro-rating fraction	
<u>Capital Cost Summary for Module</u>		<u>Total Capital Costs</u>	
Fixed Sites		\$248 million	
Transportation		27 (max.)	
Federal Data Processing Facility		<u>5 (max.)</u>	
	Total Capital Costs	\$280	

Table 7.4-13

SAFEGUARDS SECURITY PERSONNEL FOR LMFBR MODULE

Fixed Facilities	Number on Duty at Each Facility	Total Employed at Each Facility	Total Employed at All Facilities	Total Module Annual Salary and Overhead Costs (\$30 k per employee)
Power Plants	6	30	600	\$18 million
Fuel Reprocessing Facility	12	60	60	1.8
Fuel Fabrication Facility	24	120	120	3.6
Federal Waste Storage Facility	4	20	<u>20</u>	<u>0.6</u>
Total for Module Fixed Sites			800	24.0

Transportation Transport Link	Number of Guards Accompanying Each Shipment	Number of Shipments per Year	Total Number of Employed Guards	Annual Salary and Overhead Cost (millions of dollars)
Fresh Fuel to Power Plants	6	1380	455	13.6
PuO ₂ from Reprocessing Plant	12	233	154	4.6
Irradiated Fuel to Reprocessing Plant	2	2140	<u>235</u>	<u>7.1</u>
Totals			844	25.3

Complete Module

Total Number of Security Personnel
Total Costs (salary and overhead)

1644
\$ 49.3 million/year

become unknown or inaccessible to recovery. Intensive studies of alternative types of such reserve forces and required communications, transportation, and other systems are currently under way. These studies include the assessment of possible use of a new type of Federal protective service to provide all necessary security personnel for a national system of safeguards.

It should be emphasized that these safeguards measures have been postulated solely for the purpose of making a preliminary estimate of the costs of LMFBR safeguards.

7.4.9.3 Estimated Costs of Safeguarding Reference LMFBR Fuel Cycle Module

Estimated capital costs of physical safeguards components for all parts of the module are presented in Table 7.4-12; costs of security personnel are given in Table 7.4-13, and an overall summary of capital and operating costs of safeguards applied to the entire module is given in Table 7.4-14.

In general, the cost allocations in these tables appear to be rather liberal. Present allocations per man-year for White House special protective service personnel, for example, are approximately \$20,000, including fringe benefits, arms, uniforms, etc., compared to \$30,000 per protective service man-year used in this analysis. Doorway monitors that will detect passage of approximately 1 g of plutonium (unshielded) in 1 sec are now commercially available for \$10 to 12 dollars, and explosives sensors can be purchased for a few thousand dollars; therefore, an allocation of \$0.5 million for such devices at a fuel fabrication plant would correspond to a high degree of redundancy at several monitoring points. Estimates of the costs of alarmed perimeter fences are based on an assumed cost of \$100 per linear foot of fence, sufficient for several types of redundant alarm systems.

Thus, the indicated fractions of the module capital and operating costs that are presented in Table 7.4-14 are judged to be on the high side of ranges of costs attributable to the kind of safeguards system postulated in this analysis.

The data in the tables do not include costs of safeguarding transport of radioactive waste materials. For each 80,000-MWe module, there would be 686 shipments per year exceeding 10^4 Ci of various radioactive waste materials. Shipments from the reprocessing plant to a burial ground or Federal repository consist of 59 shipments of solid high-level waste, 13 shipments of noble gas fission products, 104 shipments of cladding hulls, and 62 shipments of alpha-emitting solid waste. In addition, there would be 48 shipments of tritium from the reactors and 400 shipments of alpha-emitting solid waste from the fuel preparation and fabrication facilities to the

Table 7.4-14

LHFBR MODULE SAFEGUARDS COST SUMMARY

	Cost (millions of dollars)
Total Capital Equipment	280
Operating Costs (per year)	
Security Personnel	49.3
Fixed Charge on Capital Investment (@ 16% per year)	43.7
Pro-rated Costs of Regulatory Operations	4.0
Other Operating Costs (materials, power, fuel, etc.)	<u>5.0</u>
Total Operating Costs	102.0
Percentage Increase in Module Capital Costs due to Safeguards	0.67%
Percentage Increase in Module Operating Costs due to Safeguards	1.40%
Increase in Module Nuclear Electric Power Costs due to Safeguards	0.18 mills/kWhr

burial ground or repository. If a decision is made to protect these shipments against sabotage (beyond the protection provided by the shipping casks and containers), there would be additional capital costs for hardened vehicles of about \$1.3 million and additional operating costs for guarding the shipments of about \$2.3 million.

The following comment is pertinent:

...if the AEC tried to enforce such a system, a perfect fissionable or radioactive controls system, there would be no nuclear industry because of its interference with operations and its high costs.*

While the safeguards system outlined here should not be viewed as a "perfect" system, the AEC believes that it would be effective. The cost analysis provides no support for a contention that the nuclear industry would be forced to stop operation because of high safeguards costs.

7.4.9.4 Possible Changes in LMFBR Fuel Cycle to Improve the Effectiveness or Decrease the Costs of Safeguards

Comments were received dealing with possible safeguards-related changes in the LMFBR fuel cycle.** Representative comments were:

The probability of theft and/or sabotage could be increased at a nuclear park.†

....Not only does siting of LMFBR's in nuclear parks appear to have major advantage in reducing the hazards of diversion of SNM, but also there are several other advantages. As with all things, however, nuclear parks have disadvantageous implications.††

The nuclear park concept does cut down considerably on the transportation of radioactive materials, thus lessening the chances of transportation accidents and hijacking.§

7.4.9.4.1 Co-location of Fuel Reprocessing and Fuel Fabrication Plants

Perhaps the most obvious change in the reference LMFBR module that would appear to reduce the costs of safeguards is locating the fuel reprocessing and fuel fabrication plants on the same sites. In addition to removing the most inherently

*Hearings Transcript, pp. 179, 180, by Mrs. P. Hoffman.

** (1) Comment Letters 9, p. 1; 12, p. 19 (Attachment 2); 19, p. 6; 20, pp. 12-13; 51, pp. 38, 45; 54, p. 7. (2) Hearings Transcript, pp. 192-193.

† Comment Letter 19, p. 6, from M. Carter, R. Cushman, J. Davis, and P. Tyrrell.

†† Comment Letter 20, pp. 12, 13, from Natural Resources Defense Council.

§ Hearings Transcript, pp. 192-193, by Mrs. P. Hoffman.

vulnerable step in the fuel cycle (i.e. transportation of PuO_2 between these two plants), siting them at the same complex would have the following cost advantages:

- (1) Reduction in the number and total storage capacity of vaults for storing temporary surpluses of PuO_2 , because a common vault could be associated with both types of operations and because overall facility operations could be more nearly optimized to reduce the maximum needed inventories of surplus PuO_2 .
- (2) Economies of scale associated with facility barriers, on site guard forces, and communication systems (both internal and for summoning outside assistance).
- (3) Availability of the option to use the same transport route, vehicles, and possibly shipping containers for fresh fuel shipments as for irradiated fuel shipments.

Such co-location would possibly reduce total fuel cycle capital and operation costs significantly, aside from safeguards considerations, for reasons directly related to the items listed above. In addition to any such savings, preliminary estimates suggest that the aggregate savings in LMFBR safeguards costs would be less than \$10 million, or less than 10% of the safeguards costs without this type of co-location of facilities. This perhaps somewhat surprising result is due to the large capital and operating costs associated with the power plants, which would not be affected by this change.

7.4.9.4.2. Co-location of All Fuel Cycle Components at a Single Site (Nuclear Energy Centers)

Co-locating all facilities at a single site would eliminate offsite transportation of fresh and irradiated fuel elements as well as the transportation of separated plutonium. It would also permit large economies of scale in the establishment of site protection by consolidating perimeter protection and response forces. These factors will increase the effectiveness of safeguards against theft and sabotage and could reduce the costs of safeguards by as much as an order of magnitude.

With regard to the attractiveness of nuclear energy centers as targets in wartime, the establishment of such centers would not of itself change the conclusion in Section 7.4.4.1 that the additional effect of targeting nuclear facilities would be masked by the overall consequences of a massive strategic attack.

The other advantages and disadvantages of nuclear energy centers are discussed in Section 7.2.6.4.

7.4.9.4.3 Use of Spent Fuel Shipping Casks for Shipment of Fresh Fuel to Power Plants

As indicated in Section 7.4.6.1, gamma ray and possibly neutron shielding may be necessary around shipments of LMFBR fresh fuel that contains recycle plutonium in order to keep radiation exposure levels acceptably low. One way to provide the necessary shielding, while also considerably reducing the inherent vulnerability of fresh fuel shipments to theft, would be to ship the fresh fuel in the casks used to ship spent fuel from the power plants to a reprocessing plant. Careful scheduling of refueling operations may make this possible without requiring significant additional numbers of spent fuel shipping casks or additional rail routes. Rather than being returned empty from the reprocessing plant to the power plants, the shipping casks could be routed from the reprocessing plant to the fuel fabrication plant, loaded with fresh fuel, and shipped to the power plants.

This procedure would possibly represent an overall cost saving, aside from safeguards considerations, by making multiple use of the same shipping casks. If the fuel reprocessing and fabrication plants were also co-located, total costs would be further reduced, because there would be no need to ship empty casks between these two facilities.

The inherent vulnerability to theft of fresh fuel in transit would be considerably reduced by using this shipping option, because each cask, containing six fuel assemblies, would weigh about 75 tons, compared with only 2500 lb for each package of eight assemblies, if the shipment is in conventional shipping containers.

7.4.9.4.4 Retention or Addition of High Gamma-Ray Activity Materials in Fuel Materials

The purpose of including high gamma-ray activity materials in fuel would be to make the plutonium-bearing fuel materials "self-protecting" against theft or diversion and subsequent clandestine incorporation (without remotely operated chemical separation or physical handling equipment) into nuclear weapons. Another benefit, from a safeguards point of view, would be to increase considerably the sensitivity of monitoring instruments designed to detect the unauthorized flow of nuclear materials. Studies of the effectiveness, added fuel cycle costs, and potential disadvantages of such a safeguards measure are under way.

7.4.9.5 Comparative Costs of Safeguarding LMFBR and Alternative Nuclear Power Systems

7.4.9.5.1 Comparison Between LMFBR, LWR, and HTGR Power Modules

For this comparison, it is convenient to consider four different types of fuel cycle modules that support an 80,000-MWe generating capacity: LMFBR, LWR without plutonium recycle, LWR with plutonium recycle, and HTGR with U-233 recycle.

Characteristics of each of these four types of modules that relate to requirements for safeguards are listed in Table 7.4-15. All the parameters listed for an LMFBR module are the same as in Section 7.4.9.2, except that fresh LMFBR fuel (not including blanket assemblies) was assumed to be shipped by rail in the same casks as would be used for shipping spent fuel. (This option is described in Section 7.4.9.4.1.) This assumption was made to allow a more direct comparison with the other modules, for which preliminary analyses have suggested that it would be economically attractive to use spent fuel shipping casks for shipping recycled fresh fuel, rather than additional casks that provide a moderate amount of shielding. Such shielding, however, is not required for fresh LWR fuel that does not contain recycled plutonium.

The number of irradiated fuel shipments per year is substantially greater for the LMFBR module than for the other three, primarily because of greater cooling requirements during shipment of spent LMFBR fuel assemblies. Also, the annual number of shipments for fresh LMFBR fuel is somewhat greater than the 1380 shipments per year assumed in Section 7.4.9.2, because the spent fuel casks hold six fuel assemblies each, rather than eight.

For purposes of this analysis, all four types of fuel cycles are assumed to be in substantial commercial use, with upgraded safeguards appropriate to each fuel cycle applied. (The postulated safeguards measures are more stringent than those required by current regulations. Other sets of safeguards measures could, with equal validity, be postulated. This assumption is not believed to greatly affect the comparisons.) As mentioned above, the numerical data in the tables that follow are stated with an apparent precision that results from the manner of derivation and a desire for internal consistency. However, the data are and should be treated as approximations.

Preliminary estimates of the numbers of security personnel which might be required for effective safeguarding of fixed sites and shipments associated with each of the four types of modules are shown in Table 7.4-16.

Table 7.4-15
COMPARISONS OF LMFBR, LWR, AND HTGR
80,000-MWe MODULES

	LMFBR	LWR w/o Pu Recycle	LWR with Pu Recycle	HTGR
Number of Power Stations	20	20	20	20
Number of Fuel Reprocessing Plants	1	1	1	1
Number of SSNM Fabrication Plants	1		1	1
Number of Plutonium Storage Facilities		1		
Number of High-Enrichment Isotope Separation Plants				1
Annual Separated Plutonium Output (kg/year)	134,000	17,000	22,000	~80
Rate of Shipment of Plutonium for Recycling through Module (kg/year)	117,000		22,000	
Annual Highly Enriched Uranium Input (kg/year)				30,000
Annual Separated U-233 Output (kg/year)				14,000
Rate of Shipment of Excess Plutonium to Other Modules (kg/year)	17,000	17,000		80
Total Number of Fixed Sites that Contain Unirradiated SSNM	22	2	22	23
Mode of Shipment of Fresh Fuel Assemblies Containing SSNM	Rail, in spent fuel casks		Rail, in spent fuel casks	Rail, in spent fuel casks
Number of PuO ₂ Shipments per Year	233	30	38	1
Number of U-235 O ₂ Shipments per Year				18
Number of U-233 O ₂ Shipments per Year				25
Number of PuO ₂ + UO ₂ Shipments per Year (as rods)			48	
Number of SSNM Fuel Assembly Shipments per Year	1,840		460 ^a	944
Number of Irradiated Fuel Shipments per Year	2,140	766	766	944

^aBased upon PWR/BWR Ratio of 2/1, where all BWR assemblies and 40% of PWR assemblies contain Pu.

Table 7.4-16
SECURITY PERSONNEL FOR SAFEGUARDING DIFFERENT
80,000-MWe MODULES

	LMFBR	LWR w/o Pu Recycle	LWR with Pu Recycle	HTGR
Security Personnel per:				
PuO ₂ , U-235 O ₂ , or U-233 O ₂ Shipment	12	12	12	12
Fresh Fuel Shipment Containing SSNM	3		3	3
Irradiated Fuel Shipment	2	2	2	2
Total Number of Security Personnel Employed for:				
PuO ₂ , U-235 O ₂ , or U-233 O ₂ Shipments	154	20	25	29
Fresh Fuel Shipments Containing SSNM	310		75	155
Irradiated Fuel Shipments	235	84	84	104
Security Personnel At:				
Power Plant	6	4	5	5
Reprocessing Plant	12	8	8	8
Fuel Fabrication Plant ^a	24	4	12	16
Plutonium Storage Facility		12		
Isotope Enrichment Facility ^a		6	6	12
High-level Waste Facility	4	4	4	4
Total Numbers of Security Personnel Employed for:				
Power Plant	600	400	500	500
Reprocessing Plant	60	40	40	40
Fuel Fabrication Plant ^a	120	20	60	80
Plutonium Storage Facility		60		
Isotope Enrichment Facility ^a		30	30	60
High-level Waste Facility	20	20	20	20
Total Security Personnel for Transport	699	104	184	288
Total Security Personnel at Fixed Sites	800	570	650	700
Total Security Personnel	1499	674	834	988

^aIncludes low-enriched uranium fabrication and enrichment facilities for LWR.

The number of guards accompanying shipments of fresh fuel that contain special nuclear materials is taken to be three, rather than six, because in all cases, these types of fuels are assumed to be transported by rail in extremely heavy casks, instead of by truck in relatively light containers. Shipments of LWR fresh fuel not containing recycled plutonium are assumed to require no special security personnel as couriers.

A minimum of four security personnel on duty at each power plant is assumed for dealing with attempts to sabotage reactors in ways that might release dangerous amounts of radioactive materials, whether or not special nuclear materials are contained in the fresh fuel. Five, rather than six, guards are assumed to be on duty on HTGR power plants or LWR plants that use recycled plutonium, to reflect the substantially lower density of special nuclear materials in fresh HTGR or LWR fuel elements, compared with LMFBR elements.

Differences in the numbers of guards assigned to fuel reprocessing and fuel fabrication plants for different modules reflect, roughly, differences in annual throughputs of special nuclear materials (and, therefore, the size of areas requiring surveillance and control). Relatively small guard forces are assigned to low-enrichment isotope separation plants and fuel fabrication plants for LWRs that do not use recycled plutonium primarily to deal with attempts at industrial sabotage.

Table 7.4-17 summarizes preliminary estimates of the capital and annual operating costs of safeguarding the four types of modules. Capital costs for the LWR and HTGR systems have been estimated by using Table 7.4-12 (for the LMFBR module) as a point of departure and then making adjustments that are responsive to the relative inherent vulnerability of each part of each fuel cycle to theft or sabotage. Capital costs associated with safeguarding transported fresh LMFBR fuel have been reduced somewhat from the estimates given in Table 7.4-12 to reflect the use of irradiated-fuel shipping casks for transporting fresh LMFBR fuel elements.

The indicated differences in the operating costs of safeguarding HTGR and LWR (with plutonium recycle) modules are not significant. The significantly higher costs of safeguarding the LMFBR module are primarily attributable to the higher density of special nuclear material in the fuel and the considerably greater total annual throughput of special nuclear materials than for the other modules. However, the costs of safeguards are not even approximately proportional to the relative rates of annual throughput of special nuclear materials in each module, partly because safeguards against sabotage are required in all cases and partly because the number

Table 7.4-17

COSTS OF SAFEGUARDING DIFFERENT
80,000-MWe MODULES (millions of 1974 dollars)

	LMFBR	LWR w/o Pu Recycle	LWR with Pu Recycle	HTGR
<u>Capital Costs</u>				
Power Plants	156	75	120	100
Reprocessing Plant	13	8	8	8
Fuel Fabrication Plant	21	5	15	15
Plutonium Storage Facility		10		
High-level Waste Repository	51	51	51	51
Isotope Enrichment Plant		5	5	8
Other Fixed Sites	10	10	10	10
Transportation	15	5	7.5	10
Total Capital Costs	273	169	216	202
<u>Operating Costs (per year)</u>				
Security Personnel	45	20.2	25	29.6
Fixed Charge on Capital Investment, @ 16%	42.7	25.4	34.5	32.4
Regulatory Operations	4	3	4	4
Other	5	4	5	5
Total Operating Costs	96.7	52.6	68.5	71

of locations that require physical protection depends much less on the amounts of materials flowing through the fuel cycle than on other factors.

7.4.9.5.2 GCFR and MSBR Systems

These systems are at a less advanced state of development than LWR, HTGR, and LMFBR systems, and are therefore considered in less detail. Several approximate conclusions can be drawn, however, concerning the relative costs of safeguarding these systems compared to LMFBR fuel cycles.

Since GCFR fuel is very similar to LMFBR fuel, and the overall thermal efficiencies of both types of reactors are expected to be about the same, the costs of equivalent safeguards can be expected to be about the same for both fuel cycles.

The MSBR fuel cycle is qualitatively different from other fuel cycles in that power production, fuel reprocessing, and production of new fuel all take place at the same location. Once a MSBR power system reaches equilibrium, the only nuclear fuel shipments to the site would be thorium to make up for gradual depletion of its inventory. Because its fuel would be locally, continuously reprocessed, the only hazardous shipments from the power plant site would be a small excess of U-233 (a few percent, at most, of its rate of consumption of U-233) for starting up other MSBR plants.

It is not yet clear whether inherent opportunities for diversion or overt theft of special nuclear materials would be greater or smaller at a 4000-MWe MSBR plant than at an LMFBR plant of the same capacity. Large inventories of fission product-free U-233 outside the reactor could be avoided by more or less continuously recycling the processed uranium. On the other hand, the fuel would not be in well defined, solid units, as it is at an LMFBR power plant. This characteristic could generate requirements for careful monitoring of the fuel reprocessing stream, after fission product separation, to assure that U-233 is not diverted. Furthermore, since there would be significant in-process inventories of fission products outside the reactor core and in the process stream, special safeguards are likely to be required at MSBR plants to prevent sabotage that could release dangerous quantities of radioactive materials. Taking into account the need for safeguarding the transportation of the relatively small quantities of excess U-233 to other reactors, as well as a possible need for more security personnel at each power plant (perhaps ten instead of five), operating costs of safeguarding an 80,000-MWe MSBR module might be expected to be comparable with those associated with an HTGR module or an LWR module with plutonium recycle, or about \$80 million per year.

7.4.9.5.3 Controlled Thermonuclear Reactors

Controlled thermonuclear power systems would not use fissionable materials at all, and their inventories and rates of production of radioactive materials are likely to lead to risks that are orders of magnitude lower than risks for fission power systems of the same generating capacity. The potentially hazardous materials are tritium (inventories of which may vary considerably for different types of thermonuclear reactors) and neutron activation products in parts of the system adjoining the plasma reactor zone (also subject to very large differences among different specific CTR concepts). Total costs of safeguards for CTR systems can therefore be expected to be much smaller than for fission systems.

7.4.9.6 Comparative Costs of Safeguarding the U.S. Projected Nuclear Power System in 2020, With and Without the LMFBR

The estimated costs of safeguarding LMFBR, LWR, or HTGR power modules presented in Section 7.4.9.5.1 and the two alternative projected mixes of reactors in the year 2020 (see Section 11.2.3.3.2) can be used to compare the total costs of safeguarding each of the two projected U.S. nuclear power systems. The results of this analysis are presented in Table 7.4-18.

Recycle of plutonium in LWR reactors has been assumed in both cases. In Case A, which postulates a rapid buildup of LMFBR capacity after 1987, the excess plutonium produced by the U.S. system (roughly 500,000 kg/year) is more than sufficient for startup of new LMFBR plants at the rate projected for the year 2020 (about 200,000 kg/year). Therefore a reasonable expectation is that the overall excess of about 300,000 kg of plutonium per year over that required to sustain the power system and its projected growth would be used as a substitute for fissionable uranium in the LWR or HTGR systems, even though a plutonium fission is "worth" more in an LMFBR reactor than in the other two types. This possibility has not been included in the estimates shown in Table 7.4-18, but it is not expected to change the overall results significantly.

The overall result that total safeguards costs for Case A are only somewhat greater than for Case B may appear surprising, in view of the difference of about a factor of four in the quantities of special nuclear materials processed each year. The reasons for this relative insensitivity of costs of safeguards to annual throughputs of special nuclear materials were discussed in Section 7.4.9.5.1.

Table 7.4-18

COSTS OF SAFEGUARDS FOR ALTERNATIVE REACTOR MIXES, 2020

	Case A LMFBR Introduced 1987	Case B No LMFBR
Total Power Generating Capacity	3290 GWe	3290 GWe
LMFBR Capacity	2190 GWe	
LWR (with Pu recycle) Capacity	800 GWe	2500 GWe
HTGR Capacity	300 GWe	790 GWe
Number of 80,000-MWe LMFBR Modules	27.4	
Number of 80,000-MWe LWR Modules	10.0	31.3
Number of 80,000-MWe HTGR Modules	3.8	9.9
Number of Power Stations (4000-MWe av.)	820	820
Number of Fuel Reprocessing Plants	41	41
Number of Fuel Fabrication Plants	41	41
Number of High Enriched Uranium Isotope Separation Plants	4	10
Annual Separated Plutonium Output	3.83×10^6 kg	0.69×10^6 kg
Annual Separated U-233 Output	0.043×10^6 kg	0.14×10^6 kg
Annual Highly Enriched Uranium Input	0.11×10^6 kg	0.30×10^6 kg
Safeguards Capital Investment	$\$10.4 \times 10^9$	$\$8.8 \times 10^9$
Safeguards Annual Operating Cost	$\$3.6 \times 10^9$	$\$2.8 \times 10^9$

Although the absolute operating costs of safeguards are large in both cases, they represent less than 2% of the projected annual cost of producing nuclear electric power in the year 2020 (i.e., about \$300 billion).

7.4.9.7 Alternative Ways for Paying the Costs of Safeguards

Although the overall costs of safeguards can be expected to be very small compared with the cost of nuclear electric power, both the capital and operating costs of safeguards may represent major increases in costs at particular parts of a nuclear fuel cycle, especially in the transportation phases. Therefore, equitable mechanisms will have to be established for allocating such costs, while maintaining a high level of effectiveness of safeguards at all points in fuel cycles where they are needed.

The present high competitiveness among U.S. companies that provide nuclear fuel cycle services generates pressures to keep safeguards costs to a minimum. If, for example, large added costs for safeguarding special nuclear materials in fresh fuel shipments to a power plant are included in a proposal for a long-term contract between a fuel fabricator and a utility company, the contract may be lost to another fuel fabricator that minimizes cost by meeting current AEC safeguards requirements at minimal levels.

Approximately half the safeguards operating costs estimated in the preceding sections for fuel cycles that use recycled special nuclear materials (except the MSBR) are for transportation links. These costs also represent the highest increment over costs without safeguards, as compared with other parts of the fuel cycles. For these reasons, as well as to remove some of the problems associated with requirements that private industry provide its own armed security personnel, the possibility of establishing a Federally operated nuclear material transportation system is being studied by the AEC. One possible way to pay the costs for such a service would be to charge shippers directly for whatever security measures are deemed necessary by the AEC, as well as for the basic transportation costs. Another possibility would be to establish a special Federal fund raised by taxes on utilities that are proportional to the total costs of nuclear electric power supplied by each utility to a power grid. These and other possible methods for funding such a Federal service are currently also being studied.

A further step in the direction of a direct Federal responsibility for safeguarding nuclear materials could be to provide Federal protective services not only for transportation of nuclear materials, but for all fixed sites in nuclear fuel cycles. This possibility, as well as alternative ways for paying the costs of such Federal

services similar to the examples mentioned above, are also being considered as part of the overall study of these matters by the AEC.

The major fraction of the incremental capital costs of safeguards measures are likely to be accounted for by the power plants, as indicated in Table 7.4-12. These would include plant design features specifically incorporated to increase the effectiveness of safeguards. It would appear equitable that these added capital costs, which are less than 0.4% of the capital costs of LMFBR power plants, be covered by a very small increment in prices charged by the utilities for nuclear electric power.

7.4.10 Conclusions

In reaching the conclusions stated below, the Commission has considered all information presented in Section 7.4 and the safeguards-related information presented in Section 5. The Commission has also considered the contentions of some reviewers of the draft that the LMFBR program should be delayed because of the lack of definitive resolution of the potentially grave problems related to theft or sabotage involving nuclear materials.*

The problem of safeguards exists now in connection with military programs and with the commercial production of nuclear power. The requirement for changes in the AEC safeguards program arises out of changes in the nature of the threat and the expected increase in the commercial utilization of strategic special nuclear material. The program must evolve in a way that will ensure that adequate protection is provided at all phases of the future development of nuclear power.

The commercial exploitation of the LMFBR will not occur for another decade or more. In the meantime, if other fuel cycles come into commercial use (e.g., LWR plutonium recycle or HTGR), many of the safeguards methods and requirements that will be developed for them will be directly applicable or readily adapted to the LMFBR fuel cycle. The impact of the LMFBR on safeguards would therefore be primarily a matter of extending the application of measures already developed and demonstrated.

The AEC has concluded that the objectives of the safeguards program can be met by the application of the concepts and technology described in Section 7.4.2 and 7.4.8. The exact nature of the future LMFBR safeguards system cannot, and should not, be defined at this time. Any such definition would prematurely anticipate the results of the experience to be gained in safeguarding the intermediate power programs.

*Comment Letter 60, p. 3, from John H. Huber; Pre-Draft Letter 15 (Enclosure 1) p. 4, from Natural Resources Defense Council.

Section 7.4.9 indicates that a rigorous system of safeguards would add less than 1% to LMFBR fuel cycle capital costs and less than 2% to operating costs. Consideration of the various options available to make up the system leads to the conclusion that there is no foreseeable development that would increase costs to a degree that would preclude the establishment of a viable safeguards system to meet the safeguards objectives.

With regard to the impact of LMFBR on the hazards of war, the AEC has concluded that there would be no significant change in those hazards for any reasonable prediction of wartime events.

The societal effect of a rigorous safeguards system will not be disruptive. Although the requirements imposed on the nuclear industry will likely require additional regulations, the portion of U.S. industry affected will be small. In any case, the relative impact of safeguards on society could only be assessed in the light of other societal changes that might arise as a result of the non-nuclear aspects of the overall problem of increasing violence and terrorist activities.

It is clear that many of the safeguards-related risks associated with the LMFBR will exist whether or not the LMFBR is fully exploited. Many of these risks will exist even if the U.S. were to abandon fission reactions as a source of energy, if foreign nuclear power programs continue. With full recognition of the need to provide adequate protection against deliberate destructive acts involving nuclear materials, the Commission concludes that there is no safeguards-related reason to delay the further development of LMFBR.

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VOLUME IV

SECTION 8

**UNAVOIDABLE ADVERSE
ENVIRONMENTAL IMPACTS**

SUMMARY FOR SECTION 8

Construction and operation of commercial LMFBR facilities will result in certain inherently unavoidable adverse environmental impacts because of the nature of the facilities and activities involved. Other adverse impacts may be termed unavoidable in that they represent the residual of projected efforts to limit controllable impacts. Typical of the inherently unavoidable impacts common to all nuclear and fossil methods of generating central station electricity are the occupation of land (during facility construction and operation and after decommissioning) and the effects of waste heat discharged from power plants. Residual unavoidable impacts are those related to the normal release of radioactive materials from fuel cycle facilities and radiation doses received by the public from these releases and during transport of fuel cycle materials. These impacts are summarized in this section. Detailed discussions of these points are found in Section 4.

Doses due to radiation resulting from the LMFBR fuel cycle are relatively insignificant and much lower than doses due to background radiation and medical exposures. Although about 1500 acres of land will be required for a 1000-MWe LMFBR power plant, its supporting fuel cycle, and associated transmission lines, most of this committed land will be taken up by the exclusion area and transmission line right-of-way and will remain relatively undisturbed.

8. UNAVOIDABLE ADVERSE ENVIRONMENTAL IMPACTS OF THE LMFBR

8.1 INTRODUCTION

Construction and operation of LMFBR facilities on a commercial scale will result in certain adverse environmental impacts that are inherently unavoidable because of the nature of the facilities and activities involved. Other adverse impacts may be termed unavoidable, because they represent the residual of projected efforts to limit controllable impacts. Typical of the inherently unavoidable impacts are the occupation of land (during facility construction and operation and, in certain cases, after decommissioning) and the effects of waste heat discharged from LMFBR power plants. Residual unavoidable impacts are those related to the normal release of radioactivity and chemicals from fuel-cycle facilities and the radiation doses received by the public during transport of fuel-cycle materials. Quantitative estimates of many of these impacts are provided in Section 4 of this Statement and are summarized here, first on the basis of individual model facilities and then on a per reactor-year basis.

Section 4 also provides information on the environmental impacts of accidents postulated to occur during operation of fuel-cycle facilities. There is a finite possibility that accidents will occur and the resulting environmental impacts could be considered unavoidable. However, stringent measures will be taken to preclude the occurrence of accidents and to mitigate their effects, so that their environmental impacts are expected to be low relative to impacts of normal operation. Further, reliable and precise quantitative information on the expected frequency of occurrence of major accidental releases in the LMFBR fuel cycle is not available at this time. For these reasons, accident-related impacts are not treated in this section.

8.2 FUEL CYCLE ENVIRONMENTAL IMPACTS

8.2.1 LMFBR Power Plant

8.2.1.1 Construction

During construction of an LMFBR power plant and associated transmission lines, changes will necessarily be made in the topography of the site and related areas. These changes will result from excavation, grading, and the construction of roads, buildings, and related facilities. The potential for adverse environmental impact is not expected to be substantially different from that of any other power plant construction project of the same size. The magnitude and extent of the effects will depend upon the site location and topography and the effectiveness of provisions made to limit the effects. Because the most favorable sites will

be chosen first, the most significant impact may be the reduction in the inventory of available and suitable sites, both for future reactors and other uses.

Plant construction activities will take place over a period of five to eight years and will be confined to the area of the plant site, approximately 35 to 50 acres for a plant using once-through cooling. If an artificial cooling lake is also to be constructed, an additional 1500 acres will need to be graded and diked. The commitment of land to these uses is made for the life of the plant; a few acres may be committed for a longer time if, in the course of decommissioning, the decision is made to leave activated materials permanently buried on site. (See Section 9 for further discussion of decommissioning of LMFBR facilities.) Transmission lines will require the commitment of 20 to 50 acres/mile, depending on the total generating capacity of the site and the line voltage. These corridors can be used for agriculture, recreation, or other beneficial activities that do not interfere with operation of the transmission system. The land can be returned to former or other uses at the end of plant life if appropriate at the time. Withdrawal of land from forestry uses is expected to continue along with expanded energy production, whether by LMFBR or other types of power plants.

Unavoidable adverse impacts can be temporary, occurring only during construction, or relatively long-term (at least for the life of the plant). Temporary impacts are dust and noise from construction activities and machinery, discharge of gaseous wastes from internal combustion engines, increased traffic on local roads, aesthetically undesirable appearance of construction activities and of temporary or incomplete buildings, increased suspended solids and siltation of waterways because of dredging and offshore construction, and possible social impacts on nearby communities because of the influx of a large work force. As the level of construction activity declines, these effects will also tend to be reduced. Impacts of a more permanent nature that may remain for the life of the power plant or even longer, depending upon disposition of the facilities at the time of decommissioning, are: changes in land use, destruction or degradation of plant life and animal habitat, and alteration of surface water drainage patterns and of groundwaters.

8.2.1.2 Operation

Once the plant goes into operation, concern shifts to a new set of impacts. These include those impacts resulting from the discharge of heat and chemicals to natural bodies of water, the discharge of heat and water vapor to the atmosphere from

cooling towers, noise from mechanical draft cooling towers, and the discharge of small amounts of radioactive liquids and gases.

A 1000-MWe LMFBR power plant will discharge approximately 5×10^9 Btu/hr of waste heat to the atmosphere, released when turbine exhaust steam is condensed as part of the energy conversion process. To remove this heat using once-through cooling will require that cooling water be supplied at a rate of up to 1500 cfs with a 15°F temperature rise at the condenser; correspondingly lower flows will accompany higher temperature increases. A well-designed discharge system will ensure that this heated water is returned to the natural body of water under conditions such that other uses for the receiving water are not compromised and that effects on the aquatic environment are ecologically acceptable.

The water taken into the plant will contain fish and small organisms, the larger of which will be removed by impingement on intake screens. The remainder will pass through the cooling system. The quantity of aquatic biota that will be killed is a function of many factors including the initial population (which varies with the season), the type of cooling system employed, the design and siting of the intake, the plant operating conditions, and many others; therefore, quantitative estimates of losses for any power plant can be made only after evaluation of its specific site. Additional losses of aquatic biota can occur as a result of discharging the heated water to a natural water body. Here again, many factors are involved and a quantitative estimate of the impact requires a great deal of information about the site, the water supply, and the plant design. Methods are available for minimizing these losses through proper siting and design features. Occasional losses are not necessarily permanently disruptive to the ecosystem; the system can recover if the losses do not exceed the resiliency provided by compensatory population responses.

Where the quantity of suitable water that can be supplied to the plant is insufficient for once-through cooling or acceptably low levels of environmental damage can not be achieved, cooling ponds, spray systems, or wet or dry cooling towers may be used to reject the heat. Spray canals and wet cooling towers lose water as "drift." Some of the drift water falls to earth near the cooling tower, carrying salts with it. The remainder of the water evaporates, releasing the salts as very small particles that are carried by the winds and returned to earth. Effects expected from drift with systems using fresh water are chiefly related to biocides. As discussed in Section 4.2.5, cooling systems using salt water will require special attention to assure that impacts on local vegetation are held to acceptable levels.

Operation of spray cooling systems in winter in northern regions of the country has the potential for supplementing the natural occurrence of ground fog and for the formation of ice. Cooling towers will produce elevated vapor plumes visible for long distances.

Closed-cycle wet cooling systems must, to control the concentration of impurities in the circulating water, discharge a fraction of the water in the system and replace it with fresh water. This blowdown will generally be at a temperature higher than that of the receiving body of water. The quantity of blowdown will be less than about 2% of the quantity of cooling water discharged if the system were operated on a once-through basis. Thermal effects will be correspondingly reduced.

The water discharged from the plant will carry with it small quantities of chemical wastes, primarily from water treatment systems. Chemicals are added to the cooling water to control biological growths, control scale and sludge formation, and inhibit corrosion. Wastes from regenerating demineralizers used to purify water for plant use will also be discharged via the blowdown stream. The effects of these chemical discharges on plant and animal life are expected to be minimal.

The water discharged from the plant will also be used to dilute and disperse a small quantity of tritium. This slightly contaminated water will be the only radioactive liquid discharged from the LMFBR power plant. Using conservative assumptions for the several factors involved, the maximum cumulative annual dose received by any member of the permanent population assumed to live within 50 miles of an LMFBR power plant would be 0.001 man-rem from radioactive liquid released under normal operating conditions. The corresponding annual population dose would be 0.47 man-rem. Doses due to gaseous releases will be greatest within one mile of the plant, and the dose rate will be 0.012 millirem/year at a distance of 1000 m from the plant. Within 50 miles, the population dose rate will be 0.10 man-rem/year from this source.

8.2.2 LMFBR Fuel-Fabrication Plant

During construction of an LMFBR fuel-fabrication plant, changes will necessarily be made in the topography of the site. These changes will be confined primarily to about 150 acres where the main building is located and to access roads. Potential adverse impacts due to plant construction, both temporary and long-term, are basically the same as those described for the LMFBR power plant in Section 8.2.1.1. The principal unavoidable adverse impacts of operation are those

associated with the release of small amounts of radioactive material and chemicals. Small quantities of various radioactive isotopes of uranium and transuranic elements would be released to the environment. The maximum individual adult total-body dose resulting from both gaseous and liquid releases is estimated to be 0.059 millirem/year; the average annual population dose for people living within 50 miles of the plant is estimated to be 1.2 man-rems.

Hydrogen fluoride (HF) and NH_3 are the chemical releases of most concern. With proper treatment of chemical wastes before release, environmental impact should be minimal. Damage to vegetation is not expected for routine airborne releases of HF (~ 2.0 kg/day) under average meteorological conditions. Forage plants will not accumulate HF to levels that are toxic to livestock.

The consumptive use of water is another unavoidable environmental impact associated with the operation of a fuel-fabrication plant. Water use at such a plant is small compared with that of a power plant; the fabrication plant would use about 470,000 gpd of water, about one-half of which would be evaporated in the cooling tower.

8.2.3 LMFBR Fuel-Reprocessing Plant

During construction of a spent-fuel reprocessing plant, changes will be made in the topography of the site. The construction operations typically involve extensive excavation and disturbance of the surface of the site. The extent of damage should be of the same order of magnitude as that from other construction projects of the same magnitude. Control of the damage to surrounding areas by the construction activities is largely a function of the planning and care exercised during the construction project.

During the life of the reprocessing plant, there will be a commitment of about 1000 acres of land. After shutdown (35 to 40 years after the initial commitment), all but 50 to 100 acres of the land could be returned to other uses. The residual area might remain as an exclusion zone after decommissioning of the plant.

The operation of the reprocessing plant will entail the release of small quantities of radioactive fission products and nonradioactive chemicals. The magnitude of these quantities has been presented in Section 4.4.5.

The potential maximum individual total-body dose likely to result from exposure to the routine releases from the reprocessing plant under assumed typical meteorological conditions and population distribution is estimated to be 2.0 millirems/year. For

the average individual within a 50-mile radius, this dose is predicted to be 0.035 millirem/year. The calculated population dose of 35 man-rems/year for 1 million people living within 50 miles of the plant would be a very small fraction of the population dose from natural radiation and medical exposures.

All liquid chemical waste is discharged to a retention pond. Small quantities of nonradioactive chemical pollutants will be discharged from the reprocessing plant boiler and process stacks; 1.3 metric ton/day of nitrogen oxides, 0.05 metric ton/day of carbon monoxide, and trace quantities of other air pollutants will be discharged. No significant adverse environmental effects are expected as a result of these discharges. The total quantity of water required for the plant is 1,400,000 gpd, and most of this water would be evaporated. The heat discharge from the plant is about 2.2×10^8 Btu/hr, and the adverse environmental impact associated with it will be negligible.

8.2.4 Transportation

Packages that contain significant quantities of material having penetrating radiation will be shielded to reduce external dose rates to at least those levels specified in the Department of Transportation regulations. Since most of the packages are expected to be shipped in a vehicle used exclusively for that particular shipment, the external dose rates would be no greater than 10 millirems/hr at a distance of 6 to 8 ft from the accessible surfaces of the vehicle. At greater distances from the vehicle, the dose rate would be lower. As these packages are shipped over public highways or over established rail routes, the general public along these routes would be exposed to small increases over background radiation levels.

8.2.5 Radioactive Waste Management

8.2.5.1 Retrievable Surface Storage Facility

For purposes of establishing environmental impacts in this Statement, the Hanford Reservation in southeastern Washington state was assumed as a reference site for the retrievable surface storage facility (RSSF). Construction of the RSSF would disturb from 100 to 150 acres of land for the water-basin or air-cooled vault concepts or up to 2300 acres for the sealed storage cask concept. Excavation would destroy the habitats of small mammals (mainly rodents) but would have no measurable impact on the larger wildlife.

Construction would be accompanied by noise and dust at the site but would not affect the public outside the reservation. Disturbances of the land surface would result in a slight increase in vehicular traffic hazard on the nearby highways due to the dust. This dust increase would be expected to be minor, and it would be minimized during construction by appropriate dust control techniques. On completion of construction phases, ground surfaces would be stabilized for the long term.

During operation of the RSSF, heat from the radioactive waste would be rejected to the atmosphere via open forced-air cooling towers or via direct air cooling of cask or overpack surfaces. Waste in storage in the year 2010 would release about 200 MW/hr or about 680 million Btu/hr, but this heat release would drop by a factor of 2 every 30 years thereafter as a result of radioactive decay. During the winter, the maximum expected rate of water release in cooling tower evaporation might cause an increase in the fogging of highways within a few miles of the reference Hanford site for the RSSF, where fog naturally occurs 30 to 40 days/year.

Normal operation of the RSSF would result in a small increase in the annual amount of radionuclides released to the environment, estimated at less than 1 mg (0.001 Ci/year). The result would be air concentrations both on and off the site well below applicable Federal guidelines. At the point of nearest approach, the site boundary approximately five miles away, radiation exposures for the public would be less than 0.001 millirem/year for a member of the general public. Occasional releases to the receiving and handling cell air might come from the contaminated casks, the failure of a canister, or the cleanup operations in a contaminated area. This air would be filtered through three HEPA filters in series before discharge.

With the sealed storage cask concept, radiation dose rates (primarily from neutrons) ranging up to 20 rems/hr, depending on the type and age of waste, would be encountered in the annulus between the cask and the concrete shield. Radiation fields would be harmful and possibly fatal to small mammals intruding into the annulus of the vertical casks via the air flow ports at the base of the shield or near the surface of the horizontal casks. The losses would be small relative to the large regional fauna population.

In the sealed storage cask concept, there will be a low level of neutron-induced radiation in the soil and dust in the vicinity of the casks. However, even under the worst possible conditions of blowing dust, the exposure of a member of the general public would be less than 0.1 millirem/year. Some activation of dust

particles in the cooling air discharged from the air-cooled vault concept would also occur, but the activity would be much less than in the sealed cask concept.

8.2.5.2 Land Burial Facility

The volume of other-than-high-level waste produced by each 1000-MWe LMFBF and its supporting fuel cycle is estimated at about 34,000 ft³/year (see Section 4). The land area required for burial is approximately 0.1 acre/year. The commercial burial sites will remain as restricted areas for the indefinite future. In addition to the use of land, the principal unavoidable environmental effects of constructing and operating a land burial facility are: (1) the temporary disruption and dust and noise during construction of the office and laboratory, (2) the periodic excavation and filling of trenches and the accompanying dust and noise, and (3) the exclusion of access to the area by the perimeter fence. There will be no routine releases of radioactivity from these facilities.

8.2.5.3 Noble Gas Storage Facility

Construction of the noble gas storage facility (NGSF) would disturb from 50 to 100 acres of land and would destroy the habitats of small mammals but would have no measurable impact on the larger wildlife. Construction would produce noise and dust, but the soil would be stabilized during and after construction to minimize effects of winds.

During operation of the NSGF, heat from the noble gas containers would be rejected to the atmosphere via direct air cooling. Approximately 2.8 MW of radionuclide decay heat would be dissipated to the atmosphere by peak load but would drop to 0.1 MW by the year 2050. About 14,400 to 28,800 gpd of water would be used during the operating life of the NSGF for cooling and shielding the in-process gas containers (before storage) and for various sanitary and industrial uses. Normal radioactive material releases would be very small, and they would be exclusively to the air. Radiation exposures from the NSGF would be less than 0.001 millirem/year for a member of the general public.

8.3 RADIOACTIVE IMPACTS NORMALIZED FOR ONE REACTOR-YEAR

The doses due to operation of the model LMFBF power plant and its associated fuel cycle are given in Tables 8.3-1 and 8.3-2. The doses are those of one 1000-MWe LMFBF power plant and its fuel cycle requirements for one year. Average doses due to natural background radiation, fallout from weapons testing (based on 1970 data), and medical uses (based on average 1970 diagnostic use) were included for perspective. As shown by these tables, annual doses due to the operation of one

Table 8.3-1

MAXIMUM INDIVIDUAL DOSES DUE TO THE LMFBR FUEL CYCLE

Fuel Cycle Component	Dose ^a (millirem/year)
LMFBR Power Plant	0.033 ^b
Fuel-Fabrication Plant	0.0007 ^b
Fuel-Reprocessing Plant	0.20 ^c
Transportation	10 ^b
Radioactive Waste Management	negligible

OTHER DOSES RECEIVED BY INDIVIDUALS

Source	Dose ^d (millirem/year)
Natural Background	130
Fallout	4
Medical (diagnostic only)	72
Television	0.1

^aNormalized for one 1000-MWe LMFBR power plant and its supporting fuel cycle for one year.

^bTotal-body dose.

^cGI tract dose.

^d1970 average doses (USAEC Report WASH-1250).

Table 8.3-2

YEARLY AVERAGE POPULATION TOTAL-BODY DOSES DUE TO THE LMFBR FUEL CYCLE

Fuel Cycle Component	Dose ^a (man-rem)
LMFBR Power Plant	0.57
Fuel-Fabrication Plant	0.015
Fuel-Reprocessing Plant	0.44
Transportation	2.9
Radioactive Waste Management	<u>negligible</u>
Total	4.0

OTHER POPULATION DOSES

Source	Dose ^b (man-rem)
Natural Background	490,000
Fallout	15,000
Medical (diagnostic only)	272,000
Television	377

^aNormalized for one 1000-MWe LMFBR power plant and its supporting fuel cycle for one year.

^b1970 average doses (USAEC Report WASH-1250); 3,774,000 people in 50-mile radius.

1000-MWe LMFBR power plant and its supporting fuel cycle are considerably smaller than these other doses, particularly natural background and medical doses.

The maximum individual doses for the LMFBR power plant are the site boundary inhalation doses that are due primarily to the leakage of radioactive noble gases. The annual population dose is due primarily to the ingestion of water containing tritium that diffuses through the cladding and piping of the LMFBR power plant and is discharged in the steam generator blowdown. The maximum individual doses for the fuel-fabrication plant releases are the total-body doses at the site boundary from all exposure pathways and all normal releases. The annual population dose is the total-body dose from all exposure pathways and all normal releases from the fuel-fabrication plant. The maximum individual dose for the fuel-reprocessing plant is the GI tract dose due to ingestion of crops grown at the site boundary (containing mostly Ru-106 released to the atmosphere from the reprocessing plant). The annual population dose is the total-body dose from all exposure pathways for atmospheric releases from the reprocessing plant (there are no liquid releases from the reprocessing plant). The maximum individual doses for transportation are total-body doses due to direct radiation (truck shipments of high-radiation level materials--12 min of exposure at a rate of 50 millirems/hr). The population dose for transportation is the total-body direct radiation dose due to all shipments of radioactive material for one 1000-MWe LMFBR power plant and its supporting fuel cycle for one year and is received by individuals along the shipping routes.

8.4 NONRADIOLOGICAL IMPACTS NORMALIZED FOR ONE REACTOR-YEAR

The major nonradiological impacts due to operation of one 1000-MWe LMFBR power plant and its supporting fuel cycle for one year are given in Table 8.4-1. The land usage, however, is unchanged for the life of the various LMFBR fuel cycle facilities.

Table 8.4-1

NONRADIOLOGICAL IMPACTS OF LMFBR FUEL CYCLE^a

Water Required	1 billion gpd ^b (once-through cooling)
Land Usage	
Fuel cycle	12.5 acres at reprocessing plant 12.5 acres at fabrication plant 2.5 acres at burial ground <u>27.5 acres</u>
LMFBR Plant Site	400 acres
Transmission Lines	1050 acres ^c
Total	1478 acres
Chemical Discharges (metric ton/year)	
Atmospheric	Aquatic
NO _x - 5 (reprocessing plant)	NH ₄ OH - 29 (fabrication plant)
CO - 0.2 (reprocessing plant)	Cl ₂ - 17 (reactor)
NH ₃ - 0.02 (fabrication plant)	Ca(OH) ₂ - 1.7 (fabrication plant)
HF - 0.01 (fabrication plant)	

^aNormalized for one 1000-MWe LMFBR power plant and its supporting fuel cycle for one year.

^bAn equivalent amount would be required for LMFBR power plants using cooling ponds or lakes. Plants using wet cooling towers would use only about 4% of this amount.

^c50 miles at 21 acres/mile.

VOLUME IV

SECTION 9

**SHORT TERM BENEFITS AND
LONG TERM LOSSES**

SUMMARY FOR SECTION 9

This section compares the annual and cumulative environmental effects of the total projected United States electrical generation industry in the year 2020 with and without the LMFBR. The difference between these two cases is representative of the environmental impact of the LMFBR Program.

Evaluations of the environmental impacts of the particular energy conversion systems utilize the results of previous AEC studies. One study, the "Year 2000 Study," estimated population doses resulting from extensive use of nuclear facilities in large regions of the U.S. Another study, the "Risk-Cost-Benefit Study," provided the basis for making comparisons of overall societal costs between alternate energy conversion systems. The regional and comparative approaches used in this section as well as in Section 11 include the aggregate effects of the power plants and their associated fuel cycle components and, thus, differ somewhat from the "model plant" and "model site" concepts utilized in Section 4.

The projected demand for electrical energy is based on relationships among energy demand, GNP, and projected populations. Whereas alternate projections are considered in Section 11, only the most likely projection is considered in this section. Projections of the "mix" of central station electric power plant types were made in Section 11, taking into account such factors as the anticipated economic parameters of each plant (such as capital cost and fuel cost), the expected availability of fuel, and the growth capability of supporting industries. In this section the assumption is that the non-nuclear component is represented by fossil-fueled generating capacity, primarily coal-fired plants. Environmental effects associated with wastes and effluents, land use, transmission lines, transportation of fuel and wastes, and doses to both facility personnel and the general public were estimated.

The accumulation of radioactive wastes is one index of environmental impact. The solid radioactive wastes are stored, and the major impacts are the land required for this storage and the guardianship that may be required.

Routine releases of radionuclides from nuclear facilities introduce not only fission products but also transuranic radionuclides and various activation products into the biosphere. The releases are dispersed by air and water transport and, over a period of time, build up in the air and water, on the soil, and at the bottoms of lakes, rivers, and oceans. The buildup is not strictly cumulative,

because the radionuclides decay with time, and the result is their eventual removal from the environment.

Non-radioactive wastes occur primarily in the generation of electrical power by non-nuclear plants. The emissions of various sulphur and nitrogen oxides and particulate matter are not strictly cumulative, because they are eventually removed from the environment by precipitation. Unfortunately, knowledge of environmental impacts from these airborne pollutants from fossil-fueled plants is imprecise, and no attempt at quantifying the impacts has been made in this section.

As nuclear facilities are brought on-line, their contributions to the overall radioactive burden will be determined by their location relative to population centers and the local radionuclide transport from the facility site to these centers. The results of the "Year 2000" studies for two large regions of the country were combined and applied to estimate the radiological dose implications of the projected nuclear power industry. The annual dose, the fifty-year dose commitment, and the cumulative dose were computed and compiled for projected nuclear power facilities with and without the LMFBR. The potential buildup of radionuclides in the environment was also computed. Preliminary data from the "Year 2000" studies indicate that the population-weighted average concentrations of radionuclides are a factor of roughly 100,000 less than the "maximum permissible concentrations" as defined in 10 CFR 20.

Effects on local ecosystems are uniquely defined by site and facility characteristics. Land use, both short- and long-term, for the power plants and their supporting facilities are compared for several energy conversion schemes. Transmission lines and the land use for corridors are independent of plant type.

Health and safety considerations were quantified for some aspects of the power generation industry. Occupational safety is related to the amount of mining associated with a total power system. Public safety was quantified by estimating the fuel transportation hazards (non-radiological) imposed on the public by the two alternate power generation approaches. The radiological health effects for occupational groups and the general public were considered by calculations of radiation doses.

The results from this section of the Statement indicate that, compared with current nuclear power systems, the LMFBR will lead to reductions in total heat discharge, water consumption, land use, radioactive waste production, radiation doses,

uranium mining, and occupational hazards (mostly due to virtual elimination of mining). On the other hand, there will be increases in shipments of irradiated nuclear fuel and the amount of plutonium handled, for which adequate precautions must be taken.

9.1 CUMULATIVE ENVIRONMENTAL EFFECTS TO THE YEAR 2020

9.1.1 Introduction

This section deals with the environmental effects, accumulated from now until the year 2020, of the total United States electrical generation industry. Two cases are considered. In one case the LMFBR is assumed to be in use commercially in 1987 and to increase in numbers according to the projections of reference 1 to the year 2000, with subsequent increases to the year 2020 based on expected competition between various nuclear energy conversion schemes. In another case, the LMFBR is not introduced commercially, and nuclear plants similar to those currently under construction supply the energy that would otherwise have been projected to come from the LMFBR. The difference between these two cases is representative of the environmental impact of the technology being developed as the LMFBR Program. A brief discussion of the expected roles that each energy conversion technique will play and of the environmental effects associated with a unit of generation* from each will be followed by the summation of these effects to the year 2020 and a discussion of the impact of the LMFBR Program.

This section draws partly on results from two studies undertaken by the AEC as part of a continuing program to determine the environmental impact of various (primarily nuclear) energy conversion techniques. One study,² known as "The Year 2000 Study," involves estimation of population dose in a large region resulting from extensive use of nuclear facilities (such as might be expected by the year 2000) in that region. The other study,³ known as the "Risk-Cost-Benefit Study," estimates some of the external societal costs for alternative energy conversion systems. Some of the underlying assumptions of the "Year 2000 Study" are somewhat different from those used in Section 4 of this Statement. The "model plant" concept used in Section 4 emphasizes boundary doses and effects within 50 miles of the facility (with the notable exception of plutonium releases) and concerns the LMFBR fuel cycle only. The regional model considers effects of other fuel cycles on a consistent basis, aggregate impacts from multiple facilities, impacts from multi-fuel plants, and the effects of regional (rather than local) geography, meteorology, hydrology, and demography.

*In this section, environmental effects are based on a unit of electrical energy, the gigawatt-year. A gigawatt is one billion watts or one million kilowatts. A gigawatt-year is the energy produced in one year's continuous operation of a plant whose capacity is one gigawatt. A 1250-MWe power station operating at 80% capacity factor would also produce a gigawatt-year of energy in one year. The unit used in Sections 4 and 8 is the 1000 MWe-yr for a plant assumed to operate at full power for 80% of the year. Effects estimated for the latter unit need to be divided by 0.8 to obtain the gigawatt-year unit.

9.1.1.1 Projected Use of Electrical Energy

A forecast of the use of electrical energy to the year 2020 is shown in Figure 9.1-1. This forecast, like many others, is based on projections of energy use per capita and of U.S. population. A more detailed description of its derivation is found in ref. 1. As illustrated in Figure 9.1-1, not all of the electrical energy requirements will be met by large, central station units. Hydroelectric power and energy produced in fossil-fuel peaking units (including gas turbines and internal combustion units) will supplement the central station generation of electrical power during periods of peak demand or when otherwise appropriate. Figure 9.1-1 shows the relative contributions of these various generation techniques to meeting the aggregate demand.

Figure 9.1-1 was interpreted by one commenter* as showing a fixed rate of growth for projected demand for electrical generating capacity. Other commenters suggested that independent projections be used and that consideration of scenarios involving a lower standard of living would be appropriate. The projection used here is discussed in the following paragraphs and is compared with a variety of different projections in Section 11.2.4.9.

Table 9.1-1 was included in response to a comment from the Mid-America Coalition for Energy Alternatives** and shows peaking capacities as a percentage of the total projected capacity shown in Figure 9.1-1. As Table 9.1-1 shows, by 2020 the small decrease in fossil-fuel peaking units will be compensated for by an increase in pumped storage units.

Table 9.1-1
CAPACITY CONTRIBUTIONS OF ELECTRICAL GENERATION PEAKING FACILITIES
(percentage of central station capacity)

Year	Internal Combustion Gas Turbine (%)	Pumped Storage (%)	Total (%)
1970	5.5	1.1	6.6
1980	8.0	3.5	11.5
1990	7.7	4.5	12.2
2000	6.8	4.0	10.8
2010	5.5	3.3	8.8
2020	4.3	2.6	6.9

*Comment Letter 25, p. 16.

**Comment Letter 22, p. 9.

PROJECTED DEMAND FOR ELECTRICAL GENERATING CAPACITY 1970-2020

Figure 9.1-1

That portion of the energy expected to be supplied by central station electrical generation will be generated in units fueled by fossil fuels (coal, oil, gas) or by nuclear power such as that obtained from an LWR, HTGR, or LMFBFR. Projections of the "mix" of these types of plants have been made,^{1,4,5} taking into account the anticipated economic parameters of each (capital cost and fuel cost), the expected availability of fuel, and the growth capability of supporting industries. Of particular interest is the situation where the LMFBFR plays its expected role, in contrast to the situation in which the LMFBFR does not compete and the other energy conversion techniques are used instead. Figures 9.1-2 and 9.1-3 show the expected contributions of the various energy sources for these two cases. The data displayed in these figures are taken from the cost-benefit studies discussed in Section 11.2. The fossil component is the same for both cases so that the primary competition is between the LMFBFR and the nonbreeding nuclear options. Non-nuclear strategies are discussed in Section 11.

The fossil-fuel component of Figures 9.1-2 and 9.1-3 is actually composed of the estimated contributions from all fossil sources, including coal, oil, and gas, but it could be considered to include contributions from solar or geothermal energy or other sources. The specific contributions of residual fuel oil and natural gas are uncertain and currently in a state of change. Figure 9.1-4 shows the assumptions made in this Statement concerning the use of fossil fuels through the year 2000. In general, most of the fossil-fuel component results from the combustion of bituminous coal. Subbituminous coal and lignite are assumed to play increasingly important roles, while those of oil and gas decline to essentially zero very early in the next century.

The use of natural gas for producing electrical energy has been growing for several years. Recently, the Edison Electric Institute (EEI) published a projection of natural gas usage through 1985.⁶ A portion of the projection was based on availability of natural gas from foreign suppliers. The expected generation of electricity from natural gas generally involved successively smaller increments of generation in succeeding years. This decrease in generation of electricity from gas implies a decrease in the rate at which new plants are brought on-line and an eventual decline of that form of energy conversion as shown in Figure 9.1-5. Recent developments indicate that foreign supplies of natural gas may be unavailable to the United States or that national independence of them will be sought. In such a case, the use of natural gas to generate electricity would decline much more rapidly, as shown by the lower curve in Figure 9.1-5. This lesser contribution is assumed to be

PROJECTED CENTRAL STATION CAPACITY BY ENERGY SOURCE: 1970-2020
Figure 9.1-2

PROJECTED CENTRAL STATION CAPACITY BY ENERGY SOURCE
WITHOUT THE LMFBR; 1970-2020

Figure 9.1-3

PROJECTED UTILIZATION OF FOSSIL FUELS FOR GENERATION
OF ELECTRIC POWER 1970-2000

Figure 9.1-4

8-1'6

PROJECTED ROLE OF NATURAL GAS IN THE ELECTRICAL GENERATION INDUSTRY

Figure 9.1-5

the case in this section. When the critical shortage of natural gas for other uses is considered, an even lower projection may be warranted.

The role of residual fuel oil in the next few decades is uncertain. Oil usage increased sharply after the mid-1960's, and most projections have been remarkably different from actual usage. For this report, the more recent EEI projection⁶ was used (Figure 9.1-6). Considering the rapid growth of this form of energy conversion, the EEI projection could have been considered conservative in many respects, but more recent international and domestic developments may lead to a halt in the growth of residual fuel oil usage and even cause a reversal through conversion of oil burning units to the use of coal.

In recent years, coals with lower heating values have also been used to fuel larger plants. Very rough projections of the use of lignite and subbituminous coal were made by assuming that the proportion of electricity generated by these fuels would remain fairly constant and that their use would grow as local demand grew (as indicated in Figure 9.1-4). Bituminous coal is assumed to be used to generate all electrical energy from fossil units that is not generated by one of these four fuels (oil, gas, lignite, subbituminous coal).

The introduction of moderately advanced fossil-fuel burners (using liquified or gasified coal) has not been specifically addressed in this portion of the Statement. The overall pollutant burden (primarily the contained ash and sulphur) that must be handled in processing coal to produce electricity remains roughly the same, regardless of the processing scheme involved; only the locale and the cost of pollution abatement measures will change.

In very general terms, the overall impact lessens as the pollutant removal point is moved from the post-combustion handling step to the mining step. In this regard, in-situ gasification or liquefaction (which may have limited applicability at strip mines) shows great promise, because the offending materials are not removed from the ground. In any event, the health effects of these pollutants are not considered in the cumulative impacts developed in this section. Thus, fossil fuels are generally assumed to have advanced pollution control technology available. Advanced fossil-fuel pollution control technology is discussed in Section 6A.

The Mid-America Coalition for Energy Alternatives* inquired why the growth rate for fossil-fuel generating capacity shown in Figures 9.1-2 and 9.1-3 appears to be

*Comment Letter 22, p. 9.

9.1-10

PROJECTED USE OF RESIDUAL FUEL OIL IN THE ELECTRICAL GENERATION INDUSTRY

Figure 9.1-6

inconsistent with the projected utilization of fossil fuels for electrical generation shown in Figures 9.1-4, 9.1-5, and 9.1-6. Figures 9.1-2 and 9.1-3 depict capacity projections. Fossil-fuel plants will be expected to operate at lower plant factors than nuclear plants, because the "variable" costs of fossil-fuel plants are larger than for nuclear plants. Thus, even though there is an increase in coal-fueled capacity between 1990 and 2000, the generation of electricity by fossil fuels does not increase as substantially as it does after 2000.

9.1.1.2 Basis for Comparison of Electrical Power Generation Methods

The various techniques for producing electrical energy differ in terms of the consumption of this energy in their respective fuel cycles. Since the same total power demand is to be supplied in every case, this difference in use of electrical energy is factored into the analysis by requiring each energy conversion technique to produce enough additional electrical power to compensate for its associated fuel cycle use. Table 9.1-2 lists the electrical energy required for various conversion schemes, detailed according to use. In the nuclear generation methods, enrichment of the fuel in U-235 is the major use of electrical energy. Those techniques that minimize or bypass that step require less total generation. Thus, 1.046 units of generation are required from an LWR to produce a single unit of "deliverable" energy, while slightly over 1.000 units of generation are required from an LMFBFR.

9.1.2 Waste Generation and Disposal

9.1.2.1 Heat

Heat dissipated to the environment is not considered to accumulate but is, instead, ultimately radiated to outer space within a short time after release. Thus, the heat dissipation impact is proportional to the heat rejection at the time of consideration and not the total heat discharged over the time period involved.

The heat rejection to the environment is found primarily in the generating station, with relatively minor contributions from the fuel cycle. In fossil-fuel generating stations, a portion (roughly 10%) of the heat of combustion is lost to the system through the stack. The rest of the energy that is not converted into electricity is generally dissipated in the condenser. The subsequent release to the environment may be to the air from dry (nonevaporative) or wet (evaporative) cooling towers, to artificial or natural lakes and ponds, or to rivers. Of course, even when the heat is assimilated by a water body, it normally is transferred to the

Table 9.1-2

ELECTRICAL ENERGY USAGE OF VARIOUS CONVERSION TECHNIQUES
(table entries are kWhr required/kWhr produced)

	Coal ^a	Oil ^a	Gas ^a	LWR ^b	LMFBR ^c	HTGR ^c
Mining and Milling	0.00119	0.00167	0.00167	0.00039		0.00020
Conversion and Enrichment				0.04548		0.03073
Fuel Fabrication				0.00022	0.00012	0.00007
Reprocessing				0.00006	0.00003	0.00004
Desulfurization	0.01431	0.00857				
Total ^{d/}	0.01550	0.01024	0.00167	0.04615	0.00015	0.03104

^aUSAEC Report WASH-1224 (to be published).

^bRequirements from USAEC Report WASH-1237, modified to account for updated mass balances as used in the cost-benefit studies reported in Section 11.2

^cRequirements from USAEC Report WASH-1237, adjusted to LMFBR and HTGR mass balances (Section 11.2).

^dIn-plant (at the power generation station) electrical energy uses are assumed to be the same for all conversion techniques.

atmosphere by energy exchange at the water surface, largely through the mechanism of evaporation.

The amount of heat released to the environment is a direct function of the efficiency of the energy conversion process. In the electrical generation industry, efficiency is commonly measured by the heat rate, the amount of energy required to produce 1 kWhr of electrical energy. Because the thermal equivalent of 1 kWhr is 3413 Btu, a heat rate of 3413 Btu/kWhr would indicate 100% efficiency, 6826 Btu/kWhr would correspond to 50% efficiency and so forth. Technological improvements have caused a dramatic reduction in heat rate (improvement in efficiency) over the decades, and this trend is expected to continue, although at a slower rate.

Figure 9.1-7 shows representative historical and projected future heat rate data through the year 2000. The data for the year 2000 were considered representative of the period 1970 to 2020. The projection for bituminous coal follows roughly the FPC data.⁴ The projections for oil and gas reflect the results of analysis of National Coal Association data⁷ as shown also in Figure 9.1-7. The lignite and subbituminous coal data were developed from a multiple regression analysis of FPC data from operating plants.⁸ During the 1960's, the average heat rate of a coal-fired plant was determined to increase by about 33 Btu/kWhr (about 0.3%) for each 100 Btu/lb decrease in the heat value of coal. Application of these results to lignite and subbituminous coals (6700 Btu/lb and 9500 Btu/lb, respectively, compared with 13,000 Btu/lb for bituminous coal) indicated a heat rate for subbituminous coal plants some 12.6% higher than for bituminous coal plants and some 22.4% higher in the case of lignite. These ratios were maintained throughout the rest of the century in the projection shown in Figure 9.1-7. Nuclear efficiencies were taken from ref. 1. The resulting process heat requirements for the various energy conversion techniques are shown in Table 9.1-3. The likely path of their dissipation, to air or water, is also shown. Generally, the dissipation to water includes the potential for dissipation in cooling towers, including dry towers which do not evaporate water.

As noted earlier, the discharge of heated effluents to the environment is not really an environmental impact but is, instead, an index of such impact. Actual impacts are better described by determining the effects of the heated discharge, as discussed in Section 4.2. The effects of this discharge in terms of evaporation of water and its consequent removal from downstream uses is discussed elsewhere in this section. Biological impacts have not been included in this section for two reasons. First, the variety of potential impacts is strongly dependent upon the specific plant site. Second, individual discharges are presumed to be within applicable state and Federal regulations designed to protect the environment. In

PROJECTED HEAT RATES OF VARIOUS ENERGY CONVERSION TECHNIQUES
Figure 9.1-7

Table 9.1-3

EQUIVALENT PROCESS HEAT USAGE

Energy Usage (BTU/kWhr)	Coal			Oil	Gas	LWR	LMFBR	HTGR	Geothermal
	Bitum.	Subbitum.	Lignite						
Mining and Milling ^a	73	111	172	52	52	14	0	0	0
Fabrication and Processing ^a	0	0	0	0	0	<1	<1	<1	0
Transportation ^a	35	52	80	67	62	<1	<1	<1	0
Base Heat Rate ^b	9,300	10,470	11,380	9,780	9,350	10,250	8,230	8,750	22,000
Cooling Tower Penalty ^c	306	371	422	328	290	417	294	325	0
Desulfurization Penalty ^a	162	60	107	39	4	0	0	0	0
Total	9,876	11,064	12,161	10,266	9,758	10,681	8,524	9,075	22,000
Energy Dissipated (10 ¹² Btu/GW-year)									
To Air	9.26	10.37	11.65	10.14	11.62	0.12			
To Water ^d	47.78	57.12	67.92	49.85	43.20	66.83	44.00	51.20	162.82

^aFrom USAEC Report WASH-1224 (to be published), adjusted as needed for updated mass balances.

^bFrom projections, Figure 9.1-7.

^cEvaporative cooling towers, consistent with USAEC Report WASH-1224 (to be published), modified to account for different heat rates.

^dDissipation to rivers, lakes, ponds, or from cooling towers to the air.

addition, decisions regarding site selection and plant cooling water supply selection for a particular installation will be made with due regard for all pertinent factors, including environmental impact at candidate sites.

One commenter* submitted the following remarks concerning the first two sentences of the preceding paragraph:

"The point is well taken, but heated effluents have an environmental impact that must be dealt with in a meaningful way, and the index-versus-impact argument should not be used to justify inadequate consideration of thermal impacts. If appropriate site selection criteria were formulated and adhered to then the effects of thermal discharge on the biota would be lessened."

All LMFBRs will presumably meet the same site suitability criteria as LWRs, HTGRs, and fossil-fuel plants. The actual impacts of waste heat discharges cannot be predicted in this Statement, because the majority of sites for LMFBRs (and other plants) are not now selected.

9.1.2.2 Radioactive Wastes

Radioactive wastes from nuclear reactors and their associated fuel-cycle processing steps can be conveniently categorized in major groups. High-level wastes are essentially the fission-product wastes from chemical reprocessing plants. Current AEC regulations require solidification of these wastes. The major trade-off between short-term uses and long-term commitments is that the generation of electricity by LMFBRs is accompanied by the generation of high level wastes that will be hazardous essentially forever. Further discussion of the processing and storage of spent fuel and subsequent long-term commitments for management of high level wastes can be found in Section 4 of this Statement. Low-level wastes include gaseous, liquid, and solid waste products from the reactor and the fabrication and reprocessing plants. All of these wastes are discussed more fully in Section 4, and a brief review of pertinent data is presented in Table 9.1-4. In addition to these wastes, some routine releases of radioactive material from nuclear plants will take place. The accumulation of these releases is only an index of the environmental impact. The low-level solid wastes generated are buried, and their true impact is the land use required for their disposal and the guardianship that may be required. The impact of routine releases is not the actual release but the resultant dose to the populace and any health effects from that dose. These measures of impact are treated elsewhere in this section.

*Comment Letter 19 (M. T. Carter et al), p. 6.

Table 9.1-4

GENERATION OF RADIOACTIVE WASTES PER GIGAWATT-YEAR

	LWR	LMFBR	HTGR
High-Level Solids, ft ³ ^a	69	69	63
Low-Level Solids, ft ³ ^a	39,000	32,500	7,500
Plutonium-Contaminated Solids, ft ³ ^a	3,000	9,700	0 ^c
Cladding Hulls, ft ³ ^a	72	206	0
Mine Tailings, metric ton ^b	105,200	0	55,000

^aFrom data in Sections 4.5 and 4.6, HTGR assumed on a par with LMFBR, except no fuel cladding.

^bFrom USAEC Report WASH-1237, adjusted to update mass balances.

^cPlutonium and higher transuranics produced in the HTGR fuel cycle are included in the high-level solid wastes.

Several reviewers of the Draft Statement* expressed an interest in radioactive waste inventories categorized in other than volume units. The amount of radioactive material in high- and low-level wastes measured in total curies differs by only a few percent for nuclear power systems with and without the LMFBFR. The only significant difference in quantities of radioactive waste material is in the category of cladding hulls and plutonium contaminated wastes as shown in Figure 9.1-5. In general, the volume of the waste is the critical index for environmental impact. The volume of waste material determines the land requirements for disposal.

9.1.2.2.1 Routine Releases

Routine releases of radionuclides from nuclear facilities introduce not only fission products but also transuranium nuclides and various activation products into the biosphere. These releases are dispersed by air and water transport and, over a period of time, build up in the air and water, on the soil, and at the bottoms of lakes, rivers, and oceans. The buildup is not strictly cumulative, because the radionuclides decay, resulting in their removal from the environment. A few representative values of elemental release rates from the entire fuel cycle are found in Table 9.1-6. Cumulated concentrations, in the air and on the ground, are found in a later portion of this section. Most of the emitted plutonium (in terms of curies) is Pu-238, formed by transmutation of Pu-241 to Cm-242 and subsequent decay by alpha particle emission. Recycled plutonium in the equilibrium LWR fuel cycle assumed for "The Year 2000 Study" and previous cost-benefit studies has a much high Pu-241 content than that in the LMFBFR cycle. It should be noted that in terms of whole-body dose, or dose to the lungs, Pu-241 is not a large contributor, despite the fact that about 30 times as much Pu-241 is released as Pu-238 in the LMFBFR fuel cycle. However, Am-241, the decay product of Pu-241, makes a substantial contribution to the bone dose (see Appendix II.G).

9.1.2.2.2 Activity Retained in Radioactive Waste Systems

Virtually all effluents from nuclear facilities are treated to remove contained radionuclides. The portion removed from the effluent streams then remains in the radioactive waste treatment system until the material (such as resins) is removed for burial or other handling. Of particular interest are the noble gases, which may be delayed in charcoal beds or bottled. Modern LWR plants using charcoal beds with "holdup times" on the order of one day for krypton and 15 days for xenon would release only a very small amount of radioactive noble gases, the rest having decayed to nonradioactive species. By the end of 60 days, which is typical of a PWR, the inventory in the radioactive waste system is down to about one ten-thousandth of the original amount, and about 80% is krypton.

*Comment Letters 22 (Mid-America Coalition for Energy Alternatives), p. 9; 38 (NRDC), p. 32 (General Comments); 64 (General Electric), p. 6.

Table 9.1-5

ACCUMULATION OF TRANSURANIC WASTES
(cladding hulls and plutonium-contaminated wastes^a-
millions of curies)

Year	With Breeder	Without Breeder
1980	50	50
1990	300	300
2000	1,350	900
2010	4,600	2,150
2020	10,400	3,900
2050 ^b	18,000	6,400

^aAssumes all radioactivity due to long-lived radionuclides (half-life >50 years).

^bIncludes wastes generated in 2021 to 2050 time period at plants in operation in 2020.

Table 9.1-6

REPRESENTATIVE RELEASE RATES OF RADIOACTIVE ELEMENTS
(release rates in curies per gigawatt-year)

Gaseous Effluents	LWR-U ^a	LWR-Pu ^a	LMFBR	HTGR
Tritium	28.1×10^3	37.0×10^3	1.35×10^3	36.8×10^3
Krypton ^b	4.28×10^3	2.67×10^3	2.08×10^3	4.37×10^3
Xenon ^b	48.5	48.5	negligible	negligible
Strontium	0.97×10^{-3}	0.61×10^{-3}	0.61×10^{-3}	0.98×10^{-3}
Iodine	72.7×10^{-3}	72.7×10^{-3}	1.01×10^{-3}	4.51×10^{-3}
Cesium	5.30×10^{-3}	5.06×10^{-3}	2.30×10^{-3}	6.00×10^{-3}
Plutonium ^c	44.1×10^{-6}	266×10^{-6}	122×10^{-6}	64.7×10^{-6}
Transuranics ^d	89.6×10^{-6}	1965×10^{-6}	121×10^{-6}	6.7×10^{-6}
Liquid Effluents				
Tritium	142	142	60	74
Strontium	1.13×10^{-3}	1.13×10^{-3}	0	0.45×10^{-3}
Iodine	88.0×10^{-3}	88.0×10^{-3}	0	0
Cesium	0.86×10^{-3}	0.86×10^{-3}	0	8.4×10^{-3}
Plutonium ^c	14.5×10^{-6}	86.3×10^{-6}	39.7×10^{-6}	16.8×10^{-6}
Transuranics ^d	9.5×10^{-6}	38.8×10^{-6}	42.5×10^{-6}	0.14×10^{-6}

^aLWR-U refers to an LWR that is refueled with uranium fuel re-enriched in U-235. LWR-Pu refers to an LWR refueled with recycled plutonium. This latter type of fuel is expected to dominate the industry around the turn of the century. The "representative" LWR is taken from a population in which one-third of the reactors are BWRs and the remainder are PWRs.

^bComment Letters 53, p. 21; 38, p. 33 (General Comments); and 22, p. 9 (Environmental Protection Agency, Natural Resources Defense Council, and Mid-America Coalition for Energy Alternatives) noted an apparently more sophisticated radioactive waste treatment system was assumed in the Draft Statement for LMFBRs than for LWRs or HTGRs. These entries now include the effect of bottling noble gases at the reactor which reduces the LWR release of krypton by ~20% and the HTGR release by ~33%. The xenon release was reduced to ~1% of that in the Draft Statement.

^cIncludes Pu-238, Pu-239, and Pu-240, which make up the bulk of the biologically important (alpha-emitting) plutonium emissions. Actually, about 30 times as many curies of Pu-241 are emitted, but the biological effect of this emission in terms of whole-body or lung dose is less than a few percent of that of the plutonium listed. However, AM-241, the decay product of Pu-241, makes a substantial contribution to the bone dose (see Appendix II.G).

^dIncludes Am-241, Cm-242, and Cm-244, the other major alpha-emitting radionuclides.

9.1.2.2.3 Fission Products Delivered to Waste Storage

By far the greatest amount of fission products is separated from the fuel at the reprocessing plant, solidified, and delivered for interim storage to a retrievable surface storage facility prior to transfer to some ultimate waste repository (see Sections 4.6 and 7.3). Most of the activity decays during the "cooling time" before the spent fuel is shipped to the reprocessing plant. For example, only about 2.4% of the original fission product radioactivity is still present when the fuel from a PWR is shipped to the reprocessor. After the first year, the radionuclide activity of the waste products decreases by some 25% each year. Considering the anticipated growth of the industry (about 11 to 12% per year to 2000, and about 5% thereafter) together with the decay, at any one time the total activity in accumulated high-level solid wastes is near three times the amount produced that year (somewhat greater prior to 2000 and somewhat less thereafter). Thus, in the year 2000, some 8.5×10^{10} Ci of high-level wastes, occupying about 60,000 ft³, will be produced, and the total inventory from the entire nuclear power industry, including the LMFBR, will be roughly 22×10^{10} Ci. In the year 2020, some 21.4×10^{10} Ci (171,000 ft³) will be produced, and the inventory will amount to about 62×10^{10} Ci in 3 million ft³ of wastes. The actual releases of radionuclides are only about one ten-thousandth of the amount retained in the fuel after one year's decay or about one-millionth of that produced in the reactor.

9.1.2.2.4 Other Radioactive Wastes

A number of other types of radioactive wastes are generated in the nuclear industry. They include cladding hulls (metallic tubes from which the previously contained UO₂ fuel has been removed) from the reprocessing plants and various types of low-level wastes such as contaminated supplies and equipment. These low-level wastes will be buried in large 55-gal drums in approved burial grounds. Recently, the EPA inventoried the contents of a solid waste repository in Kentucky.⁹ The specific activity of solid waste buried there in 1970 to 1972 (representative of power reactor operations) ranged from an average of less than 0.1 Ci/ft³ (for ~600,000 ft³) to about 20 Ci/ft³ (for 1700 ft³). Overall, the specific activity of the buried material is ~0.15 Ci/ft³. The cladding hulls (and other transuranic wastes) will be stored retrievably at a federal repository (see Section 4.6).

In addition, the uranium mine tailings produced at the mill are somewhat radioactive due to the residual uranium content and the uranium decay daughter products, some of which have very long half-lives and one of which (radon) is gaseous. These materials are confined to the mill site. It is currently anticipated that tailings

ponds from uranium milling activities will be restored to resemble the surrounding terrain when the mill is decommissioned. Despite this reclamation, the land will most likely not be available for unrestricted use, except possibly for grazing. Present regulations prohibit release of tailings material to the surrounding area and restrict access to the tailings storage area. These regulations are binding on all owners of the land for a 50-year period from dating from licensing of the mill site.

9.1.2.3 Nonradioactive Wastes

Nonradioactive wastes occur largely in the generation of electrical power by non-nuclear techniques. Emissions of sulphur dioxide, nitrogen oxides, carbon dioxide, and particulate matter (fly ash) have all received considerable attention in recent years. A brief review of these and other emissions is given in Table 9.1-7. The emissions are not strictly cumulative, because they enter the environment and are removed from the air by precipitation. Consequently, only annual values will be cited for these airborne pollutants. Those potential pollutants that have been removed from the effluent streams and retained at the plant site do not actually contribute to the pollutant burden but occupy, at least temporarily, land at the site. Thus, their impact is measured in terms of land use.

A well-known fact is that some airborne pollutants (such as SO_2 and NO_x) can have somatic effects on man. Unfortunately, our knowledge of these effects is imprecise. As a result, further "tracking" of these pollutants into the biosphere is not included in this assessment. This situation has the general effect of underestimating, perhaps substantially, the environmental effects of fossil-fuel generating stations.

9.1.3 Radiological Implications

Much of our current knowledge concerning the potential radiological implications of large-scale utilization of nuclear facilities comes from "The Year 2000 Study,"² a study undertaken to determine, on a regional basis, the kinds and amounts of radioactive materials that will be reaching large segments of the U.S. population from routine releases in the nuclear industry. Transport of radionuclides by air and water was simulated in this study, and some 45 separate pathways leading to human exposure were considered, including inhalation, ingestion of water and many types of food, and direct exposure to radionuclides in the air, in the water, and on the ground. Eating habits, recreational habits, population growth patterns, and food production techniques were also considered. Much of this information was catalogued according to age group (child, teen, adult) and urban-rural classification. Sources

Table 9.1-7
SELECTED NONRADIOACTIVE WASTE DATA

	Bituminous Coal	Subbituminous Coal	Lignite	Oil	Gas	LWR	LMFBR	HTGR	Geothermal
Plant Heat Rate, (Btu/kWh) ^a	9,768	10,091	11,909	10,147	9,644	10,667	8,524	9,075	22,000 ^b
Heating Value (10 ⁶ Btu/unit) ^c	26	19	13.4	6.3	1,045	69	69	69	1,014
Consumption (units/GW-year) ^c	3,300,000	5,030,000	7,785,000	14,110,000	80,800	1,350,000	1,100,000	1,150,000	160,000
Percentage Ash ^c	12.58	11.48	8.44						
Bottom Ash (tons/GW-year)	72,750	72,750	72,750						
Fly Ash Removed (tons/GW-year)	410,200	571,200	650,500	1,867	570				
Fly Ash Emitted (tons/GW-year) ^d	4,160	5,780	6,570	280					
Percentage Sulfur	2.59	0.56	0.76	1.69					0.025 ^e
SO ₂ Retained (tons/GW-year)	68,500	22,513	47,300	37,500					20,000
SO ₂ Emitted (tons/GW-year)	17,100	5,600	11,800	9,370	24				
Other Emissions (tons/GW-year)									
Airborne									
NO _x (as NO ₂) ^f	36,000	36,000	36,000	27,200	15,800	17.6 ^g	6.8 ^h	11.6 ^g	803,000
CO ₂	8,000,000	8,000,000	8,000,000	6,000,000	6,000,000				
CO ⁱ	1,330	1,330	1,330	10,000	16				
Hydrocarbons ^j				1,730	1,467				
Aldehydes ^j				250	110				
Organics ^j					153				
Trace Metals ^j	41,600								
Ammonia							0.028		16,000
Hydrogen Fluoride						1.04	0.014	0.52	
Waterborne									
Chloride	25.4	30.4	36.1	26.5	23.0	47.1	23.4	32.9	
Ammonium Hydroxide						27.5	39.9	13.7	
Calcium Hydroxide						10.4	24	10.2	
Iron ^j	2.7	4.1	6.4			.55		.28	
Sulfuric Acid ^j	107	163	252			3	0.3	4	

^aSee Figure 9.1-7; includes cooling tower and desulfurization penalties.

^bObserved at The Geysers (see Section 6A.4.6-11).

^cUnits are tons for coal and lignite, barrels for oil, millions of cubic feet for gas, millions of pounds of steam for geothermal, and grams of fissile material for nuclear.

^dSource: Federal Power Commission, "Steam-Electric Plant Air and Water Quality Control Data--Summary Report," February 1973; lignites assumed from North Dakota, subbituminous coal from the mountain states. Computations follow USAEC Report WASH-1224 (to be published).

^eAs H₂S.

^fUSAEC Report WASH-1224 (to be published) used for coal values; FPC report in footnote c for oil and gas; USAEC Report WASH-1224 data for coal correspond roughly to FPC data assuming pulverized coal and dry-bottom firing.

^gFrom USAEC Report WASH-1237, adjusted for mass balances.

^hFrom Table 8.4-1.

ⁱFrom USAEC Report WASH-1224.

^jFossil fuel contribution is primarily acid mine drainage.

of drinking water (and its treatment), distribution of foodstuffs, and food chain relationships of radionuclide concentration were also elements of the study. Although simplified models were often used to permit processing the vast amounts of data necessary to such a comprehensive evaluation, the results are indicative of the overall impact to be expected.

Two types of dose results were developed in "The Year 2000 Study." The first of these is the annual dose to the population in the year 2000. This dose results from radionuclides emitted from nuclear facilities in the year 2000 and those remaining emissions from all previous years. Thus, a gradual accumulation of radionuclides in the environment would contribute to the annual dose. The second type of dose result is the dose commitment. This dose will be received (over the 50 years following uptake) as a result of the body's retention of radionuclides ingested or inhaled during that year. The dose commitment does not include exposure to external sources and may, therefore, be smaller than the annual dose.

Subsequent to the original "Year 2000 Study,"² which covered the Upper Mississippi River Basin (UMRB), a second study was initiated to similarly examine the Tennessee Valley Region (TVR). In the course of the second study, which involved Oak Ridge National Laboratory and the Tennessee Valley Authority (TVA), the models simulating atmospheric and aquatic transport of radionuclides were improved in several ways to estimate more accurately the transport effects. The improved model was then used to "update" the UMRB study. Table 9.1-8 summarizes some very preliminary results from these two studies, utilizing only the air transport mechanisms.

Although the population doses calculated in the two cases are similar, the details differ considerably, and these differences are a direct consequence of the difference in characteristics between the two areas. In the TVR, transport of radionuclides occurs in a generally northeast-southwest direction, paralleling the regional terrain features. Because the population is also concentrated in the valleys, the plant emissions tend to be transported to the people much of the time. In the UMRB, on the other hand, the patterns of population and radionuclide transport are quite different, and much of the radioactive material is removed from the atmosphere in large, sparsely populated areas. As a result, the average concentrations of many radionuclides in populous areas of the UMRB are an order of magnitude below those of the TVR.

Table 9.1-8

SUMMARY OF YEAR 2000 STUDY RESULTS

Year 2000 Dose (Total Body)	TVR ^a	Updated UMRB ^b
Year 2000 Total Population Dose, man-rem	23.3	51.0
Year 2000 Average Dose, millirem	0.0033	0.0018
Dominant Pathways (contribution in percent)		
Air Submersion	56	53
Air Inhalation	14	23
Tritium Transpiration	11	22
Fishing on River Bank	3	
Exposure to Soil	16	2
Major Nuclides (contribution in percent)		
Xe-133	37	32
Cs-134 and -137	21	3
Kr-85	18	21
H-3	23	45
Year 2000 Dose Commitment (Total Body)		
Year 2000 Total Population 50 Year Dose Commitment, man-rem (from releases during the Year 2000)	85.4	41.5
Year 2000 Average Dose Commitment, millirem	0.012	0.0022
Dominant Pathways (contribution in percent)		
Air Inhalation	96	98
Milk	3	2
Beef and Lamb	1	
Major Radioactive Materials (contribution in percent) ^c		
Plutonium, Curium	95	97
Strontium	5	3
Total Dose from Year 2000 Exposure, man-rem	108.7	92.5

^aTVR=Tennessee Valley Region.^bUMRB=Upper Mississippi River Basin.^cAirborne transport only.

A generic comment regarding the assessment of the environmental impact of radionuclides was submitted by Russell H. Ball.* He stated:

I find tabulations and summations of the number of curies of mixtures of radionuclides to be quite uninformative as regards environmental effects.

The assumptions of linearity of the dose-response relationship and of no threshold lead to the concept of man rem as the measure of public impact of radiation exposure. In view of this I suggest the adoption of a generic policy for all environmental reports of expressing approximations of radiation exposures on the basis of man rem exposures to the population. For reports that are not site-specific, such as WASH-1535, such doses should be calculated on the basis of standardized assumptions of the population distribution, meteorology, hydrology and exposure pathways. All standardized assumptions should be fully described and the methodology of all calculations should be presented.

He then explained that this method would allow reviewers of environmental reports to compare the effects of a wide variety of radionuclides and that conversion factors could then be used to translate unit release rates (Ci/year) into total man-rem/GWe-year delivered to the standard population.

Population doses reported in Sections 4, 8, and 9 of the Statement were developed similarly to the method described. This topic is discussed in considerable detail in "The Year 2000 Study" report² referenced earlier in this section and in Appendix II.I. Briefly, releases from selected (about 50) radionuclides are developed based on assumed process streams and radioactive waste treatment steps. Transport of released radionuclides is simulated using local meteorology, and local concentrations are calculated. Population dose is then computed using conversion factors that translate concentrations (pCi/m^3) into dose (man-rem/year) and that take into account the radiological and biochemical properties of the individual radionuclides.

9.1.3.1 Annual Dose from Nuclear Facilities

The "Year 2000" studies covering the TVR and UMRB (updated) can be interpreted in terms of effects from a particular reactor type as shown in Table 9.1-9. The exposure impacts are based on all fuel cycle emissions associated with a particular reactor type. The highest regional dose estimated is used for calculations of cumulative exposures as listed in Tables 9.1-15 and 9.1-16.

*Comment Letter 30, pp. 1-2.

Table 9.1-9

PUBLIC EXPOSURE TO RADIATION FROM NUCLEAR FUEL CYCLES

Population Dose (man-rems/GW-year)	LWR ^a	LMFBR	HTGR
Based on TVR Results	0.3	0.030	0.4
Based on UMRB Results	0.4	0.02	0.7
Used in this Statement (airborne transport)	0.4	0.03	0.7
Dose due to Transportation ^b	1.0	2.2	0.4
Dose due to Recirculated Krypton ^c	0.7	0.7	1.5
Dose due to Waterborne Transport	4.7	0.2	4.7
Dose due to Worldwide Tritium	0.5	0.02	0.5
Doses - Year 2000	7.3	3.2	7.8
- Year 2020	8.2	3.6	8.8
Population 50 Year Total-Body Dose Commitment (man-rems/GW-year)			
Based on TVR Results	1.0	0.7	0.6
Based on UMRB Results	0.8	0.4	0.7
Used in this Statement - Year 2000	1.0	0.7	0.7
- Year 2020	1.1	0.8	0.8
Total 50-Year Total-Body Dose (man-rems/GW-year)			
Year 2000	8.3	3.9	8.5
Year 2020	9.3	4.4	9.6

^aThe LWR is assumed to use recycled plutonium.

^bTransportation dose is computed by assuming that all shipping casks will meet the same standards for surface dose rates as discussed in Section 4.5 and Appendix II.M. For spent fuel, the average shipment distance depends upon the growth patterns of the industry and is projected to be 200 miles in the Year 2000 and beyond. UF₆ shipments are expected to average 600 miles. Other shipments of fresh fuel materials are assumed to average 200 miles. Radioactive waste shipping distances are the same as those given in Table 4.5-1.

^cRecomputed from the Draft Statement to include bottling of noble gases. If the world population is used instead of the U.S. population, the doses in man-rems/GW-year would be LWR-10.5, LMFBR-10.2 and HTGR-21.2.

There are three sources of population dose not covered in ref. 2. The first of these is the dose due to transportation of radioactive materials. This dose has been discussed in some detail elsewhere (see Section 4.5), and the effect is simply added to the results from "The Year 2000 Study" in Table 9.1-9 after adjusting to the shorter shipping distances in the regional model (see footnote b of Table 9.1-9). Also, the calculations consider only routine releases of radionuclides. Thus, accidental releases other than "normal" leaks in operating radwaste systems are not included. Finally, the effects of accumulation and circulation through the earth's atmosphere (for radionuclides such as Kr-85) is not included in "The Year 2000 Study." If one assumes that the released krypton is dispersed in a volume between 20 and 50° north latitude, which extends some 6 km in depth, the dose from the recirculated radionuclide can be estimated. This estimate has been made, and the results are given in Table 9.1-9. Tritium is not included in this fashion, because it is assumed to have been scavenged from the atmosphere by precipitation. However, the scavenged tritium will eventually be dispersed throughout the hydrosphere. The dose due to ingestion of tritium "recirculated" in this manner was estimated by assuming uniform dispersal throughout the hydrosphere and daily ingestion of 2.5 liters of water from food and drink. These estimates are also given in Table 9.1-9. In the cases of both krypton and tritium, a worldwide population growth rate of 1.8% per year was assumed with a baseline population of 6.13 billion people in the year 2000.

Finally, since only air transport mechanisms were considered in the preliminary TVR and updated UMRB results, an entry is required to account for waterborne radionuclide transport. In the original study² the major impact of water-borne transport was determined to be the effect of tritium in drinking water. This effect was estimated by assuming the gaseous releases to be uniformly mixed in the national surface runoff. In all cases, release data developed for "The Year 2000 Study" have been assumed to be applicable to the year 2020, with appropriate adjustments for population growth in estimating man-rem doses.

In addition to the dose rate to the general population, the dose rate to people working in the nuclear industry must be considered. Typical exposures and annual doses for the various fuel cycle steps are given in Table 9.1-10. These data are similar to those in ref. 3 but have been modified to account for updated mass balances.

At each step in the nuclear fuel cycle, considerable precautions are taken to limit the exposure of industrial workers. For example, uranium miners are limited to 4

Table 9.1-10

OCCUPATIONAL EXPOSURE TO RADIATION

Fuel Cycle Steps ^a		Equivalent Dose, (man-rem/GW-year) ^b		
		LWR ^e	LMFBR	HTGR
Uranium Mine	(1.2 man-WLM/ton of U ₃ O ₈)	139		73
Reactor Plant	(400 man-rem/GW-year)	400	400	400
Reprocessing Plant	(1 man-rem/metric ton of uranium)	40	22	12
Other Fuel Cycle Steps	(0.5 man-rem/metric ton of uranium)	<u>20</u>	<u>11</u>	<u>6</u>
Total Fuel Cycle		599	433	491
Transportation ^c				
Fresh Fuel		0.8	1.0	.7
Irradiated Fuel		1.0	2.0	1.1
Low-Level Waste		0.7	0.7	0.2
High-Level and Process Waste		<u>1.0</u>	<u>2.9</u>	<u>0.1</u>
Total Transportation		3.5	6.6	2.1
Total Dose		602	440	493
Malignancies ^d		0.120	0.088	0.099

^aFrom USAEC Report WASH-1224, modified to account for updated mass balances.

^bBased on 1 man-WLM = 0.6 man-rem, an equivalence based on malignancy rates reported in USAEC Report WASH-1224.

^cBased on Table 4.5-1, modified to put shipping distances on a par with those assumed in USAEC Report WASH-1209 (the "Year 2000" study).

^dBased on a rate of 0.0002 malignancies/man-rem, from USAEC Report WASH-1224.

^ePlutonium recycle.

WLM (Working Level Months--170 hr exposure to air containing enough Rn-222 and daughter products to yield 1.3×10^5 MeV/liter of alpha particle energy upon total decay) per year. The assessment of impact in this section has assumed that each miner receives this limiting exposure--an assumption that overestimates the impact. The biological effects of exposure such as miners receive have been determined by the U.S. Public Health Service in an extensive study of lung cancer in American uranium miners. In the other fuel cycle steps, exposure is limited to 5 rem per worker per year. The biological effect of the exposure that these workers receive is of the same order of magnitude as for the miners. These estimates of biological effect must be considered as only order of magnitude estimates rather than as statistically precise estimates, because certain assumptions concerning the effects of long-term exposure to low levels of radiation are involved. In very general terms, the assumptions lead to the same total radiation effect (number of cases of cancer, for example) being predicted for a group of one million people each receiving 0.1 rem/year (100,000 man-rem) as for a group of one hundred million people receiving 0.001 rem/year per person (again 100,000 man-rem). These assumptions of linearity of effect are involved for both occupational exposure and for dose to the general population.

Ref. 3 also indicates that one may expect an impact of 6000 man-days lost per malignancy and a malignancy rate of 0.0002 malignancies/man-rem. Data from Tables 9.1-9 and 9.1-10 are used later to assess the occupational and public health impacts.

In regard to the models discussed in this section, the following points were made by J. C. Sheppard* of Washington State University:

It appears that the AEC has conservatively estimated the environmental radiation impacts but it is impossible to check the validity of the data as summarized in the TVR and UMRB (WASH-1209) studies. Studies of the "Year 2000" type can be very misleading. Basically, the "Year 2000" studies, which use the HERMES code (HEDL-TME-71-168) are analogous to Forrester type modelling -- "Limits of Growth, Urban Dynamics, etc."

He stated that it was his experience that models may be used to justify positions or opinions. He further stated that no model is a unique representation of real or mature systems and that uncertainties in the results may be substantial. He believed, however, that carefully constructed models may give insight on the behavior of natural systems. He also feels consideration should be given to random occurrences such as the weather. He summarized his comments as follows:

*Comment Letter 21, pp. 1-2.

When one considers the low success rate of demographic predictions, which have more substance than those of the "Year 2000" studies, it seems to me that the AEC should express some reservations or qualifications about the "Year 2000" studies. Studies of this type are unprovable at one end, difficult to disprove for those without access to large computers, misleading to the uninformed, and most likely incorrect at the other end.

Although the "Year 2000" model (HERMES) is analogous to the "World Dynamics" model in that both tend to deal with mechanisms and can easily be non-unique, the following differences can be important:

- (1) The region size for which HERMES was designed is sufficiently small to permit inclusion of many details. These details are simulated by including actual data such as local meteorological station measurements, local food production and consumption, and local recreation habits. Much of this information was localized at the county level. On the other hand, the region size is large enough to represent multiple source-receptor relationships as opposed to a single source or single receptor analysis.
- (2) There is essentially no feedback in the HERMES model. It merely determines the consequences, in terms of population dose, of combinations of projections of nuclear plant operation and demography with existing meteorology, hydrology, and living habits. It is a "simulation" model rather than a "predictive" one.

Nevertheless, the results may not reflect the situation as it will exist in 2000, or even 1980. But, together with the "model plant" approach used in Section 4, the HERMES results do indicate, to the best of our present ability to determine them, the approximate foreseeable consequences of the LMFBR Program.

9.1.3.2 Dose Commitment from One Year's Exposure

Results from ref. 2 indicate that, on the average, a dose commitment of from 0.5 to 1.0 man-rem/GW-year will result from operation of nuclear facilities in the year 2000. Again, the details are strongly dependent upon the region. Tritium is a major contributor in the UMRB, accounting for one-third of the dose commitment, but constitutes less than 10% of the dose commitment in the TVR. Table 9.1-9 indicates the dose expected from a unit of production from each type of reactor. The approach again has been to take the least favorable combination of individual effects to obtain the value used for calculations in this part of the

Statement and to assume that the results from the year 2000 will also apply to the situation in the year 2020.

9.1.3.3 Environmental Buildup of Radionuclides

As nuclear facilities are brought on-line, their contributions to the overall radionuclide burden will depend upon their locations relative to population centers and upon the mechanisms available in the intervening area to transport the radionuclides either by air or by water from the emission site to the populace. Remote siting of nuclear facilities tends to cause regions of high population density to have lower overall radionuclide concentrations than regions of lower density close to the site. Preliminary data from the studies in ref. 2 indicate that the population-weighted average concentrations (which, at least to first order, take into account the relationship between concentration and population dose rate) are a factor of roughly 100,000 less than the maximum permissible concentrations as defined in Appendix B to 10 CFR 20. Three examples of the projected concentrations of airborne radionuclides are given in Figures 9.1-8, 9.1-9, and 9.1-10. The methods used to make the projections tend to overestimate the concentrations so that actual data may well indicate lower average concentrations in the country as a whole. The calculated points for TVR and UMRB are shown for reference.

The nuclides selected for the figures are representative of the overall dose patterns. Xenon concentrations, for example, tend to parallel those of Kr-85. Other airborne radionuclides are not major contributors to dose. Although not illustrated, soil concentrations of cesium do not increase rapidly after the year 2000. For example, Cs-134 concentrations (representing accumulation) increase by only 70% between 2000 and 2020 despite a three-fold increase in nuclear capacity during that time. Total accumulation of Cs-137 (roughly one-third as effective in surface exposure dose as Cs-134) over that time span increases by nearly a factor of 4, and the effective concentration, taking into account their respective dose effects, increases by a factor slightly greater than 2. Soil concentrations of plutonium are not an important factor in dose assessments.

An inquiry* was made as to why Figures 9.1-8, 9.1-9, and 9.1-10 used the assumption that no new plants would be constructed after the year 2020. The analysis was intended to cover only the time period 1970 to 2020.** Thus, plants built after 2020 were not considered; however, effluents from those plants built before 2020 and in

*Comment Letter 25 (C. Kepford), p. 17.

**Prediction of new LMFBR capacity to be added after the Year 2020 would be very difficult due to cumulative uncertainties.

AVERAGE AIRBORNE TRITIUM CONCENTRATIONS IN U.S.A.

Figure 9.1-8

AVERAGE AIRBORNE Kr-85 CONCENTRATIONS (NOT INCLUDING RECIRCULATION) IN U.S.
Figure 9.1-9

AVERAGE AIRBORNE CONCENTRATION OF ALPHA-EMITTING TRANSURANICS IN U.S.A.

Figure 9.1-10

operation after 2020 were considered so that the forward commitments could be included. It seems likely that new plants will be built after 2020, that many of them will be breeders, and that many may belong to any of several alternative technologies, such as fusion.

9.1.3.4 Cumulative Population Dose

The results of ref. 2 give only the dose and dose commitment for an exposure in the year 2000. The results can be interpreted in terms of a cumulative dose resulting from continual exposure to emitted radionuclides from nuclear facilities through the year 2000 and beyond by using the data in Table 9.1-9 and assuming, of course, no improvements in waste handling beyond the techniques considered for the studies of the year 2000. Such improvements, occurring at the reactors, would have a rather small effect on dose, because the majority of the emissions occur at the reprocessing and fabrication plants. Since multipurpose plants were assumed for these facilities, reductions in dose from improvements in waste handling would affect reactor types similarly, causing no major change in dose comparisons; that is, the dose from LWRs would be reduced by roughly the same proportion as the dose from LMFBs or HTGRs.

9.1.4 Effects on Local Ecosystems and Land Use

This compilation of environmental impacts does not detail the impacts to local ecosystems, because so many aspects are site-specific in nature. In some sense, a measure of local impact is obtained from the land area disturbed. This section deals largely with land use.

During construction of a plant, a certain amount of environmental damage is caused by construction of roads, by establishment of a lay-down area, and by construction activities in general. Frequently, the roads later become the normal access routes to the site, and the lay-down area is either included in the fenced-off portion of the site or restored, insofar as possible, to its original condition. For the purposes of this tabulation, construction effects are not included separately but are included in the land use figures for the facility in question.

Three types of land usage are considered in this section. First, there is a base facility usage, that represents the acreage required to site the facility in question. If it is a large facility serving several generating stations, the land usage is allocated to each station served. The second concept is that of annual usage, in which a given amount of land is used or disturbed for each unit of electrical energy produced. The land disturbed by strip mining is an example of this type of land usage. Finally, there is the concept of committed land, which

represents land that has been disturbed and will not be returned to a natural state. In the case of the nuclear fuel cycles, this concept represents the area required for the permanent storage of high-level wastes, bottled noble gases, and transuranic wastes (estimated to be 45 square miles in the year 2000, including surrounding exclusion zones), the area to be occupied by the reactor plants after decommissioning (assuming they are not all dismantled, as was successfully accomplished at Elk River), the area disturbed by uranium mining and storage of mining and milling wastes, and land required for burial of low-level radioactive wastes. For the fossil-fuel cycles, committed land is the land disturbed by subsidence only, because all other areas are assumed to be returned to a near-natural state, if necessary. This process includes complete reclamation of all lands strip mined for coal. Table 9.1-11 lists the land usage impacts per gigawatt for the various fuel-cycle steps in the major electrical energy generation processes.

Consideration must also be given to the land usage effects of decommissioning. Plant sites are assumed to continue to be active through several generations of central station activities and decommissioned plants may simply be absorbed in the land usage at such sites. Consequently, although entries are included in Table 9.1-11 for decommissioning, this commitment of land may not actually be required.

A second way in which the impact on ecosystems may be measured, in quantities that are not site-specific, is water usage. Unfortunately, much of the water usage impact is related to the site. For example, evaporation of water will be strongly dependent upon the cooling schemes used--once-through, cooling pond, or cooling tower. Also, water usage figures, particularly for process industries, do not generally convey the environmental impact, because the water may be reused many times. In general, process water use is only a small portion of the total water usage in the cycle and so is not considered in detail herein. Other water impacts include oil spills, acid mine drainage, and waste water from coal cleaning plants.

For this tabulation, water usage is computed as follows:

- (1) The total condenser heat load is determined from data in Table 9.1-3.
- (2) Once-through cooling is expected to account for a portion of the cooling,¹⁰ as shown in Figure 9.1-11. Use of once-through cooling is assumed not to increase after the year 2000. For each trillion (10^{12}) Btu released in a year through such a cooling technique, the water

Table 9.1-11

LAND USE BY VARIOUS ENERGY CONVERSION SCHEMES

Base Facility (acres/GWe)	Coal	Oil	Gas	LWR	LMFBR	HTGR	Geothermal
Mining	0	1910	300	250	0	130	0
Milling--Processing	79 ^a	100	0	50	0	25	0
Conversion, Enrichment	0	0	0	60	0	40	0
Fuel Manufacture	0	0	0	12	12	12	0
Power Plant	250	80	100	333	333	333	4500
Reprocessing	0	0	0	12	12	12	0
Cooling Tower	70	75	65	100	66	77	245
Total	399	2165	465	817	423	519	4745
Land Usage (acres/GW-year)							
Mining - Surface Mines	960	0	0	12	0	6	
Milling--Processing	9	0	0	3	0	2	
Conversion, Enrichment	0	0	0	0	0	0	
Fuel Manufacture	0	0	0	0	0	0	
Power Plant	8	0	0	0	0	0	
Reprocessing	0	0	0	0	0	0	
Waste Storage	0	0	0	0.006	0.006	0.006	
Low-Level Waste Storage	0	0	0	1.72	2.50	0.78	
Total	977	0	0	17	3	9	
Land Committed (acres/GWe)							
Mining	7740	0	0	300	0	160	
Decommissioning	0	0	0	100	100	100	
Waste Storage	0 ^b	0	0	65 ^c	94 ^c	29 ^c	
Total	7740	0	0	465	194	289	

^aIncludes base facilities for underground mining.

^bAssumes that land required for storage of fly ash and SO₂ removal wastes is fully reclaimed.

^cBased on total for entire nuclear industry to year 2000.

POTENTIAL USE OF ONCE-THROUGH
COOLING 1970-2000
(DATA FROM REFERENCE 12)

Source: D. E. Peterson et al., "Thermal Effects of Projected Power Growth: The National Outlook," Report HEDL-TME-73-45, July 1973.

POTENTIAL USE OF ONCE-THROUGH COOLING IN THE U.S., 1970-2000

Figure 9.1-11

evaporated from the surface of the water body will be equivalent to a constant flow of approximately 0.27 cfs. The analogous values for supplemental cooling systems are 0.35 cfs* for cooling ponds and 0.64 cfs for cooling towers. The presumption is that about 20% of the plants would use cooling ponds and the rest would use wet towers.⁴

The estimates of water evaporated by condenser cooling are probably larger than the consumptive water use that will actually occur. Some areas of the country will require the use of dry cooling towers because there is insufficient water available for cooling tower or pond make-up requirements. Also, these estimates cannot be used to determine total consumptive use of fresh water from precipitation run-off, because some current and potential sites permit the use of saline water.

9.1.5 Plutonium Considerations

Plutonium production and use data are derived from the cost-benefit calculations reported elsewhere in this Statement. During most of the time period before 2000, plutonium is produced mainly in LWRs, and its production rate could limit growth of the LMFBR cycle. However, plutonium would probably be recycled and used in LWRs as well as in LMFBRs before the end of the century.

Plutonium is considered by many to present a special hazard because of its high toxicity. For this reason, plutonium toxicity is discussed in detail in Section 4.7 and Appendix II.G. Previously discussed figures concerning population dose include effects due to plutonium and other transuranium nuclides.

9.1.6 Transmission Lines and Corridors

In very general terms, the environmental impact of transmission is independent of plant type. Nuclear plants will possibly be clustered into nuclear energy centers with an attendant increase in transmission requirements at any particular site. The increased acreage will usually be small, however, because under such circumstances, higher voltage lines can be used. The total land use for the power system would decrease with the use of nuclear energy centers. The FPC has estimated⁴ that the 65,000 miles of transmission lines anticipated in 1970 would grow to 118,000 miles by 1980 and 159,000 miles by 1990. These estimates remain unchanged for various mixes of central station fuel sources. Extrapolation of these data indicate that

*If a cooling pond is constructed specifically for power plant waste heat rejection, then the consumptive loss should be adjusted for normal losses, and additions due to precipitation.

some 205,000 miles of transmission lines could be required by 2000 and 280,000 miles by 2020.

9.1.7 Transportation Aspects

Transportation of nuclear fuels and wastes is expected to grow significantly as the nuclear industry expands. Even so, this growth will comprise only a very small part of all freight shipments. Table 9.1-12 shows the relative transportation requirements for coal and the nuclear fuel cycles. The oil and gas requirements are significantly smaller than those of coal, largely because oil-burning (or gas-burning) facilities are sited close to sources of supply, including gas pipelines and deep-water ports where such fuels are imported. The transportation requirements of a coal-fired plant are immense. Coal is frequently transported in unit trains consisting of perhaps 100 cars loaded with coal. A single 1000-MWe coal plant would require a train load of coal for each day's operation. The LMFBR, on the other hand, requires much less than a single such train load of fuel in an entire year.

The assumptions made in developing the data (ton-miles/GW-year) in Table 9.1-12 differ somewhat from those used in Section 4. In that section, rather large reprocessing plants and fabrication plants dealing only with LMFBR fuel were considered. The approach used in this analysis to provide consistency with the studies in ref. 2 has been to assume multipurpose plants of an intermediate size. These multipurpose plants tend to reduce the shipment distance compared with that reported in Table 4.5-1, and as a result, the radiation dose is also reduced. The reduction in radiation dose is offset by the fact that doses from routine releases in the nuclear fuel cycle computed with these assumptions are larger than they would be if only a few large, remotely sited plants were considered.

9.1.8 Health and Safety Considerations

9.1.8.1 Occupational Safety

Occupational safety data from ref. 3, as modified to account for more recent mass balance data, are presented in Table 9.1-13 and summarized in Table 9.1-14. A fatality was assumed to be the equivalent of 6000 man-days lost. This estimate in no way measures the priceless value of human life, but represents an average cost to the industrial community of the loss of that person's productivity. Clearly, this cost is less than the value of this life to society. In fact, the estimate cannot even include contributions made outside of working hours. The approach is, nevertheless, consistent and useful in comparing various alternatives.

Table 9.1-12

TRANSPORTATION REQUIREMENTS FOR VARIOUS FUEL CYCLES

Truck Shipments	Shipments per Gigawatt-year ^a				Million Ton-miles per Gigawatt-year ^b			
	Coal	LWR	LMFBR	HTGR	Coal	LWR	LMFBR	HTGR
Fuel Materials								
U ₃ O ₈		9.5	---	7.9		0.144	---	0.120
UF ₆		39.4	2.51	19.5		0.354	0.022	0.176
UO ₂		7.9	3.22	3.95		0.025	0.010	0.012
PuO ₂		1.1	3.64	0		0.001	0.005	0
Fabricated Fuel		<u>52.2</u>	<u>25.1</u>	<u>13.8</u>		<u>0.076</u>	<u>0.035</u>	<u>0.020</u>
Total Fuel Materials		110.1	34.5	45.1		0.600	0.073	0.328
Low-Level Wastes and Bottled Gases		81.2	76.6	17.0		0.200	0.191	0.042
<hr/>								
Rail Shipments								
Fossil Fuels	33,750				1025			
Irradiated Fuels		16.35	33.44	18.28		0.372	0.762	0.418
Process Wastes (Cladding Hulls, Plutonium Wastes)		12.45	41.16	8		1.001	2.981	0.151
High Level Wastes		0.94	0.94	0.86		0.158	0.158	0.144

^a A shipment consists of one truck or rail car which is equivalent to 100 tons of coal, 3 tons of irradiated LWR fuel (and 111 tons of cask), or 0.7 tons of irradiated LMFBR or HTGR fuel.

^b Average shipment distance for coal is 300 miles (Source: "Bituminous Coal Facts--1970," National Coal Association, Washington, D.C., 1971). For nuclear fuel, it is dependent upon the growth patterns of the industry and is projected to be 200 miles for irradiated fuel in the year 2000 and beyond. Construction of large reprocessing plants could increase the 200 miles to perhaps as much as 500 miles. UF₆ is assumed to be shipped 600 miles, and the other fuel materials only 200 miles. Shipping distances for waste materials are as specified in Table 4.5-1. U₃O₈ shipping distance is assumed to be 1000 miles (WASH-1248).

Table 9.1-13

OCCUPATIONAL SAFETY ASPECTS OF ENERGY CONVERSION^a

Occupational Fatalities per GW-year	Coal	Oil	Gas	LWR	LMFBR	HTGR
Mining and Milling	1.31	0.13	0.03	0.124	0	0.0648
Enrichment				0.001	0	0.0007
Fabrication				0.0006	0.0003	0.0002
Reprocessing				0.0001	0.0001	0.0001
Transportation	0.073	0.04	0.03	0.003	0.003	0.0003
Plant Operation	0.04	0.04	0.04	0.013	0.013	0.013
Total	1.42	0.21	0.10	0.1417	0.0164	0.0791
Occupational Non-Fatal Injuries per GW-year						
Mining and Milling	54	14.0	3.3	6.1	0	3.2
Enrichment				0.28	0	0.18
Fabrication				0.35	0.17	0.11
Reprocessing				0.10	0.10	0.06
Transportation	6.8	1.5	1.7	0.06	0.06	0.06
Plant Operation	1.6	1.6	1.6	1.73	1.73	1.73
Total	62.4	17.1	6.6	8.62	2.06	5.34
Occupational Man-Days Lost per GW-year						
Mining and Milling	11,107	1540	453	1100	0	575
Enrichment				21.6	0	14.6
Fabrication				11.3	5.7	3.4
Reprocessing				3.2	3.2	1.9
Transportation	760	293	240	17.3	17.3	17.3
Plant Operation	467	467	467	147	147	147
Total	12,334	2300	1160	1300.4	173.2	759.2

^aData from USAEC Report WASH-1224 (to be published), modified to account for different mass balances.

Table 9.1-14

HEALTH AND SAFETY ASPECTS OF ELECTRICAL ENERGY GENERATION
(all entries are per GW-year in Year 2000)

Occupational Safety ^a	Coal	Oil	Gas	LWR	LMFBR	HTGR
Occupational Fatalities	1.42	0.21	0.10	0.142	0.016	0.079
Occupational Non-Fatal Injuries	62.4	17.1	6.6	8.62	2.06	5.34
Occupational Man-Days Lost	12,334	2300	1160	1300	173	759
Occupational Health						
Malignancies ^b				0.120	0.080	0.099
Simple Pneumoconiosis ^a	0.8					
Massive Fibrosis ^a	0.008					
Man-Days Lost ^a	848			756	534	594
Public Safety ^a						
Transportation Fatalities	0.73			0.012	0.010	0.004
Non-Fatal Injuries	1.6			0.107	0.071	0.034
Man-Days Lost	4667			91	73	29
Public Health ^b						
Malignancies ^c				0.0017	0.0008	0.0017
Man-Days Lost				10	5	10

^aFrom USAEC Report WASH-1224 (to be published), modified to reflect updated mass balances.

^bSee Section 9.1.3.

^cBased on regional studies of the Tennessee Valley Region and the Upper Mississippi River Basin, to be published.

By far the largest risk is in the fuel mining step, and at least to the first order, the occupational injury and fatality rates are proportional to the amount of mining involved. The LMFBR represents a rather special situation in this regard, for no mining at all is anticipated for the period of this study. Current stockpiles of uranium hexafluoride tails from operation of the gaseous diffusion plants will provide the uranium feedstock for LMFBR fuel for many years to come. These stockpiles are the result of processing natural uranium to produce the slightly enriched (in U-235) uranium needed for LWRs. As use of enriched uranium continues, the stockpile of depleted uranium for use in LMFBRs will grow.

9.1.8.2 Public Safety

A major interface between the electrical generation industry and the public is in the transportation of fuel materials to the generating station. This portion of the Statement deals with only that part of this interface associated with nonradiological accidents (radiological effects are discussed briefly in Section 9.1.3 and in greater detail in Section 4.5). Table 9.1-14 gives a measure of the public safety impact of fuel transportation for the various energy conversion techniques. Coal, with its very large transportation requirement, poses a significantly greater nonradiological hazard to the public with regard to transportation, than do the nuclear fuel cycles. Addition of impacts due to fuel transportation in the nuclear fuel cycle do not appreciably change the results. For example, the LMFBR requires only about one-tenth of one percent the accident exposure (number of ton-miles) as the coal-fired plant. On this basis, LMFBR fuel transportation also involves only one-thousandth the (nonradiological) public safety impact of coal transportation for a similar plant.

9.1.8.3 Occupational Health

Radiological aspects of occupational health are included in the discussion in Section 9.1.3. The numerical data are summarized in Table 9.1-15. Data relating to coal workers pneumoconiosis (CWP, or "black lung") have been extracted from ref. 3.

9.1.8.4 Public Health

Public health effects of radiological emissions were discussed in Section 9.1.3, and they are summarized in Table 9.1-15. Somatic effects of nonradioactive (fossil fuel) pollutants have not been included for two major reasons. First of all, the effects are not well known quantitatively, although qualitative evidence of these effects is found in the many situations where atmospheric temperature inversions

Table 9.1-15

SUMMARY OF ENVIRONMENTAL IMPACT WITH LMFBR PRESENT
(cumulative 1974 to 2020 except where indicated)

	Fossil	LWR	LMFBR	HTGR	Total
Energy Production, Year 2020					
Capacity Operating (GW)	2,070	850	2,250	210	5,370
Annual Generation (GW-year)	750	570	1,650	150	3,120
Cumulative Generation (GW-year)	17,100	16,200	22,700	2,500	58,500
Committed Generation 2020 to 2050 (GW-year)	9,300	10,400	25,600	3,100	48,200
Heat Rejection in the Year 2020					
To Air (10^{15} Btu)	7.1	0	0	0	7.1
To Water (10^{15} Btu)	37.1	37.8	72.7	7.8	155.4
Radionuclides Released in the Year 2020					
To Air					
Tritium (megacuries)	0	19.0	2.23	5.6	26.8
Krypton (megacuries)	0	1.67	3.4	1.26	6.3
Xenon (megacuries)	0	0.03	0	0	0.03
Iodine (curies)	0	41.7	2.51	0.68	44.9
Strontium (curies)	-	0.32	0.91	0.15	1.38
Cesium (curies)	0	2.56	3.80	0.91	7.27
Plutonium (millicuries)	0	137	201	10	348
Transuranics (millicuries)	0	1,020	200	0.73	1,221
To Water					
Tritium (megacuries)	0	0.08	0.10	0.01	0.19
Iodine (curies)	0	50	0	0	50
Strontium (curies)	0	0.68	0	0.07	0.75
Cesium (curies)	0	0.49	0	2.6	3.1
Plutonium (millicuries)	0	45	66	2.5	113
Transuranics (millicuries)	0	20	70	0.02	90
Other Radioactive Wastes					
Cladding Hulls (Million ft ³)	0	1.17	4.7	0	5.9
Pu-Contaminated (Million ft ³)	0	49	220	0	269
Low-Level Solid (Million ft ³)	0	630	740	18.5	1,388
High-Level Solid (Million ft ³)	0	1.12	1.57	0.16	2.85

Table 9.1-15 (continued)

	Fossil	LWR	LMFBR	HTGR	Total
Uranium Mine Tailings (millions of tons)	0	1,705	0	136	1,841
Nonradioactive Wastes					
Released to Air in the Year 2020					
Fly Ash (millions of tons)	3.3	0	0	0	3.3
Sulphur Dioxide (millions of tons)	11.8	0	0	0	11.8
Nitrogen Oxides (millions of tons)	27	0.01	0.01	0	27
Carbon Dioxide (millions of tons)	6,000	0	0	0	6,000
Ammonia (millions of tons)	0	0	0.05	0	0.05
Hydrogen Fluoride (millions of tons)	0	0.59	0.02	0.08	0.69
Released to Water in the Year 2020					
Chlorine (thousands of tons)	19.7	26.6	38.6	5.0	89.9
Ammonium Hydroxide (thousands of tons)	0	15.6	66	2.0	84
Calcium Hydroxide (thousands of tons)	0	5.9	40	15.5	61
Iron (thousands of tons)	2.2	0.31	0	0.04	2.0
Sulphuric Acid (thousands of tons)	88	4.5	0.5	0.6	94
Radiological Implications					
Annual Dose (thousands of man-rems)	0	4.7	5.9	1.3	11.9
Dose Commitment ^a (thousands of man-rems)	0	0.6	1.3	0.12	2.0
Natural Background (thousands of man-rems)	-	-	-	-	30,000
Land Use					
Land Affected (square miles)	24,000	2,020	1,590	290	27,900
Land Committed (square miles)	10,200	855	553	111	11,719
Water Use in the Year 2020 (thousands of cfs evaporated)					
	20	15	44	4	83
Plutonium Produced and Used (metric tons)	0	4,500	26,000	0.09	30,500
Transmission Lines (thousands of miles)	108	44	117	11	280
Transportation					
Truck Shipments in the Year 2020					
Fuel Materials (thousands)	0	62.8	57	6.8	126.6
Low-Level Waste (thousands)	0	46	127	2.6	176
Ton-miles (billions)	0	0.46	0.44	0.05	0.95

Table 9.1-15 (continued)

	Fossil	LWR	LMFBR	HTGR	Total
Rail Shipments in the Year 2020					
Fossil Fuel (thousands)	27,200	0	0	0	27,200
Spent Fuel (thousands)	0	9.2	55	2.8	67
Process Waste (thousands)	0	7.0	68	0	75
High-Level Waste (thousands)	0	0.53	1.55	0.13	2.21
Ton-miles (billions)	820	0.86	6.4	0.10	827
Occupational Health					
Malignancies (thousands)	0	2.04	2.02	0.24	4.3
Simple Pneumoconiosis (thousands)	13.4	0	0	0	13.4
Massive Fibrosis (thousands)	0.13	0	0	0	0.13
Man-Days Lost (millions)	14.2	12.2	12.1	1.47	40.0
Occupational Safety					
Fatalities (thousands)	23.9	2.3	0.36	0.20	26.8
Non-Fatal Injuries (thousands)	1,060	140	47	13.2	1,260
Man-Days Lost (millions)	209	21	3.9	1.9	236
Public Health					
Malignancies	0	30	20	4.8	55
Man-Days Lost (thousands)	0	180	120	30	330
Public Safety					
Fatalities (thousands)	12.2	0.19	0.23	0.01	12.6
Non-Fatal Injuries (thousands)	27	1.73	1.61	0.08	30
Man-Days Lost (millions)	78	1.47	1.66	0.07	81
Resources Used					
U ₃ O ₈ (millions of tons)	0	2.3	0	0.3	2.6
ThO ₂ (millions of tons)	0	0	0	0.05	0.05
Coal (billions of tons)	55	0	0	0	55
Oil (billions of barrels)	9.2	0	0	0	9.2
Gas (trillion standard cubic feet)	102	0	0	0	102

Table 9.1-15 (continued)

	Fossil	LWR	LMFBR	HTGR	Total
<u>Forward Commitments^b</u>					
Other Radioactive Wastes					
Cladding Hulls (millions of ft ³)	0	0.75	5.3	0	6.0
Pu-Contaminated (millions of ft ³)	0	31.5	250	0	281.0
Low-Level Solid (millions of ft ³)	0	400	830	23	1,253
High-Level Solid (millions of ft ³)	0	0.72	1.8	0.19	2.7
Uranium Mine Tailings (millions of tons)	0	1,090	0	169	1,259
Radiological Implications					
Cumulative Dose (thousands of man-rems)	0	97	112	30	239
Land Use					
Land Affected (square miles)	14,100	271	100	42	14,513
Occupational Health					
Malignancies (thousands)	0	1.31	2.28	0.3	3.9
Simple Pneumoconiosis (thousands)	8.3	0	0	0	8.3
Massive Fibrosis (thousands)	0.08	0	0	0	0.08
Man-Days Lost (millions)	8.8	7.8	13.6	1.8	32.0
Occupational Safety					
Fatalities (thousands)	14.8	1.47	0.41	0.24	16.9
Non-Fatal Injuries (thousands)	650	90	53	16.4	809
Man-Days Lost (millions)	128	13.5	4.4	2.3	148
Public Health					
Malignancies	0	19	23	6	48
Man-Days Lost (thousands)	0	114	138	36	288
Public Safety					
Fatalities (thousands)	7.6	0.12	0.26	0.01	8.0
Non-Fatal Injuries (thousands)	16.7	1.11	1.8	0.10	19.7
Man-Days Lost (millions)	49	0.94	1.9	0.09	52

Table 9.1-15 (continued)

	Fossil	LWR	LMFBR	HTGR	Total
Resources Used					
U ₃ O ₈ (millions of tons)	0	1.45	0	0.34	1.79
ThO ₂ (millions of tons)	0		0	0.06	0.06
Coal (billions of tons)	34		0		34
Oil (billions of barrels)	0		0		0
Gas (trillion standard cubic feet)	0		0		0

^aDue to releases in Year 2020.

^bForward commitment = commitment in the future caused by operation in the present.

have trapped such pollutants in confined valleys for extended periods of time. Secondly, the assumption made in this section is that all nonradiological emissions produce no effect if they are within state or Federal standards, even though data may exist to refute this position. This assumption has the general effect of understating the environmental impact of fossil-fueled power plants.

One commenter* inquired why Table 9.1-13 in the Draft Statement (Table 9.1-15 in this Statement) shows an apparent capacity factor of 75% for LMFBR operation and Figure 4.5-1 uses 80%. The 75% capacity factor (actually 73.8%) represents an estimate of the way LMFBRs will be used in utility systems. The actual capacity factor for an individual LMFBR will be established by the utility as it integrates the LMFBR into its generating system and optimizes scheduling of all its plants to produce lowest cost energy reliably. The 80% capacity factor found in many places in the Statement is representative of the "middle years" (5 to 15) of the plant's lifetime, when it is new enough to be one of the best (and cheapest to operate) plants in the system, but old enough to have all the construction and new plant "bugs" removed. Section 11.2.4.11 discusses capacity factors in greater detail.

9.1.9 Demographic Effects

The current approach in siting nuclear power plants is to locate them some distance from population centers. There are a number of incentives for siting several nuclear plants and associated facilities together at one site. Such an arrangement could reduce fuel shipping and nuclear safeguards requirements while minimizing overall land use. A reasonable expectation is that such clustering, which seems to be particularly beneficial to the LMFBR, could cause some population shifts away from urban areas as communities nearer the cluster site grow to accommodate the influx of workers seeking housing near their work location. Overall, such demographic shifts are expected to be small.

9.1.10 Energy Conservation

The effect of the LMFBR can be measured in a number of ways. Interestingly enough, one measure is that of energy conservation. As an example (see Table 9.1-2), consider the LWR fuel cycle, which requires an electrical input of some 4.6% of the plant's output. By contrast, the LMFBR cycle requires essentially no electrical input, which really means that constructing a 1000-MWe LMFBR instead

*Comment Letter 25, p. 17.

of a 1000-MWe LWR would actually produce a savings of some 46 MWe. This approach can also be applied to the process-heat usage. Such a comparison was made of the various energy conversion techniques and presented in Table 9.1-3. The overall energy requirements of the LWR are seen to be about 25% greater than those for the LMFBR, and, in fact, the LMFBR will compete favorably on an energy use basis with the better coal-fired units (heat rate of ~ 8100 Btu/kWhr) that will be introduced late in this century.

9.1.11 Overall Impact to the Year 2020

The overall cumulative environmental impact to the year 2020 can be represented by the aggregate of parameters discussed in this section of the Statement. A summary tabulation of this information is given in Table 9.1-15, and a similar tabulation for the case without the LMFBR is given in Table 9.1-16. The impact of the LMFBR Program in this time span is, then, determined by the difference in impacts between the anticipated case where the LMFBR enters the market and competes effectively with the other generation techniques and the case where the LMFBR is excluded. The difference that was obtained by subtracting the entries in Tables 9.1-15 and 9.1-16 is shown in Table 9.1-17. These results support several of the arguments favoring introduction of the LMFBR and continuation of the program for its development.

One argument that has been advanced in support of the LMFBR concerns its improved thermal efficiency, which is expected to result in smaller discharges of waste heat. The results presented here indicate that an increase of nearly 17% in heat discharge and 18% in consumptive use of water would occur in the year 2020 if the LMFBR were not present. This is offset somewhat by the production of more low-level radioactive wastes, amounting to about a 4% increase, and a factor of 3 increase in cladding hulls and plutonium-contaminated wastes. The total volume of radioactive waste is largely contributed by the low-level material, so that the overall increase is also only about 4% with the LMFBR present.

A second argument supporting the LMFBR is that it helps conserve natural resources. By the year 2020, a savings of 22,000 metric tons of fissile U-235 would accrue, because some 4 million tons less of U_3O_8 are required if the LMFBR is developed and introduced in a timely manner. Furthermore, introduction of the LMFBR would cause a net savings in affected land of some 2035 square miles ($\sim 5\%$ of the total) and would reduce the land committed to some form of guardianship or permanent disturbance by some 850 square miles (or 3% of the total).

Table 9.1-16

SUMMARY OF ENVIRONMENTAL IMPACT WITH LMFBR NOT PRESENT
(cumulative 1974 to 2020 except where indicated)

	Fossil	LWR	HTGR	Total
Energy Production, Year 2020				
Capacity Operating (GW)	2,070	2,500	800	5,370
Annual Generation (GW-year)	750	1,790	580	3,120
Cum. Generation (GW-year)	17,100	32,800	8,600	58,500
Committed Generation (GW-year)	9,300	29,300	9,600	48,200
Heat Rejection in the Year 2020				
To Air (10^{15} Btu)	7.1	0	0	7.1
To Water (10^{15} Btu)	37.1	120	29.8	187
Radionuclides Released in the Year 2020				
To Air				
Tritium (megacuries)	0	53	21.4	74
Krypton (megacuries)	0	6.5	4.8	11.3
Xenon (megacuries)	0	0.09	0	0.09
Iodine (curies)	0	132	2.6	135
Strontium (curies)	0	1.29	0.57	1.86
Cesium (curies)	0	8.4	3.5	11.9
Plutonium (millicuries)	0	252	38	290
Transuranics (millicuries)	0	1,670	2.8	1,673
To Water				
Tritium (megacuries)	0	0.25	0.04	0.29
Iodine (curies)	0	157	0	157
Strontium (curies)	0	2.2	0.26	2.5
Cesium (curies)	0	1.5	9.8	11.3
Plutonium (millicuries)	0	82	9.5	92
Transuranics (millicuries)	0	39.3	0.08	39.4
Other Radioactive Wastes				
Cladding Halls (millions of ft ³)	0	2.4	0	2.4
Pu-Contaminated (millions of ft ³)	0	99	0	99
Low-Level Solid (millions of ft ³)	0	1,280	64	1,344
High-Level Solid (millions of ft ³)	0	2.3	0.54	2.8

Table 9.1-16 (continued)

	Fossil	LWR	HTGR	Total
Uranium Mine Tailings (millions of tons)	0	3,450	470	3,920
Nonradioactive Wastes				
Released to Air in the Year 2020				
Fly Ash (millions of tons)	3.3	0	0	3.3
Sulphur Dioxide (millions of tons)	11.8	0	0	11.8
Nitrogen Oxides (millions of tons)	27	0.03	0.01	27.1
Carbon Dioxide (millions of tons)	6,000	0	0	6,000
Ammonia (millions of tons)	0	0	0	0
Hydrogen Fluoride (millions of tons)	0	1.9	0.30	2.2
Released to Water in the Year 2020				
Chlorine (thousands of tons)	19.7	84	19.1	123
Ammonium Hydroxide (thousands of tons)	0	49	8.0	57
Calcium Hydroxide (thousands of tons)	0	18.6	59	78
Iron (thousands of tons)	2.2	0.98	0.16	3.3
Sulphuric Acid (thousands of tons)	88	14.3	2.3	105
Radiological Implications				
Annual Dose (thousands of man-rems)	0	14.7	5.1	19.8
Dose Commitment ^b (thousands of man-rems)	0	2.0	0.5	2.5
Natural Background (thousands of man-rems)	-	-	-	30,000
Land Use				
Land Affected (square miles)	24,000	4,500	950	29,450
Land Committed in the Year 2020 (square miles)	10,200	1,995	375	12,620
Water Use in the Year 2020				
(thousands of cfs evaporated)	20	58	18.8	97
Plutonium Produced and Used (metric tons)	0	9,200	1.3	9,201
Transmission Lines (thousands of miles)	108	130	42	280

Table 9.1-16 (continued)

	Fossil	LWR	HTGR	Total
Transportation				
Truck Shipments in the Year 2020				
Fuel Materials (thousands)	0	197.1	26.2	223.3
Low-Level Waste (thousands)	0	145	9.9	155
Tons-miles (billions)	0	1.43	0.21	1.64
Rail Shipments in the Year 2020				
Fossil Fuel (thousands)	27,200	0	0	27,200
Spent Fuel (thousands)	0	29.2	10.6	39.8
Process Waste (thousands)	0	22.2	0	22.2
High-Level Waste (thousands)	0	1.68	0.5	2.18
Ton-miles (billions)	0	2.74	410	823
Occupational Health				
Malignancies (thousands)	0	4.1	0.84	4.9
Simple Pneumoconiosis (thousands)	13.4	0	0	13.4
Massive Fibrosis (thousands)	0.13	0	0	0.13
Man-Days Lost (millions)	14.2	24.8	5.1	44.1
Occupational Safety				
Fatalities (thousands)	23.9	4.7	0.67	29.3
Non-Fatal Injuries (thousands)	1,060	283	46	1,389
Man-Days Lost (millions)	209	43	6.5	258
Public Health				
Malignancies	0	61	17	78
Man-Days Lost (thousands)	0	366	102	468
Public Safety				
Fatalities (thousands)	12.2	0.39	0.03	12.6
Non-Fatal Injuries (thousands)	27	3.5	0.29	31
Man-Days Lost (millions)	78	3.0	0.25	81
Resources Used				
U ₃ O ₈ (millions of tons)	0	5.6	0.94	6.6
ThO ₂ (millions of tons)	0	0	0.18	0.18
Coal (billions of tons)	55	0	0	55
Oil (billions of barrels)	9.2	0	0	9.2
Gas (trillion standard cubic feet)	102	0	0	102

Table 9.1-16 (continued)

	Fossil	LWR	HTGR	Total
Forward Commitments				
Other Radioactive Wastes				
Cladding Hulls (millions of ft ³)	0	2.11	0	2.11
Pu-Contaminated (millions of ft ³)	0	89	0	89
Low-Level Solid (millions of ft ³)	0	1,140	73	1,213
High-Level Solid (millions of ft ³)	0	2.02	0.61	2.63
Uranium Mine Tailings (millions of tons)	0	3,080	530	3,610
Radiological Implications				
Cumulative Dose (thousands of man-rems)	0	272	92	364
Land Use				
Land Affected (square miles)	14,100	765	133	14,998
Occupational Health				
Malignancies (thousands)	0	3.7	0.96	4.7
Simple Pneumoconiosis (thousands)	3.3	0	0	8.3
Massive Fibrosis (thousands)	0.08	0	0	0.08
Man-Days Lost (millions)	8.8	22.1	5.8	36.7
Occupational Safety				
Fatalities (thousands)	14.8	4.2	0.77	19.8
Non-Fatal Injuries (thousands)	650	250	52	952
Man-Days Lost (millions)	128	38	7.4	173
Public Health				
Malignancies	0	54	18	72
Man-Days Lost (thousands)	0	324	108	432
Public Safety				
Fatalities (thousands)	7.6	0.35	0.04	8.0
Non-Fatal Injuries (thousands)	16.7	3.13	0.33	20.2
Man-Days Lost (millions)	49	2.66	0.28	52

Table 9.1-16 (continued)

	Fossil	LWR	HTGR	Total
Resources Used				
U ₃ O ₈ (millions of tons)	0	5.04	1.07	6.11
ThO ₂ (millions of tons)	0	0	0.20	0.20
Coal (billions of tons)	34	0	0	34
Oil (billions of barrels)	0	0	0	0
Gas (trillion standard cubic feet)	0	0	0	0

^aDue to releases in the Year 2020.

Table 9.1-17

Summary of Environmental Impact of LMFBR Program
Through the Year 2020

	Total With LMFBR Present	Total With LMFBR Not Present	Increase Due to LMFBR	Decrease Due to LMFBR
Heat Discharge in 2020 (10^{15} Btu)	162	194		32
Water Evaporation in 2020 (thousands of cfs)	83	97		14
Accumulated Radioactive Wastes, including Forward Commitments ^a (million ft ³)				
High-Level Wastes	5.5	5.4	0.1	
Low-Level Wastes	2,641	2,557	84	
Cladding Hulls and Pu-Contaminated Wastes	562	193	369	
Radionuclide Releases in 2020				
To Air				
Tritium	26.8	74		47
Noble Gases (megacuries)	6.3	11.3		5
Iodine, Strontium, Cesium (curies)	53.6	148.4		94.8
Transuranic Alpha Emitters (millicuries)	1,569	1,963		394
To Water				
Tritium (megacuries)	0.19	0.29		0.1
Iodine, Strontium, Cesium (curies)	54	171		117
Transuranic Alpha Emitters (millicuries)	203	131	72	
Transportation Effects in 2020				
Fuel Material Shipments (thousands)	126.6	223.3		96.7
Irradiated Fuel Shipments (thousands)	67	40	27	
Low-Level Waste Shipments (thousands)	176	155	21	
High-Level Waste Shipments (thousands)	2.21	2.18	0.03	
Total Ton-Miles by Truck (billions)	0.95	1.64		0.69
Total Ton-Miles by Rail (billions)	831	823	8	

Table 9.1-17 (continued)

	Total With LMFBR Present	Total With LMFBR Not Present	Increase Due to LMFBR	Decrease Due to LMFBR
Radiological Implications (thousand man-rem)				
Dose to Public in 2020	12	20		8
Commitment from 2020 Releases	2	2.5		0.5
Accum. Dose, incl. Forward Commitments ^a	514	752		238
Health and Safety Aspects, Including Forward Commitments ^a				
Occupational Fatalities	43,700	49,100		5,400
Public Fatalities	20,600	20,600	---	---
Occupational Man-Days Lost (millions)	456	512		56
Public Man-Days Lost (millions)	133	133	---	---
Land Usage, Including Forward Commitments ^a (square miles)				
Total Land Affected	42,413	44,448		2,035
Land Committed ^b	11,720	12,570		850
Resource Utilization, Including Forward Commitments ^a				
U ₃ O ₈ Mined (million tons)	4.4	12.7		8.3
ThO ₂ Mined (million tons)	0.11	0.38		0.27
Coal Mined (billion tons)	89.4	89.4	---	---
Plutonium Produced and Used (thousand metric tons)	62.7	17.4	45.3	

^aA forward commitment is a commitment in the future caused by operation in the present.

^bLand which has been disturbed and will not be returned to a "natural" state.

Finally, proponents of the LMFBR have indicated qualitatively that it has advantages in terms of radionuclide releases and the corresponding radiological complications. This quantitative evaluation supports that argument in many ways. For example, a decrease of about 66% in the year 2020 dose and 25% in the corresponding dose commitment can be expected if the LMFBR is introduced. Similarly, a decrease of about 50% in the accumulated dose would be anticipated. However, although the decrease is significant, the effect is small. The total accumulated dose over the period 1974 to 2020 corresponds to an average of less than 5 millirems to an individual, or less than one-thousandth of the natural (background) dose an average individual would receive in that time span.

If the LMFBR were not introduced before the end of the century, some increase (about 10%) in occupational fatalities (due to both health and safety aspects) and injuries might be observed. Public health and safety are virtually unaffected. With respect to these factors, the anticipated impact is small and essentially independent of energy source.

Introduction of the LMFBR will cause a significant increase in shipment of irradiated fuel, largely because the LMFBR spent fuel cask is expected to hold less fuel than the cask for LWR fuels. Shipments in the fuel cycle as a whole decrease if the LMFBR is not present. However, compared with the total of fuel shipments including coal, the decrease is negligible, amounting to less than 1%; and because coal currently accounts for only about 10% of rail freight, the nuclear increment is less than one-thousandth of the total.

In summary, then, introduction of the LMFBR is beneficial in terms of reductions in heat discharge, water consumption, land use, radioactive emissions (except plutonium), radiation dose, and resource utilization, and of improved health and safety of occupational workers. On the other hand, there will be an increase in shipments of irradiated nuclear fuel, in production of solid radioactive wastes, and in emissions of plutonium. The increases tend to be outweighed by the decreases--shipment of fresh fuel decreases, land use decreases, and radiation dose decreases.

The Mid-America Coalition for Energy Alternatives* questioned the claim that there will be less radioactive material releases from LMFBRs. The claim that the releases, on the whole, tend to be lower for the LMFBR is justified because certain process

*Comment Letter 22, p. 10.

variables that tend to favor radionuclide retention in LMFBF systems. For example, the affinity of tritium for sodium permits the "capture" and handling of tritium as an easily contained solid. In other systems, tritium is presumed to diffuse through systems designed to contain other radionuclides.

In fact, in comparison with other currently available or easily developable technologies, the LMFBF offers benefits in nearly every category examined. Naturally, in comparison with technologies with more long-term development programs, the LMFBF may not be as attractive. However, a point worth noting is that as technological development programs proceed and more knowledge of application is gained, the attractiveness of the technology is often eroded substantially. In contrast to many of the alternative energy conversion techniques potentially available through development, the LMFBF can be considered to have "arrived." Design and construction of the Fast Flux Test Facility, though a long and difficult process, has revealed many of the problem areas to which solutions have already been found. In a very real sense, the experimental stage has been passed and the talents of the industry can now turn to the engineering and demonstration of the LMFBF technology.

Two commenters* expressed disagreement with the AEC's statement that the LMFBF has arrived. The AEC feels that the LMFBF has arrived in the sense that many of the development problems have been faced and solved, and the emphasis now is on design and operation of a nearly full-size system. The same cannot be said for many of the alternatives. Naturally, some problems remain in LMFBF systems (as they do in coal and other systems), and in that sense, it is still developmental. Perhaps the key point is that industry believes it knows where the problems are, and it can now turn to their solutions.

*Comment Letters 22 (Mid-America Coalition for Energy Alternatives), p. 10; 25 (C. Kepford), p. 17.

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9.2 DECOMMISSIONING

9.2.1 LMFBR Power Plants

Sufficient experience is already available from the AEC's civilian power program to indicate that the decommissioning of large LMFBR power plants will not introduce any significant new or unknown technical problems of a safety or environmental nature that differ substantially from those that may occur during refueling and maintenance. Under AEC regulations, procedures for dismantling of the plant will be subject to specific AEC approval and will be required to meet standards for protection of the workers and the general public.

Under the regulations set forth in 10 CFR 50, no licensee may surrender a license or dismantle a nuclear facility until he has applied for and received authority from the AEC to do so. The application is evaluated by the AEC to assure that adequate safety measures will be taken in the course of the decommissioning and also that necessary precautions will be taken regarding any radioactivity that may remain thereafter at the site. At the time of the original application to construct the reactor, the licensee is required to demonstrate financial resources sufficient to cover the eventual decommissioning.

The LMFBR demonstration plant will be designed for a 30-year operating life. This time span would place the decommissioning of the first commercial-size LMFBR plant at about the year 2010, and significant numbers of LMFBRs would not be decommissioned until the year 2020 or later.

The decommissioning of LMFBR power plants would involve removal of spent fuel; decontamination of accessible areas; removal of radioactive equipment, components, and sodium; and sealing the plant against any radioactive leakage that could be harmful to the health and safety of the public. By the time decommissioning of the LMFBR demonstration plant or future LMFBRs becomes necessary, a wealth of additional experience will have been gained from the decommissioning of LWR plants where similar decommissioning considerations are involved. To date, experience with the decommissioning of civilian nuclear power reactors is limited to six facilities that have been shut down or dismantled: Hallam Nuclear Power Facility,¹ Carolina Virginia Tube Reactor (CVTR),¹ Boiling Nuclear Superheater (BONUS) Power Station,¹ Pathfinder Reactor,¹ Piqua Reactor,¹ and the Elk River Reactor.²

There are several alternatives that can and have been used in the decommissioning of nuclear reactors:

- (1) Remove the fuel (possibly followed by decontamination procedures), seal and cap the pipes, and establish an exclusion area around the facility (the Piqua decommissioning operation was typical of this approach),
- (2) In addition to the steps outlined in (1), remove the superstructure and encase in concrete all radioactive portions that remain above ground (the Hallam decommissioning operation was of this type),
- (3) Remove the fuel, all the superstructure, the reactor vessel, and all contaminated equipment and facilities; fill all cavities with clean rubble; and top with earth to grade level (these procedures were applied in decommissioning the Elk River Reactor).

Decommissioning alternatives (1) and (2) would require long-term surveillance of the reactor site (on the order of several hundred years) and are commonly referred to as entombment. Alternative (3), commonly referred to as dismantling, would not require any subsequent surveillance. Another alternative, mothballing, appears likely to be chosen in cases where other reactors at a site are still operating. However, mothballing would merely postpone eventual decommissioning until a more advantageous time, probably resulting in lower costs and lesser environmental impacts (smaller radioactive releases during decommissioning) due to decommissioning operations. The alternative of converting an LMFBFR power plant to other uses, including production of power by other means, appears unlikely at this time.

In some cases, decommissioning will cause short-term environmental impacts to the site similar to those that occur during the power plant construction phase. There will be temporary disturbances such as increased traffic and noise due to the decommissioning activities and the permanent restoration of most of the site to other uses. The greatest long-term environmental impact would be associated with entombment alternatives in the commitment of land. In dismantling, there would be a commitment of land elsewhere for the burial of solid radioactive waste, but such burial sites are generally in remote or sparsely populated areas, and the pre-empted land is not as potentially valuable for other uses as a power plant site is likely to be.

If entombment were the alternative chosen, it could be accomplished by removing and reclaiming the fuel elements, decontaminating or otherwise fixing in place radioactive materials, removing salvageable equipment, and finally, sealing the reactor components. Concrete and other materials could be used to entomb the reactor and highly radioactive parts associated with it.

The debris, salvageable components, and radioactive materials could be transported from the site by truck, rail, or barge. The Federal regulations governing the packaging and shipping of radioactive materials are formulated in Part 173 through 178 of Title 49, Chapter I, "Transportation," in the Code of Federal Regulations. Burial grounds suitable for disposal of radioactive waste are currently located at Sheffield, Illinois; Morehead, Kentucky; West Valley, New York; Barnwell, South Carolina; Beatty, Nevada; and Richland, Washington. A considerable amount of earthmoving might be required to restore parking areas and to adjust the site grade as would be dictated by future uses. A security fence would be erected on the ground above the entombed reactor site.

The onsite entombment of the reactor will provide time for radioactive decay of activated materials and fission products. The structural integrity will probably be designed to provide a minimum 100-year decay time. The design-life limitation is the time required for the average contact dose rate of the most active component to decay to a β - γ level of 0.2 millirem/hr. The entombment area will be permanently identified as a radioactive area.

The cost to completely dismantle a future LMFBR power plant is anticipated to be several million dollars and to require more than a year to complete. Experience in dismantling small commercial power reactors indicates that such costs will be in the neighborhood of 10 to 15% of construction costs. These costs are subject to variation, because the degree of dismantlement will be governed largely by the intended new use of the site.

In cost-benefit considerations that follow the procedures of the Office of Management and Budget, future decommissioning costs are discounted to obtain their present worth. Using a discount rate of 8.75% per year for 30 years of operation, costs incurred at the end of that operating period would be divided by 12.4 to determine their present worth. If the plant area were to be restored to its original conditions, the present worth of the future costs involved would be only about 1% of the original construction cost. Thus, the decommissioning costs would not affect either the overall LMFBR program cost-benefit analyses or the cost-benefit analysis for a given LMFBR power plant.

In the decommissioning of all types of nuclear power plants, significant volumes of slightly contaminated water and air are expected to be generated. Contaminated water will be generated by decontamination activities and by the cutting of radioactive material under water. Contaminated air will be generated by

activities such as torch cutting of radioactive material and dust generation during removal of activated concrete.

Normally, contaminated air contained in the plant building can be disposed of by using the existing ventilation systems. To prevent undesirable high levels of air-borne activity, however, some decommissioning activities may be performed within controlled volumes such as contamination control envelopes. Treatment and disposal of contaminated water in nuclear power plants should be possible by using existing liquid waste treatment systems of the plants.

As mentioned previously, some experience exists in decommissioning nuclear power reactors. A number of reports are available concerning past decommissioning operations.³⁻¹¹ The following decommissioning alternatives were chosen:

- (1) Mothballing (CVTR)
- (2) Dismantling (Elk River)
- (3) Conversion (Pathfinder)
- (4) Entombment (BONUS, Piqua, and Hallam)

The Pathfinder nuclear power plant, decommissioned in 1969, was converted into a fossil-fueled power plant. A total of 57,000 lb of radioactive piping and equipment was removed from the plant and shipped to a burial ground. The turbine was dismantled, decontaminated, and overhauled, and it is now used with fossil-fueled boilers to supply the steam. Components of the original reactor such as the off-gas holdup tanks and the liquid waste discharge line were buried in an area of new construction at the station.^{1,5}

The BONUS power station, decommissioned in 1971, is now used as an exhibition center. The most radioactive components contained within the entombment structure will have decayed to such an extent that after 140 years their direct contact dose rate would be about 0.2 millirem/hr. The entombment structure is adequate to last at least 140 years under normal conditions.^{1,6,7}

The Piqua nuclear power facility, decommissioned in 1969, was transformed into a warehouse that can be used safely with minimal constraints. These constraints include maintaining the integrity of the overall reactor complex, controlling the flow of water into and out of the entombment structure, and restricting the storage of dangerous materials. Based on an acceptable surface radiation dose level of 0.2 millirem/hr, the controls on water level can be safely discontinued in 2041.

If a small amount of silver is removed, all constraints can be safely discontinued in 2088.^{1,8,9}

The Hallam nuclear power facility, decommissioned in 1969, was entombed. The entire primary sodium inventory (550,000 lb) was shipped to Hanford for storage and eventual reuse. A total of about 5.5 Ci of Na-22 were contained in the shipment. The entire secondary sodium inventory (220,000 lb) was shipped to Atomics International, Canoga Park, California, for future use. Residual sodium remaining in the secondary sodium system components was disposed of by removing system components and reacting the sodium in a specially constructed steam cleaning facility. Residual sodium remaining in the primary system was reacted using a nitrogen-steam mixture. The weather-proof isolation structure was designed for a minimum 100-year life.^{1,10}

9.2.2 LMFBR Fuel-Cycle Facilities

Fuel-cycle facilities fall into two general categories: first, fuel-fabrication or refabrication facilities, where the radioactive material inventories involve relatively low levels of penetrating radiation; and second, facilities for processing irradiated fuel, where very much higher levels of penetrating radiation are involved.

Because of the low levels of penetrating radiation, the fuel-fabrication facilities will not have extensive massive shielding to be demolished or much unapproachable equipment to be disconnected and decontaminated or packaged as waste by remotely-controlled means. The primary safety need will be for contamination control during the disassembly work. To a great extent, such control will be similar to that already routinely used for equipment repair and replacement operations during the operating life of the facility, and the normal filtration equipment for the exhaust ventilation system will still be usable. During demolition of potentially contaminated structural portions of the facility, special precautions (for example, working within temporary adjustable contamination control enclosures) may be advisable. The use of such temporary enclosures is a well-established technique for some current in-plant maintenance operations.

Several uranium mills, a uranium-concentrates warehouse, and a reconsignment facility have been razed successfully by use of relatively conventional techniques.

Irradiated-fuel processing plants are massively-shielded and remotely-controlled and maintained. Although several of the older U.S. processing plants are no longer used for their original purpose, they have been converted to other nuclear uses

(for example, equipment decontamination and radioactive waste treatment), so that the need for their final decommissioning has not yet arisen.

An AEC regulation (10 CFR 50, Appendix F) states that one of the design objectives of fuel processing plants is to facilitate decontamination and removal of all significant radioactive wastes at the time of final decommissioning of the plant. The techniques used during normal operation of the plant for remote maintenance and equipment replacement will also be applicable to decommissioning. For example, in some of the older plants mentioned above, all of the original equipment (tanks, centrifuges, connecting piping) has been completely removed and replaced with new equipment required by improved processes. The final removal of equipment could be handled similarly, except for piping embedded in the shielding. Because of the massive nature of the reinforced concrete shielding making up the walls, floor, and roof of the main processing area, complete demolition of the plant would probably not be economically justified, and any radioactive material not removed by decontamination would be entombed within the structure by sealing the entrances and apertures.

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VOLUME IV

SECTION 10

**IRREVERSIBLE AND IRRETRIEVABLE
COMMITMENTS OF RESOURCES**

SUMMARY FOR SECTION 10

The implementation of the LMFBR Program requires a significant commitment of the Nation's resources, comparable in overall magnitude to that required for implementing most new major energy sources. These resources encompass land, water, air, materials, capital, and manpower. Resources that may be irreversibly committed by construction and operation of the LMFBR fuel cycle facilities are: (1) land required for long-term storage of radioactive wastes from the fuel cycle and of structural materials that have become radioactive through activation or contamination, (2) construction materials that cannot be recovered and recycled economically, and (3) materials consumed or reduced to unrecoverable forms of waste.

The land requirements for a site to accommodate the facilities for a 1000-MWe LMFBR power plant (except for cooling) is expected to be about 50 acres within a 400-acre minimum exclusion area. Moreover, if an artificial lake is constructed to meet plant cooling requirements, up to 2000 additional acres will be needed. The reprocessing plant would require a temporary commitment of about 1000 acres of land and a potential permanent commitment of about 100 acres. The fabrication plant would require a temporary commitment of approximately 1000 acres. Land requirements for radioactive waste management would consist of both temporary and essentially permanent commitments. Five burial facilities would be sufficient for all such LMFBR waste through the year 2000 and 50 facilities would suffice through the year 2020. Estimates indicate that such waste generated by the entire LMFBR fuel cycle through the year 2200 would require the essentially permanent commitment of about 3600 acres of land. The retrievable surface storage facility (RSSF), the noble gas storage facility (NGSF) and the alpha waste storage facility (AWSF) would each require about 1500 acre sites. Of this, about 150 acres of each site would be an essentially permanent commitment.

The commitment of material resources to the projected LMFBR industry does not appear to be critical and the extent of irreversible and irretrievable commitment is small. Moreover, relative to the LWR, the LMFBR requires a significantly lesser commitment of the Nation's uranium resources. In addition, because the LMFBR produces more plutonium than it consumes, it could add greatly to the Nation's net nuclear fuel resources.

Although the estimated manpower needs of the LMFBR program constitute a small part of the Nation's prospective work force, manpower may still be a critical problem for the LMFBR. A large number of construction craftsmen must be highly trained.

A strong and continuing commitment on the part of the utilities, the nuclear industry, and the government will be necessary to assure that adequate numbers of technically trained personnel (such as construction craftsmen, design engineers, and plant operators) are available when needed. The need for trained personnel is not unique to the LMFBFR but is true of any electrical power generation system that might be broadly deployed in the future.

The LMFBFR Program requires the commitment of extensive financial resources by both the Nation's utilities and the Federal Government. Federal funds are authorized and appropriated on an annual basis, and programs are reviewed and approved consecutively each year by the originating agency, the Office of Management and Budget, and the Congress. Hence, the level of support to be accorded to the program in future years will continue to be thoroughly scrutinized on a yearly basis as a part of the comprehensive budgetary review process. In addition, research and technology development for the LMFBFR Program is expected to be of substantial benefit to other energy technologies.

10.1 NATURAL AND OTHER RESOURCES10.1.1 Introduction

The LMFBR power plant and associated transmission lines, fuel cycle facilities, and radioactive waste handling and storage facilities require the commitment of material and other resources. Irreversible commitments concern changes set in motion which at some later time could not be restored to the present state. Irretrievable commitments concern the use of resources that are neither renewable nor recoverable for subsequent use. Of particular concern are natural and material resources such as land, materials of construction, and consumable resources used in operation of the plants. Some of these resources are recoverable and can be reclaimed for further use; others are not. Resources which may be irreversibly committed by construction and operation of the plant are (1) land required for long-term storage of both radioactive wastes from the fuel cycle and structural materials which have become radioactive through activation or contamination, (2) construction materials that cannot be recovered and recycled economically, and (3) materials consumed or reduced to unrecoverable forms of waste.

10.1.2 Land Resources

Land requirements for power plants are not significantly different for LMFBR, LWR, or coal-fueled plants of equivalent size. A site to accommodate the reactor and turbine building and adjacent facilities (except for cooling) is expected to be 35 to 50 acres per 1000-MWe plant with a 400-acre minimum site size, which could accommodate once-through cooling at a lake or river. Artificial cooling lakes would require as much as 2000 additional acres for a 1000-MWe plant.

Transmission corridors leading from new sites are often required to accommodate the transmission lines from new generating plants to the utility electrical distribution system. It is essential that new plant siting and transmission line placement be considered jointly in arriving at an economical and reliable arrangement. New lines about 50 miles in length are common for new plants. Typically, new right-of-way areas greater than the area of the plant site would be required (1050 acres per 1000-MWe plant--see Table 8.4-1). Nearly all the land appropriated for the power plant sites, cooling ponds, or transmission lines could be restored to alternative uses following plant decommissioning (see Section 9.2).

The model LMFBR fuel-reprocessing plants and fuel-fabrication plants have a capacity of five metric tons per day and serve about eighty 1000-MWe LMFBR power

plants. It is conservatively estimated that the model fuel-reprocessing plant would require a temporary commitment of 1000 acres of land and a potential permanent commitment of about 100 acres. The model fuel-fabrication plant would require a temporary commitment of 1000 acres. These land commitments would be expected to be reversible; after decommissioning, the land could be made available for alternate uses.

Land requirements for radioactive waste management would consist of both temporary and essentially permanent commitments. The burial grounds would be relatively small, only about 100 acres. Five such burial facilities would be sufficient for all the LMFBR low-level, solid radioactive wastes through the year 2000 (50 facilities would be sufficient for all such radioactive waste produced through the year 2020). Although burial grounds could be decommissioned and the land be made available for alternate uses, burial grounds are considered permanent commitments of land. Even if a burial ground were decommissioned, the low-level, solid radioactive wastes that would be removed would have to be stored or buried elsewhere. It is estimated that the low-level solid waste generated by the entire LMFBR fuel cycle through the year 2000 would require the essentially permanent commitment of about 300 acres of land. Similarly, the entire LMFBR fuel cycle through the year 2020 would require the essentially permanent commitment of about 3600 acres.

The retrievable surface storage facility (RSSF) for high-level radiation waste storage, the alpha waste storage facility (AWSF) for alpha waste storage, and the noble gas storage facility (NGSF) would each have site areas of about 1500 acres. The RSSF, AWSF, and NSGF would each occupy about 150 acres of their 1500-acre sites. These 150-acre land commitments would be essentially permanent. If the RSSF, AWSF, or NSGF were decommissioned, many of the alternate means of storing or disposing of the stored radioactive wastes (see Sections 7.2.5 and 7.3.5) would require similar essentially permanent commitments of land.

10.1.3 Water and Air Resources

The environmental impact of the thermal, chemical, and radioactive effluents of the LMFBR fuel cycle and the associated transportation is quite low and no irreversible effects on air and water use are foreseen. The use of water and air does not constitute an irreversible or irretrievable commitment of resources.

10.1.4 Material Resources

Consideration of the material resources involved in the implementation of the LMFBR program includes: (1) the fuel materials and supplies required for construction

and operation of all LMFBR fuel cycle facilities; (2) the continued availability of these materials from their sources (depletable, renewable, or not); (3) the recovery, reuse, or recycling of materials. Construction materials are generally expected to remain in use for the full life (~30 years) of the plant. At the time of plant decommissioning, precious metals, strategic and critical materials, or resources with small natural reserves will be considered for potential recycling.

10.1.4.1 Fuel

A summary of typical annual fuel requirements for a 1000-MWe LMFBR plant is presented in Table 10.1-1.¹ The nuclear fuel is uranium--plutonium oxide; quantities stated are for the heavy metal (Uranium or Plutonium) content only. The blanket quantities are included with the core fuel as "fuel."

The refueling of the 1000-MWe LMFBR power plant requires that about 21 tons of nuclear fuel and structural metals be fed to the reactor and through the other process steps of the fuel cycle (fuel fabrication and chemical recovery) annually. In the fuel cycle, there is a net annual production of 0.28 metric ton of Plutonium and 0.67 metric ton of long-lived fission products. This plutonium is the "bred" nuclear fuel, and the fission products are the radioactive materials that must be stored in a Federal repository. Net annual consumption of depleted uranium is 1.29 metric tons which is available from stockpiles (see Section 4.1.4). About 2.2 metric tons of austenitic stainless steel is used as part of the replaceable fuel elements; the stainless steel is not chemically consumed but is rendered radioactive in the reactor; it cannot be decontaminated and thus is considered consumed and not recoverable.

10.1.4.2 Construction Materials

Because large commercial LMFBR fuel cycle facilities have not yet been designed and built, the amounts of materials required can not be precisely estimated at this time. However, facilities of the LWR fuel cycle are in commercial operation and materials used in construction of LMFBR and LWR power plants and fuel-cycle facilities are expected to be about the same.

Estimates of the quantities of structural materials required for construction of the model LMFBR power plant are given in Tables 10.1-2 and 10.1-3. Composite materials of construction (e.g., concrete, insulation, and specific alloys) are given in Table 10.1-2, and the equivalent basic materials (i.e., elemental metals and chemical compounds) are given in Table 10.1-3. These quantities were assumed equal to those estimated for a PWR of about 1000 MWe capacity.² Detailed materials

were estimated from a design and cost estimate for a typical commercial PWR.³ The materials listed are for a plant defined as follows:

Table 10.1-1
FUEL REQUIREMENTS FOR A 1000-MWe LMFBR^{a,b}
(metric tons)

	Annual Amount (80% Capacity Factor)	Total Amount ^c (70% Capacity Factor)
Fuel Throughput		
Total Uranium and Plutonium (as metal)	18.8	493.0
Plutonium Discharge (as metal)	1.9	50.0
Fuel-Cycle Losses		
Uranium	0.33	8.7
Plutonium	0.035	0.91
Net Plutonium Production	0.28	7.3
Net Uranium Consumption	1.29	34.0

^aReference 1, Sections 10 and 4.5.

^bSee Figure 4.5-1.

^cAverage capacity factor for the 30-year life of the plant.

Table 10.1-2

ESTIMATED QUANTITIES OF COMPOSITE MATERIALS^a
CONTAINED IN A TYPICAL 1000-MWe LMFBR POWER PLANT^b

Material	Total Estimated Quantity
Aluminum	18 Metric Tons
Babbitt	<1 Metric Ton
Brass	10 Metric Tons
Bronze	25 Metric Tons
Carbon Steel	32,731 Metric Tons
Concrete	98,130 cu yd
Copper	694 Metric Tons
Galvanized Iron	1,257 Metric Tons
Inconel	124 Metric Tons
Insulation (Thermal)	922 Metric Tons
Lead	46 Metric Tons
Nickel	1 Metric Ton
Paint	17,500 gal
Silver	<1 Metric Ton
Stainless Steel	2,080 Metric Tons
Wood	4.8×10^6 bd ft

^aIncluding field construction materials consumed.^bI. T. Dudley and R. H. Bryan, "Estimated Quantities of Materials Contained in a 1000-MW(e) PWR Power Plant," ORNL-TM-4515 (June 1974).

Table 10.1-3

ESTIMATED BASIC MATERIALS USED IN CONSTRUCTION
OF A 1000-MWe LMFBR POWER PLANT AND COMPARISON WITH
PRODUCTION, USES, AND RESERVES OF THESE MATERIALS

Material	Basic Materials in LMFBR Plant ^a (metric tons)	Annual World Production ^b (metric tons)	Annual U.S. Consumption ^b (metric tons)	U.S. Reserves ^b (metric tons)	Strategic and Critical Material ^c
Aluminum	18	9,089,000	4,227,000	8,165,000	Yes
Asbestos	138	2,985,000	712,000	1,800,000	Yes
Chromium	410	1,590,000	398,000	2,000,000	Yes
Copper	730	6,616,000	1,905,000	77,564,000	Yes
Lead	50	3,329,000	1,261,000	32,024,000	Yes
Manganese	410	7,711,000	1,043,000	907,000	Yes
Magnesia	780				No
Molybdenum	160	64,770	23,420	2,858,000	No
Nickel	480	480,000	129,000	181,000	Yes
Silver	<1	8,989	5,005	41,057	Yes
Steel	35,000	574,000,000	128,000,000	2,000,000,000	No
Tin	2	454,200	82,100	47	Yes
Zinc	2	5,001,000	1,630,000	30,600,000	Yes

^aReference 1000-MWe LMFBR. See text for basis of estimation and for contribution of other fuel-cycle facilities.

^bProduction, consumption, and reserves were compiled, except as noted, from the U.S. Bureau of Mines publications Mineral Facts and Problems (1970 ed., Bur. Mines Bull. 650) and the 1969 Minerals Yearbook. The production, consumption, and reserves are expressed in terms of contained element, regardless of the form. "Production" usually includes material recovered from both primary ores and secondary sources such as scrap recovery. Production and consumption figures are for 1969 unless otherwise noted. Estimates of reserves were published in 1969 but are based on data compiled over a number of years. The reserves stated are the quantities extractable at currently competitive prices; they include inferred as well as measured and indicated ores, when such information was available. Usually, resources recoverable with advanced methods or at greater cost are much greater than the reserves listed.

^cDesignated by G. A. Lincoln, "List of Strategic and Critical Materials," Office of Emergency Preparedness; Fed. Regist. 37(39): 4123 (Feb. 26, 1972).

- (1) An existing road in good condition connects the plant site with other highways.
- (2) Railroad access is provided by constructing a five-mile-long spur.
- (3) The reference plant is located 2000 ft from the shoreline of a river which could supply an adequate amount of makeup water and condenser cooling water.
- (4) Communications, electric power, and water facilities for construction activities exist at the plant site boundary.
- (5) All sewage will receive primary and secondary treatment in the plant prior to discharge to the river.
- (6) No air or marine transportation facilities are required.
- (7) The electrical power transmission lines and the switchyard are not included as part of the plant.
- (8) No shipping casks are included.
- (9) None of the fuel, cladding or absorber materials used in fuel elements and control rods were included.
- (10) Operating materials or other materials consumed during power plant operations were not included.

Of the total materials, a portion is recoverable and can be reused. Because of radioactivity from activation or contamination, some materials are not recoverable and would be sent to permanent storage.

The amount of concrete used in a 1000-MWe reactor plant is on the order of 100,000 cu yd with as much as an additional 20% if a natural-draft cooling tower is used. Other building materials (iron, wood, etc.) are of sizeable quantities but are clearly a small fraction of current consumption and noncritical in nature.

The model fuel-cycle facilities consisted of fuel-fabrication plants, fuel-reprocessing plants, and radioactive waste storage facilities. The fabrication and reprocessing plants are assumed to be of five ton per day capacity, and they serve eighty 1000-MWe LMFBR power plants (see Sections 4.3 and 4.4). The total fuel-cycle resource commitment is estimated to constitute the same sort of resource commitment as several LMFBR power plants, and is, therefore, insignificant when compared to the resource commitment of the projected total number of LMFBR power plants.

10.1.4.3 Consumable Materials

The LMFBFR power plants and fuel-cycle facilities consume chemicals and certain replaceable components in addition to water, fuels, and the materials of construction already discussed. These additional requirements are:

- (1) Chemicals for treating natural water for cooling water systems. The use depends on the water quality; the chemicals most commonly used are chlorine and sulfuric acid.
- (2) Ion-exchange resins for removal of radioactivity from aqueous waste streams. The quantity depends on source terms and methods of treatment.
- (3) Ion-exchange resins for purification of water for internal plant uses. The quantity used depends on the water quality and type of resin.
- (4) Chemicals for regeneration of ion-exchange resins. These chemicals are usually sulfuric acid and sodium hydroxide; the quantity used depends on water quality.
- (5) Containers for packaging radioactive effluent from the radioactive waste systems. The number of containers depends on the amount of radioactive materials to be disposed of and the particular process used in the various systems. These containers are steel, concrete, and other common structural materials.
- (6) Sodium coolant for the primary and secondary coolant loops of the power plant. The sodium inventory in an LMFBFR plant, with three primary and three secondary loops, contains about 30,000 ft³ of sodium for the primary system and about 41,000 ft³ for the secondary system.¹ The total inventory (both loops) is approximately 2000 metric tons.
- (7) Miscellaneous chemicals, principally nitric acid and solvents for the reprocessing plant. These are not critical materials from a resource standpoint, and amounts not recycled are handled as wastes.

All of the above chemicals are of common types and are used in moderate amounts relative to U.S. industrial practice. Sodium is a low-cost industrial material obtained from virtually inexhaustible salt resources. Sodium is not chemically transformed in its use as a coolant and is retained, except for small removals, during the plant lifetime. The sodium in the primary loop is rendered radioactive, which may make it unacceptable for uses other than as primary coolant in LMFBFR power plants.

In order to gain perspective on cumulative uses of possibly critical material resources, the quantities of mineral resources consumed in LMFBFRs (structural

materials and cladding) are related to current production and reserves of these materials (see Table 10.1-3).

In summary, the commitment of resources to the projected LMFBR industry does not appear to be appreciable or critical; the extent of irreversible and irretrievable commitment of resources is small. Moreover, one notable feature of the breeder, relative to the LWR, is its significantly lesser commitment of the Nation's uranium resources. This is chiefly due to its use of plutonium produced in the course of operation of LWRs for its fissile fuel and depleted or natural uranium for its fertile fuel and blanket components. In addition, since it produces more plutonium than it consumes, the breeder adds to the Nation's net nuclear fuel resources.

10.2 MANPOWER RESOURCES

10.2.1 Introduction

This section presents estimates of the numbers of personnel directly involved in design, construction, and operation of the individual LMFBR facilities described in Section 4, and makes preliminary projections of maximum numbers of personnel needed during the periods of maximum growth and utilization of the LMFBR. In making these estimates, emphasis is placed on manpower needs for LMFBR power stations, as these would be much more numerous than other facilities in the LMFBR fuel cycle.

Next, indirect LMFBR manpower needs are discussed, considering the areas of manufacturing, training, and possible growth in numbers of government personnel associated with the LMFBR.

Finally, the projected LMFBR manpower estimates are compared with U.S. work force projections, and general conclusions are drawn on the problem of manpower for the LMFBR.

10.2.2 Manpower Directly Applied to LMFBR Facilities

10.2.2.1 Power Stations

10.2.2.1.1 Construction

Requirements for power station construction workers are customarily expressed in terms of man-hours per kilowatt of electrical generating capacity. Such requirements will vary considerably depending on such factors as the number of generating units to be constructed at a given station (in general a multiple-unit station requires fewer man-hours per kilowatt than a single-unit station), the size of

the units (larger units usually require fewer man-hours per kilowatt), worker productivity, need for environmental controls (cooling towers, pollution abatement equipment, waste disposal, etc.), and special design features.

Studies undertaken by United Engineers and Constructors for the AEC indicate that construction labor requirements for LWR power stations range from about six man-hours per kilowatt for a multiple-unit station with 2,000,000-kW units to eight man-hours per kilowatt for a single 1,300,000-kW unit station. It is assumed that the construction labor requirements for LMFBR power stations will be approximately the same as those for LWRs. For purposes of developing a projection of LMFBR construction worker requirements, a range of six to nine man-hours per kilowatt was selected. In addition, it was assumed that the station construction period (construction permit issuance to construction completion) will be five years, that each worker will be on the job 2000 hr per year, and that man-hour distribution over the period will be:

- 1st year - 10% of total man-hours
- 2nd year - 24% of total man-hours
- 3rd year - 33% of total man-hours
- 4th year - 24% of total man-hours
- 5th year - 9% of total man-hours

Using these assumptions, the number of workers needed for construction of a 4000-MWe LMFBR station would average about 4000 during the peak (3rd) year of the construction period.

To estimate the total numbers of workers involved in construction of LMFBR power stations over the time period addressed in this Statement, the assumptions mentioned above can be applied to the LMFBR growth projection discussed in Section 11. Table 10.2-1 expresses this growth in terms of cumulative LMFBR capacity on-line as a function of time. Figure 10.2-1 provides a range of estimated total construction manpower corresponding to this growth. Early in the next century the maximum annual manpower needs might range from about 300,000 to 500,000 workers.

10.2.2.1.2 Operating Staff and Utility Headquarters Staff

About 80 personnel are required on-site for the operation, maintenance, and technical support for a single-unit LWR nuclear station; this increases to about 130 for a two-unit station.⁴ The unit size does not have a strong influence on the number of personnel needed. In a two-unit group, approximately 40% of the personnel are involved in plant operations, 30% perform maintenance, and the

Table 10.2-1

CUMULATIVE GENERATING CAPACITY--
U.S. CENTRAL STATION LMFBR POWER PLANTS
(in operation at end of calender year shown)

Year	Millions of Kilowatts
1987	2
1989	13
1991	39
1993	88
1995	156
1997	248
1999	369
2001	501
2003	702
2005	923
2007	1118
2009	1338
2011	1559
2013	1695
2015	1865
2017	2061
2019	2193

10.2-4

U.S. LMFBR ELECTRIC POWER PLANTS--
ANNUAL REQUIREMENTS FOR PLANT CONSTRUCTION WORKERS

Figure 10.2-1

remainder are engaged in management, engineering, technical, and administrative functions. It is estimated that about half of the personnel should be on-site or in training for on-site assignments during the three years prior to startup.

The headquarters group is the earliest group formed (about ten years prior to plant operation). For utilities which contract the principal engineering effort, the number of personnel required is on the order of 25 to 30 for a single-unit station.⁴ Thirty-five is estimated for a two-unit station. Headquarters staff is divided about equally between power generation and engineering assignments during the plant operating phase.

Early LMFBR stations may involve larger on-site and headquarters staffs than are needed for LWR stations, because of differences in the reactor plant and the possible desire to assign additional personnel for training. It is believed, however, that in later years, LMFBR station staffing requirements would be about the same as indicated above for LWRs.

The estimated personnel requirements for the utility's headquarters staff and the on-site staff for a two-unit LMFBR station are presented in Table 10.2-2. The maximum total number of such personnel would be required at the end of the time period considered in this Statement (the year 2020). Assuming that a representative LMFBR station consists of two 2000-MWe units, there would be about 550 stations, and about 91,000 personnel (off-site and on-site) would be engaged in activities directly related to LMFBR station operation.

10.2.2.1.3 Design and Construction Engineering and Management

Services for engineering and management are performed off-site and on-site. The off-site work preceding construction consists of design engineering, purchasing, inspection, equipment expediting, project scheduling, estimating, preparation of procedures and manuals, activities relating to regulatory requirements, and off-site project management. Off-site activities typically begin about eight years prior to start of operation, and they are substantially complete by startup. Based upon informal discussions with architect engineers and others, it is estimated that about 135 individuals are needed during the first four years, and about 45 during the remainder of the construction period. The higher numbers are needed in the early period primarily because of the greater workload associated with licensing requirements.

On-site or field services consist of craft labor supervision, planning, scheduling and cost control, field engineering, quality assurance, equipment and materials handling, personnel safety, purchasing, accounting, and security. Site forces vary with craft labor but this is not a strong effect. A constant staff of 200 over the five-year construction period is assumed.

The two-unit LMFBR station requirements for design and construction engineering and management are shown also in Table 10.2-2. The numbers of such personnel can be expected to reach a maximum of about 43,000 around the year 2000, when the rate of LMFBR additions is greatest (about twenty-five 4000-MWe stations per year).

10.2.2.2 Other Facilities and Transportation

10.2.2.2.1 Spent Fuel Reprocessing Plant

Based upon information on the Barnwell Nuclear Fuel Plant⁵ (to be constructed at Barnwell, South Carolina for the reprocessing of LWR fuel), it is estimated that the "model" LMFBR fuel reprocessing plant described in Section 4.4 would require a peak work force of about 2000 during a four-year construction period, and would require an operating staff of about 500. Considering that each LMFBR reprocessing plant, with a throughput of 1500 metric tons per year, will serve about 80,000 megawatts of LMFBR electrical generating capacity, about 28 such plants would need to be brought on-line by the year 2020 (see Table 10.2-1).

A detailed examination of construction phasing for reprocessing plants has not been made. However, the maximum commitment of construction personnel in any single year would probably not need to exceed about 6000 in order to keep pace with LMFBR generating capacity growth. Reprocessing plant operating manpower would reach a peak of about 14,000 at the year 2020.

Design manpower needs are expected to be relatively low--about 300 individuals for each separate design.

10.2.2.2.2 Fuel-Fabrication Plant

Construction and operation manpower for the 1500-metric-ton-per-year LMFBR model mixed-oxide fuel-fabrication plant is estimated at 1800 (construction manpower peak during a four-year construction period) and 500 (equilibrium level operating staff), based upon extrapolation of information on the proposed Westinghouse Recycle Fuels Plant.⁶ Construction and operation manpower totals (for 28 fuel

Table 10.2-2

AVERAGE PERSONNEL PER YEAR FOR A TWO-UNIT LMFBR STATION

Years to Commercial Operation	Offsite Personnel		Onsite Personnel		Total Offsite and Onsite
	Design and Construction	Headquarters Staff	Construction Engineering and Management	Operation and Maintenance	
+10		35			35
+9		35			35
+8	135	35			170
+7	135	35			170
+6	135	35			170
+5	135	35	200		370
+4	45	35	200		280
+3	45	35	200	65	345
+2	45	35	200	65	345
+1	45	35	200	65	345
0 ^a		35		130	165
-1		35		130	165
-2		35		130	165
-3		35		130	165
-4		35		130	165
.		35		130	165
.		35		130	165
.		35		130	165

^aStart of commercial operation.

fabrication plants) should be about the same as for reprocessing plants. Design manpower needs also are expected to be similar.

10.2.2.2.3 Radioactive Waste Management Facilities

Section 4.6 of this Statement identifies the retrievable surface storage facility (RSSF), the alpha waste storage facility (AWSF), the noble gas storage facility (NGSF), and commercial burial grounds as facilities for storage of radioactive wastes (LMFBR and other). Manpower needs for these facilities would be small compared with other segments of the LMFBR fuel cycle. For example, the peak RSSF construction force is expected to be about 200, and the operating force about 300. Manpower needs for construction of other waste facilities would probably be less.

10.2.2.2.4 Transportation

Table 4.5-1 presents data on the transportation (rail and truck) needed to handle LMFBR fuel and radioactive wastes. Assuming two men per truck per shipment, about five men are required for direct transport services (fuel cycle materials and wastes) per year of 1000-MWe LMFBR power station operation. On this basis, as many as 11,000 workers might be directly involved in transportation for the LMFBR fuel cycle in the year 2020.

10.2.3 Indirect Manpower

10.2.3.1 Nuclear Manufacturing Industry

The manufacture of components for an LMFBR power station involves facilities, hardware, and processes which are similar to those needed for the LWR industry and for conventional fossil-fueled power stations. Individual major items are expected to require about the same expenditure of manufacturing manpower as the corresponding LWR items. The manpower needs⁷ for some major items are itemized in Table 10.2-3.

Components such as instrumentation, controls, and piping also require a high degree of skill in manufacture, and they will involve an important segment of the manufacturing labor supply. However, no significant change in manpower needs is expected for LMFBR components over components for other reactor types.

10.2.3.2 Personnel Education and Training Requirements

Advanced planning to assure the availability of trained personnel must precede the earliest stages of plant design by about ten years for all types of power

Table 10.2-3

MANUFACTURING MANPOWER ESTIMATES^a

Item	Manpower per Unit ^b
Reactor Vessel	45 to 55
Steam Generator or Intermediate Heat Exchanger	20 to 30
Turbine Generator	150

^aAtomic Industrial Forum, "Resource Needs for Nuclear Power Growth," a report of an ad hoc forum committee, 1973.

^bNumbers of people continuously applied over period of manufacture.

systems. The nuclear industry and the utilities have the primary responsibility to assure the timely availability of trained personnel. The present education and training programs for nuclear power technical staffing are conducted by reactor vendors, federal agencies, consultants, and academic institutions.⁴ These services are judged to be adequate to meet current needs. A long-term critical need can be anticipated based upon the marked decline in enrollment and interest in all areas affecting nuclear power activities, from research and planning through the operating phase of the power facilities.⁸⁻¹⁰ Therefore, regardless of the future mix of power plant types, a potential future critical problem is the availability of large numbers of trained personnel.¹¹ The need for this critical resource is essentially the same for the LMFBF as for the LWR and other power systems.

10.2.3.3 Government Personnel

It is expected that the numbers of local, state, and Federal government personnel involved in regulation of commercial nuclear power will increase as the Nation's commitment to this form of electric power generation increases. An example of this trend is provided by noting that the regulatory staff, which was at a level of about 500 in FY 1970, is expected to increase to about 1400 by the end of FY 1974.¹² Although current and continuing efforts toward design standardization should enable the AEC and other regulatory staffs to operate at higher efficiency, there is likely to be a continuing need for staff increases. Because of a variety of factors, including possible changes in institutional arrangements, it is presently not considered realistic to attempt to predict the dimensions of this growth. Further, it is not considered practicable to attempt to identify

incremental increases in government staffing attributable to the LMFBR within any overall increases associated with a growing nuclear industry.

10.2.4 Perspective on Manpower Projections

The LMFBR construction manpower projections^{13,14} can be given some perspective by relating them to estimates of the U.S. work force, which are indicated in Table 10.2-4.

Table 10.2-4
POPULATION AND MANPOWER PROJECTIONS
(in millions)

	1970 ^a	2000 ^b	2020 ^b
U.S. Population	204.9	271.7	307.4
Work Force	85.9	125.6	142.3
Contract Construction	3.3		

^aGovernment Printing Office, Statistical Almanac of the United States, Washington, D.C., 1972.

^bU.S. Bureau of the Census, Current Population Reports, Series P-25, Number 476, "Demographic Projections for the United States," GPO, Washington, D.C., 1972.

This table shows a 46% increase in the work force from 1970 to 2000. If contract construction (the category from which LMFBR construction labor would be drawn) is assumed to grow with the work force, it would reach 4.9 million by the year 2000. The largest projection of manpower for the LMFBR is for the construction peak period, soon after 2000. The peak of 350,000 to 500,000 workers would be about 7 to 10% of the contract construction work force projected at that time. The LMFBR construction peak work force would amount to about 0.3% of the national work force in the year 2000.

In 2020 the total electric generating capacity is expected to be about 5830 million kW, including about 2200 million kW of LMFBR capacity. The operating staff for the LMFBR power plants is estimated for the year 2020 at 91,000 people (see Section 10.2.2.1). If the other electrical power generating stations are similarly staffed, the total electric utility generation manpower in the year 2020 would be about 242,000 people, or about 0.2% of the total projected work force.

In summary, while this assessment has shown that the estimated manpower needs of the LMFB program constitute a small part of the Nation's prospective work force, it should not be concluded that manpower is not a critical problem for the LMFB. The need to train a large number of construction craftsmen is real. Also, the currently reported decline in science and engineering enrollments at the bachelor and higher-degree levels is cause for concern. It is believed, therefore, that a strong and continuing commitment on the part of the utilities, the nuclear industry, and the government will be necessary to assure that adequate trained manpower is available when needed. Finally, it should be recognized that the need for trained personnel is not unique to the LMFB, but applies to any advanced electrical power generation system which might be broadly deployed in the future.

10.3 FINANCIAL COMMITMENTS

The LMFB program requires the commitment of extensive financial resources by both the Nation's utilities and the Federal government. For example, monies are required for demonstration plant design and construction, basic and applied research related to the LMFB program, and the design, construction, and operation of test facilities required for the LMFB program. Estimated AEC research and development funding estimates for the period 1975-2020 (fiscal years) are given in Section 11.2.2. Estimated utility investments in LMFB central stations for the period 1985-2020 are given in Section 5.3.1.1.

In considering Federal support of energy research and development programs, it is important to keep in mind that monies are authorized and appropriated on an annual basis. Programs are reviewed and approved consecutively by the originating agency, the Office of Management and Budget, the cognizant authorizing and appropriating committees of the Congress, and finally by the Congress. At each stage in the process, there are many programs and projects competing for the limited funds available. Thus, a decision at this time to continue with the LMFB program does not commit the Federal Government to an irrevocable commitment of financial resources. On the contrary, the level of support to be accorded to the program in future years will continue to be thoroughly scrutinized on a yearly basis as a part of the comprehensive budgetary review process.

In addition, it is expected that a portion of the funds being used and to be used for research and technology development for the LMFB program will be of substantial benefit to other energy technologies. High-temperature materials and components of the type being developed under the LMFB program are critically needed for other energy technologies such as magnetohydrodynamics. Physics, fuel development, and

safety research accomplished for the LMFBFR program will be of great value to potential future gas-cooled fast breeder reactors. Funds expended on research and technology for the LMFBFR program that are of no benefit to other energy-production technology efforts constitute an irreversible and irretrievable commitment of resources. No estimates of this portion of the total LMFBFR program funding are available at this time.

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VOLUME IV

SECTION 11

COST-BENEFIT ANALYSIS

The cost-benefit analysis compares LMFBR Program costs to the potential benefits. Potential benefits are identified as direct dollar savings in the cost of electricity and as reductions in environmental impacts as a result of this form of electricity generation.

A number of alternative options and alternative strategies for power generation are feasible. Costs and benefits are evaluated by comparing the environmental and economic effects of the LMFBR with a number of other alternatives for electric power generation.

Energy demands used in this study are based on the projection that energy growth rates will decline from the current level of 7 to 8% per year to less than 4% per year by the year 2020. At the same time, projections indicate that the electrical energy fraction of the total energy demand will be about double by 2020. In recognition of the possible role of fossil-fueled power plants, hydro systems, peaking capacity, and potential energy systems under development, it has been assumed for purposes of analysis that the penetration of nuclear fission reactors would be limited to 60% of the total electric generating capacity. From a strictly economic viewpoint, nuclear plants could probably capture a larger share of the capacity, but this limit has been imposed in order to take a conservative position on the role to be played by the LMFBR.

Economic benefits of the LMFBR are represented in this analysis by the reduction in the Nation's electric energy costs from 1974 to 2020, due to introduction of the LMFBR. The economic benefit of lower electricity cost is compared with the program costs of the LMFBR. These studies indicate that the benefits are more than adequate to offset the program costs, thus producing a net economic benefit from LMFBR introduction. This conclusion holds for all cases using reasonably probable assumptions regarding the important economic and resource parameters, including cases with assumptions which selectively disfavor the LMFBR. The benefits are reduced below the program costs only when a number of assumptions are simultaneously weighted against the LMFBR in a manner which the AEC considers unlikely to occur.

The actual future energy requirements for the Nation may be greater or less than the base projections used in this study. Similarly, the electric energy generation and the penetration of fission reactors into the electric generation market may also vary from the base projections. These possibilities are treated by including some cases with different electricity demand growth projections. Other

parameters in the calculations are also varied in order to provide information on the sensitivity of calculated results to input assumptions.

Environmental and human impacts of electric power generation constitute an external cost that is not included in the cost of power. Conversion of external costs to dollars is not practical in this analysis. However, comparisons of potential effects of alternative energy generating systems can be made with impacts quantified in consistent physical units. Evaluation of the environmental effects of fission power reactor systems with and without the LMFBR and a power system with no fission reactors provides a basis for assessing the relative environmental and human impacts of the LMFBR.

Evaluation of the potential environmental impacts of fossil, fission converter, and LMFBR generation systems leads to the conclusion that introduction of the LMFBR will have an overall beneficial effect on the environment. The LMFBR has lesser impacts in terms of heat discharge, water consumption, land use, radioactive emissions (except plutonium), radiation dose, resource depletion, and health and safety of workers and the population at large. On the other hand, the LMFBR will lead to an increase in the number of shipments of irradiated nuclear fuel, in production of solid radioactive wastes, and in production of plutonium.

This study concludes that the environmental and economic benefits of the LMFBR far outweigh its program costs, and that these direct and indirect benefits will not be limited by finite fuel resource availability. LMFBR power costs are essentially independent of the cost of fuel resources, such as uranium, whereas fossil and fission converter systems have considerable cost sensitivity to fuel costs. Thus, power systems utilizing the LMFBR are freed of the economic and strategic implications of dwindling low-cost fuel resources and are assured of deriving low-cost power from the Nation's entire reserve of extractable uranium resources.

This analysis recognizes, however, that development of other energy sources and conversion techniques, plus efficient and thrifty use of our energy resources, will be needed to provide a balanced, flexible power system that assures sufficient low-cost, environmentally safe energy in the future. The role of the various possible components of a balanced future energy strategy is acknowledged, and the view of the AEC is that continued development and timely deployment of the LMFBR does not foreclose any of the other potential energy systems.

11. COST-BENEFIT ANALYSIS OF IMPLEMENTING THE LMFBR PROGRAM

11.1 FORMULATION OF THE COST-BENEFIT ANALYSIS

11.1.1 Introduction

The Cost-Benefit Analysis of the LMFBR examines the costs and benefits of developing and implementing the LMFBR as a potential energy source for central electric generating stations. The Analysis considers the internal economic costs and benefits as well as the external human and environmental impacts of the LMFBR and alternative energy systems.

As an option for electric power generation, the LMFBR may be used in the future as an integral component of the national power economy. The evaluation of the costs and benefits of the LMFBR is compared with other alternatives in the framework of projected alternative electric generating strategies. Comparison of strategies is important, because the ultimate use of any one option is affected by its relative cost and benefits. Similarly, no option alone can provide a practical solution to our electric energy needs.

Section 11.1.2 summarizes portions of Section 6 which discuss energy conversion and production alternatives to the LMFBR which will be available sometime during the period of the study (1974 to 2020). Neither the LMFBR nor any of these alternatives should necessarily be considered to be mutually exclusive. Unless the allocation of research and development monies favors one technology to the exclusion of others, all can develop simultaneously. At present, the funding of the LMFBR program does not reflect a decision by the Atomic Energy Commission as to which alternative should be implemented. If the AEC's successor, the Energy Research and Development Administration (ERDA), is called upon to allocate limited research and development dollars among promising technologies, this document presents a comparative analysis of the environmental and economic tradeoffs upon which such a decision should be based.

That allocation decision and the decision as to whether, and in what fashion, to continue the LMFBR program are the federal actions assessed in this document. Implementation of the LMFBR or any of the alternative technologies will depend upon a large number of decisions made by the private energy industry. The federal role is simply that of making promising technologies available to the private sector. Continuation of the LMFBR Program commits our society to the use of breeder reactors only if, and to the extent that, no equally attractive options are available or become available for adoption by private industry.

Alternative systems are discussed qualitatively to give an indication of their impacts, and estimates are made of their potential for meeting a portion of future power demand. This is followed by a discussion of alternative energy strategies that may be used to meet future total power demand in the event that the option to build the LMFBR is not exercised. These alternatives include consideration of a strategy in which only present technology (conventional fossil, hydro, and fission converter) is assumed to be available; they also show a strategy including both present and potential technologies, such as solar, geothermal, and fusion. The economic costs of possible future alternative power systems are not well developed at this time, and therefore, they have not been included in the highly quantitative economic cost-benefit study. Instead, it has been assumed that a fixed portion of the power generation system would be nonnuclear, and that all nonnuclear alternatives would compete for that segment of the market.

Section 11.1.3 provides a review of the external environmental and human costs associated with the following three major alternative strategies for meeting the projected power demand:

- (1) The LMFBR is assumed to be developed and widely deployed in the latter part of the 1974 to 2020 period.
- (2) The LMFBR is not developed, but nuclear power plants continue to be deployed in the form of HTGRs and LWRs.
- (3) No additional nuclear plants are built beyond those committed, thus leading to a system without any fission reactors.

If it were possible to assign dollar values to all of the costs and benefits to society associated with energy production, then these values could be internalized and the competitiveness of alternatives could be estimated entirely in terms of economics. At this time, however, it is not possible to convert all potential human and environmental impacts to equivalent dollar values. Current knowledge regarding long-term changes in the environment, as they affect human health, safety, and the viability of ecological systems, is both incomplete and nonuniform. Progress is being made in acquiring the requisite knowledge, and major development decisions must reflect, insofar as possible, considerations of the added dimensions of social and environmental impacts. An approximate evaluation can be made by examining separately the types of impacts which can now be perceived and comparing them to alternative systems.

Section 11.1.3.2 discusses the cumulative external impacts over the period 1974 to 2020, and compares them for the different strategies considered. In Section 11.1.3.3, the different strategies are examined in more detail, and the external costs associated with each component of the proposed strategies are defined and discussed. In the treatment of external costs, conventional fossil-fueled systems were evaluated on the basis of current technology. Longer-term fossil-fueled systems are likely to be based on advanced technology such as coal gasification or liquefaction. Detailed external costs for potential alternative advanced systems such as solar or fusion are not available because these systems are currently in the conceptual stage of development. As development of the LMFBR and alternative systems proceeds, additional knowledge will be accumulated on the potential environmental impacts of each system. Additional opportunities for comparative impact evaluation will be possible prior to a final decision for deployment of any type of alternative system.

The economic cost-benefit analysis in Section 11.2 compares LMFBR program costs to the potential economic benefits of using the LMFBR to generate electrical power. The potential economic benefits are defined as the net savings in electrical power cost that would result from including LMFBRs in the national electric power system.

The LMFBR program costs are presented and discussed in Section 11.2.2. The LMFBR Program is responsible for the development of the LMFBR concept, as well as for the supporting technology necessary to establish the LMFBR as a viable, commercial system for the production of electric power. With the exception of safety research, most research and development programs for the breeder will be completed or phased out following its successful commercial introduction.

The methodology used in calculating the benefits associated with the development and utilization of the LMFBR is presented in Section 11.2.3. The national electric power generating system was modeled with a linear program on a computer. For a fixed set of input variables (a case) the program selected a unique plant building program (a reactor mix) that minimizes the discounted cash flow to produce power (the present valued power cost) for the period 1974 to 2020. For each case; the model had the option of selecting any combination of available plants and fuel that enables the system to meet the total electrical energy demand of consumers. The heart of the study was based on two cases: one in which the total power demand is met with a system that allows the LMFBR industry to develop and expand freely; and one in which no breeders are built at all. The sensitivity of the benefits was evaluated in 76 other cases which varied the factors affecting the economics and timing of the LMFBR.

The cash flow to produce power includes money for capital investment, fuel or fuel-cycle costs, operating and maintenance expenses, and taxes. All cash flows have been discounted to mid-1974 using a discount rate of 10%. The individual cases are tabulated in Appendix IV.D.

Each power cost calculation started with a projected electrical energy demand. The electrical energy demand projection is essentially an extrapolation of current trends with energy input to electric power projected to grow from 25% (1970) to 65% (2020) of total energy demand. Nuclear power plants were limited to about 60% of the electrical energy demand in cases which only considered mixes of nuclear reactor types. Thus, most of the cases assume that about 40% of the electric power demand is satisfied by nonnuclear plants. The sensitivity of the benefits was also determined for several cases where higher and lower energy demands were assumed.

Within the framework of an assumed electrical power demand, the cost-benefit model selected a schedule of generating plants. Each plant follows a predetermined, life-time capacity curve, as defined in Section 11.2.3.4. Calculations covered the time period from January 1, 1974 through December 31, 2019, and the linear program selected the plant build schedules for each biennium from 1974 to 2020. The costs for reactors built prior to 2020 were calculated through to the end of their 30-year life. Thus, the minimum total power cost for plants required to meet the electrical power demand to the year 2020, including operating cost through the year 2050, was computed in terms of the mid-1974 present worth. This procedure is consistent with standard utility practices for evaluating alternatives.

The linear program model successively alters the variables in the equation which determined the present-worth cash flow until a system is found that will produce the minimum present-worth power cost for the study period. Plant selection is based strictly on the need to supply new demands and to replace retired plants. Introduction constraints were included in the model to prevent the program from introducing new reactor types at a rate faster than practical limitations would allow.

The cash flow items contributing to the "busbar" power costs computed in this study include all costs which are directly dependent on the choice of generating plant type. Cost of transmission and distribution is relatively independent of the generating plant type. The busbar cost items represent a large amount of input data for each plant. The input parameters used in the study are based on extensive study and on data from Government agencies, electric utilities, reactor manufacturers, architect-engineers, and firms engaged in fuel-cycle operations. In many instances,

the projected costs are higher than those used in previous LMFBR Program cost-benefit studies. These higher costs are due partly to general escalation from the earlier base years to mid-1974, and partly to real cost increases in some segments of the industry.

In addition to comparing alternative systems on the basis of the cost-benefit ratio, the internal rate-of-return has been calculated and included in this Statement. The rate of return on the research and development investment is computed by a trial-and-error process which iterates over a range of discount rates until the discounted research and development costs are identically equal to the discounted benefits over the study period. The rate-of-return analysis somewhat understates the impact of actions far in the future, since the forward costs of plants operating between the end of the study period (2020) and the end of their life are not included.

The results of the LMFBR cost-benefit study are summarized in Section 11.2.1, and they are discussed in greater detail in Section 11.2.4. The results indicate that introduction of the LMFBR as a commercial producer of electricity will result in significant economic benefits due to the overall lowering of power costs.

Any analysis of the Nation's power system requires consideration of a large number of variables. Prediction of the impact of economic factors involved in power generation for a 50-year period introduces uncertainty. The projected base values of the study parameters were selected on the basis of careful study of available information. However, because of the inherent uncertainties in those projections, the 76 sensitivity cases mentioned previously were developed to study variations in input parameters.

The assumptions used for each of the 76 cases, as well as their costs and benefits, are presented in tabular form in Appendix IV.D. The cases evaluate variations in: (1) introduction date of the LMFBR; (2) the availability-price relationship of newly mined uranium; (3) electrical energy demand; (4) relative capital cost differences between LMFBRs and other plant types; (5) the postirradiation cooling time for LMFBR fuels; (6) availability of carbide-fueled LMFBRs; (7) availability of the HTGR, and introduction constraints applied to HTGRs and LMFBRs; and (8) the assumptions of economic competition among nuclear and fossil-fueled plant types. Several calculations combining the effects of two or more parameters were also made. The results show that positive benefits would be realized over a wide range of conditions that could potentially exist in the power economy of the United States. Only when two or more conditions adverse to the LMFBR which are considered unlikely to occur are combined do the LMFBR benefits fall below the discounted program costs. The benefits

calculated for the LMFBR are due in large part to the savings in mining and enrichment of new uranium which would otherwise be required for operation of other nuclear plant types. The positive benefits result because the savings in fuel-cycle costs greatly outweigh the higher capital and operating costs projected for the LMFBR.

Section 11.2.5 discusses the logic of cost-benefit models as they relate to utility planning methods. The cost-benefit model that was used to evaluate the LMFBR does not generate explicit year-by-year fuel-cycle costs, nor does it directly compare individual plants such that one can point to a precise date when the LMFBR becomes economically competitive on an individual plant basis. The model considers all fuel-cycle cash flows in the power system, and works to minimize the discounted value of the total cash flows.

In response to several reviewers of the Draft Statement, a simplified economic evaluation has been added that allows one to take a closer look at the costs associated with individual plants built at a specific point in time. The new analysis is representative of an economic comparison that could be made by all of the utilities planning to install new nuclear generating capacity in 1990 and 1991. It consists of two cases: one in which LMFBRs are built, and one in which they are not built. After an optimum plant mix had been determined for each case, the 30-year discounted power costs were estimated for the plants built in the two-year period. During that period, the capital cost difference between LWRs and LMFBRs will still be high and uranium costs will still be relatively low. Therefore, those two years occur in the period in which the economic competitiveness of the breeder will be at its lowest. In the case where LMFBRs are built, about 25% of the new generating capacity is LMFBR, but this is sufficient to produce a discounted power cost savings of \$1.3 billion over the case with no breeder. In addition to these benefits, the operation of the LMFBRs will decrease U_3O_8 demand, which will in turn mean lower uranium prices for reactors already operating in 1990.

The AEC system analysis model is thought to provide a superior representation of utility methods for making the most economic choice for new plants, and is preferable to a constant dollar comparative analysis of individual plants. The individual plant approach is unable to include related benefits which the LMFBR provides through its fuel-cycle interaction with the nonbreeder reactors. These effects are included by the AEC in the cost-benefit model and are well recognized by the industry. Utility planning methods and viewpoints are discussed in Section 11.2.5.1.

11.1.2 Alternatives to the LMFBFR

The United States economy is based on the large-scale use of energy to multiply the productivity of human labor. At current growth rates, the Nation's total consumption of energy will double about every two decades. Electric energy demand nearly doubles every decade. In 1972, the conversion of fossil fuels to thermal, mechanical, and electrical energy satisfied 95% of the Nation's energy demand. Another 4% was supplied by hydroelectric power and 1% by nuclear power. However, fossil fuels, natural nuclear fuels, and available hydropower sites all represent finite resources. Domestic fossil fuels, particularly oil and gas, appear inadequate to meet the U.S. growth needs. Coal resources are becoming more expensive to use due in part to environmental costs of mining and combustion. Conversion of natural uranium to thermal energy in present nuclear reactors will encounter rising costs as low-cost uranium ores are depleted. New and improved technology is necessary to maintain our energy consumption growth rate without severe economic penalties related to finite fuel resources. Alternatively, or in addition, we must conserve energy.

Alternative energy source technologies and strategies for energy conservation must be evaluated in terms of their environmental and economic impacts. As evidenced by the National Environmental Policy Act, the Nation is unwilling to achieve economic goals at the expense of the environment. The vulnerability to foreign influences is also important in the evaluation of alternatives. The recent economic penalties suffered from reduced availability and increased cost of imported oil was an expensive lesson on the strategic value of energy resources. The President's program for Project Independence reflects the national importance of assuring that critical resources are domestically available.

Each of the alternative energy source technologies described below has made available the technical potential to convert natural resources to thermal, mechanical, and electric energy. The relative economics and comparative environmental impacts depend in large measure on their particular application. The LMFBFR is being developed as an optional electric generating technology. Many conventional and some anticipated technologies may be used to generate electricity, or they may be more valuable in other phases of the Nation's total energy supply strategy.

11.1.2.1 Alternative Technologies and Energy Sources

11.1.2.1.1 Fossil-Fueled Conventional Power Plants

The fossil fuel resources of the United States are enormous, and they will continue to supply the largest portion of total energy demand for, at least, several decades.

Over 80% of these resources are coal, and expansion of electric production using fossil fuels will most certainly have to be based on coal, because of the current and projected scarcities of petroleum and natural gas. A greater proportion of our remaining oil and gas resources will be used for direct energy applications (rather than electrical energy production) for which they are uniquely suited. Thus, a shift away from current electricity production using oil and natural gas can be expected, and new capacity will have to be supplied from coal, nuclear, and to a lesser extent, nonconventional generation plants.

Table 11.1-1 shows the projected contribution of oil and natural gas to total and electrical energy consumption through the end of this century as forecast by the Department of the Interior.

Table 11.1-1
PROJECTED CONTRIBUTIONS OF OIL AND NATURAL GAS
TO TOTAL AND ELECTRICAL ENERGY CONSUMPTION

	<u>Contribution to Energy Use (%)</u>			
	1975	1980	1985	2000
Total Use				
Oil ^a	43.8	43.9	43.5	37.2
Natural Gas	31.4	28.1	24.3	17.7
Electrical Use				
Oil ^a	15.9	16.9	16.8	6.3
Natural Gas	16.8	12.2	8.7	3.3

^aIncluding natural-gas liquids.

As Table 11.1-1 depicts, the percentage contribution of oil to electricity generation will drop from 15.9% in 1975 to 6.3% in the year 2000. The percentage contribution of natural gas will drop from 16.8% in 1975 to only 3.3% in the year 2000. The move away from the fueling of generating plants with oil and gas has begun. Some oil-fired units were converted to coal during the 1973 oil embargo, and natural gas has supplied a declining proportion of the energy consumption for electrical generation for the past several years. As our natural gas reserves are depleted, priority allocation will be given to residential and commercial consumers. Natural gas and, to a lesser extent, petroleum will simply not be available for expanded utility and industrial use in the future. When planning future expansion and replacement of electrical generating equipment, utility managers will have to select nuclear- or coal-fueled systems because these are the only fuels with developed technology and resource base adequate to meet the needs of a plant with a 30- to 40-year life. As

current oil- and gas-fired plants are retired, it is unlikely that they will be replaced with units burning the same fuel. Any new oil- or gas-fired plant that may be built will probably be designed to allow future conversion to coal as a hedge against oil and gas supply uncertainties.

If the United States were to develop a complete reliance on coal for most of its energy demands, domestic resources would be rapidly depleted. Economically recoverable coal resources are estimated in Section 6 to be adequate to meet 1972 consumption rates for 300 to 700 years. However, the apparent abundance of coal is illusory, because it does not allow for future growth of energy consumption, nor does it consider the use of coal in place of oil and gas as they become more scarce.

Enough economically recoverable coal exists in the United States to produce an important share of our domestic energy needs well into the 21st century. Coal, however, may also be substituted for nonelectrical uses of oil and gas, thus increasing the competition for the available coal supply. Industrial users will have to turn to coal to produce steam and process heat as gas and oil becomes more scarce. A large number of coal gasification and liquefaction processes are currently under development, and at least two utilities have announced plans to build gasification plants.

A 1000-MWe coal-fired power plant requires approximately 2 million tons of coal per year of operation, or about 60 million tons during its operating lifetime. If the estimated electrical system capacity additions were all fueled from coal resources, about 340 billion tons of coal would be used up to the year 2020 or committed for future use by plants built up to the year 2020. This approaches the total of about 400 billion tons of coal resources estimated to be economically recoverable by current technology (see Section 6).

In 1972, coal provided only about 20% of the total U.S. energy usage. Most of the remaining energy was provided by oil and gas, which are known to be in short supply. If coal must also substitute for oil and gas, as seems probable, then the resources would be adequate for only the next 60 to 150 years at the 1972 total energy consumption level. Allowing for continued growth of total energy consumption at about 4% per year, the energy consumption in year 2000 would be about three times that in 1972. Thus, the duration of coal resources at the year 2000 total energy consumption rate would be reduced to about 20 to 50 years. Even if all the coal resources thought to be technically recoverable (irregardless of cost) are included, the maximum duration of the coal resource is increased to only about 100 years.

The economics of fuel for electrical energy production have changed considerably in the past year. In March 1973, the average price of coal delivered to electric utilities was about 39¢ per million Btu, but by March 1974 the average price had risen to about 61¢ per million Btu. In June 1974, some coal was sold at prices up to \$1.76 per million Btu. The price of oil has risen even more dramatically. In March 1973, utilities paid an average of 68.5¢ per million Btu for residual fuel oil but a year later the average price was \$1.89 per million Btu, an increase of 176%. In May 1974, oil sold for as much as \$2.62 per million Btu. The cost of fossil fuels for utilities continue to rise and it is impossible at this time to predict when and at what level they will stabilize.

A \$1 per million Btu increase in the cost of fuel increases the average cost of delivered electricity by 9 mills/kWhr. In 1973, residential customers paid anywhere from 10 to 50 mills/kWhr for delivered electricity. A 9 mill/kWhr increase is, therefore, a sizeable increase, and in fact, consumers buying electricity from utilities fueled heavily with coal and oil have experienced cost increases of this magnitude in the past year. By way of comparison, a \$1 per million Btu increase in fossil fuel price is equivalent to a \$150/lb increase in the cost of U_3O_8 to an LWR. The current market price of U_3O_8 is about \$10 to \$15/lb.

Although problems still exist, this study has assumed that emissions problems due to the burning of coal will be satisfactorily solved at reasonable costs. The major remaining environmental and social impacts of coal use in the future will be associated with the mining. Considerable land disturbance will occur, particularly if a significant proportion of the coal is strip-mined. Adequate restoration of this land will be difficult, particularly in areas of low rainfall, such as in the western United States where most of our low-sulfur coal reserves are located, and in the mountainous Appalachian regions. The deep mining of coal will cause less land disturbance than strip mining, but is more expensive and more hazardous.

The mining of coal has historically been a hazardous occupation. Section 11.1.3 discusses and quantifies social impacts of coal mining such as fatality and injury rates and the occurrences of occupational diseases such as black lung. The implementing of the 1969 Mine Safety Act reduced fatality rates, and further improvements in mine safety may be implemented in the future. These safety regulations may increase the internalized cost of coal through both increased mine capital requirements and lower mine productivity, but hopefully will decrease the external impacts.

11.1.2.1.2 Hydroelectric Power Plants

The 51,800 MWe of currently installed conventional hydroelectric capacity is about 15% of the total U.S. electrical generating capacity. The Federal Power Commission estimates that there are 128,000 MWe of undeveloped hydroelectric capacity in the lower 48 states, but economic feasibility, environmental constraints, and legislative prohibitions will make it unlikely that this potential capacity will ever be fully developed. The Federal Power Commission estimates that an additional 30,000 MWe will be added by 1990, but by that time hydroelectric will be only about 7% of the total installed generating capacity because of the rapid growth in the total capacity. If it were practical to fully develop our hydroelectric potential, it would produce about 12% of the projected year 2000 power demand and less than 5% of the year 2020 demand. Since hydroelectric is ideally suited to provide fast response peaking power, the numerous units operating in this mode would have significantly lower capacity factors. Only the largest facilities would operate almost continuously to provide base load power. A leveling off of conventional hydro capacity will probably occur toward the end of this century.

Hydroelectric plants have both positive and negative environmental effects. They are essentially pollution-free relative to their effects on air quality and have no fuel-cycle wastes. The reservoirs also are valuable for flood control and recreation.

The presence of large dams has a major impact on site ecology, both upstream and downstream. Interference with normal river flow often alters water quality and temperature. An environmental argument against the complete development of our hydroelectric potential is made by those who are concerned about the shrinking wilderness area in the United States. The large land area flooded by the reservoir makes a major dam economically possible only in unsettled regions. The question becomes one of whether or not a significant fraction of our remaining wilderness, which is irreplaceable, should be given up for a small increase in capacity to generate electrical energy.

In any event, the total capacity of potential hydroelectric sites is not adequate for hydro to be a principal contributor in a future energy supply system.

11.1.2.1.3 Nuclear Fission Converter Reactors

Nuclear fission converter reactors are the only alternatives to hydro and fossil electric generating plants that are currently commercially available for major

utility system expansion. Converter reactors use the fissile* isotope U-235 as their naturally occurring source of energy. However, only about 0.7% of the uranium found in nature is the U-235 isotope. The remaining 99.3% is the fertile** isotope U-238, which does not readily fission in the current types of converter reactors. In an operating reactor, some of the U-238 is converted (hence the name converter reactor) to a fissile isotope of plutonium (Pu-239) which can be recovered and used as fuel for converter reactors. Even with this conversion and recycle of Pu-239 fuel, however, the fission converter reactors can use only 1 to 2% of the uranium extracted from ore deposits. The remainder becomes waste uranium, which is so depleted in the U-235 isotope that it cannot be used to fuel converter reactors.

Thus, fission converter reactors require a continuing supply of U-235, which must be obtained by mining natural uranium. A breeder reactor, however, produces more fissile material than it uses during operation, and does not require any external supply of fissile isotopes. In fact, high gain breeder reactors can reproduce their own fissile fuel needs, plus producing enough excess fissile fuel to supply new reactors built for system expansion needs.

By the end of 1973, about 24,000 MWe of installed nuclear generating capacity were producing about 4.4% of our total electric energy. These plants have demonstrated that fission converter reactors are a safe and economical method of generating electric energy. Utilities have demonstrated their confidence in converter reactors by building, ordering, or announcing a total of 217 commercial reactors, with a combined capacity of 200,000 MWe, which is equivalent to about 40% of the currently installed total generating capacity in the United States.

There is probably enough uranium in the United States to supply a growing fission converter reactor industry for some time to come--at some cost. However, uranium is distributed in the earth's crust in either small scattered deposits or in dilute (low) concentrations, and the cost of uranium will rise as the Nation is forced to use less accessible deposits and the more dilute resources. The currently known domestic resources of uranium that can be developed economically and in an environmentally acceptable manner may not be adequate to support continued growth of converter reactor capacity beyond the turn of the century. Once these high-grade ore resources are expended, lower grade ores, such as the Chattanooga shales, will have to be mined to supply the converter reactor needs for uranium. Uranium concentrations in these ores are so low that, when the uranium from a ton of shale is used in a conventional

*Easily caused to fission by neutrons of any energy.

**Isotopes that become fissile by absorbing a neutron are known as fertile isotopes.

light-water reactor (LWR), the amount of energy generated is roughly equal to the energy generated by burning a ton of coal in a coal-fired power plant. Thus, an expanding power system using dilute ores will face large-scale mining and material processing problems and risks, similar to the problems and risks in a coal-based power economy. The resulting social costs will include substantial land disruption by mining, effects of the mine wastes, and deaths and injuries in mining accidents. While these effects have not been extensively examined, it is expected that an expanding converter reactor industry based on uranium from the Chattanooga shales would have accident statistics comparable to those in a coal-based energy industry.

It has been estimated that the cost of mining and producing U_3O_8 from low concentration ores will be at least \$100 per pound of U_3O_8 and it may be even higher in actual practice. As discussed below, this will have a substantial impact on the fuel-cycle costs of fission converter reactors.

The two major portions of the fuel-cycle cost for a converter reactor are for U_3O_8 purchase and for the enrichment of that uranium to a higher concentration of the fissile U-235 isotope. For the current LWRs, each \$10 per pound of U_3O_8 leads to a fuel-cycle cost contribution of about 0.6 mill/kWhr(e). Therefore, if low concentration ores could be mined and processed for about \$100 per pound of extracted U_3O_8 , then the uranium cost alone would contribute about 6 mills/kWhr(e) to the busbar cost of electricity. The current cost of uranium enrichment is about \$42 per separative work unit (SWU), which adds about 1.1 mills/kWhr(e) to the busbar cost of electricity. Enrichment is a power-intensive operation, and its cost will increase as the cost of power increases. The enrichment cost, in turn, will lead to higher power costs. Each \$10/SWU increase in enrichment cost will increase the busbar cost of electricity by about 0.27 mill/kWhr(e).

To provide a basis for comparison with the above numbers, LWRs currently are estimated to have a busbar power cost of about 13 mills/kWhr(e), of which about 10 mills/kWhr(e) is due to the plant capital investment, about 1 mill/kWhr(e) for nonfuel operating and maintenance costs, and about 2 mills/kWhr(e) for the total fuel-cycle cost.

When the magnitude of the electric power industry is considered, uranium purchase and enrichment costs represent very large sums of money. Introduction of the breeder reactor would allow the development of a nuclear utility system fueled with a plentiful supply of U-238, which is already stockpiled in large quantities as waste material from the LWR uranium enriching operations, and with fissile plutonium which would be produced in the operating breeder reactors. In other words, it would be possible to

reach a self-sustaining industry which does not require mining of any new uranium. This cost-benefit study estimates that this situation could be achieved by about 2015 to 2020, depending on the conversion efficiency of the available breeder reactors and the date of their large-scale commercial introduction. Moreover, the nonbreeder reactors that were built in the years prior to 2000 would experience lower fuel-cycle costs due to the reduction in U_3O_8 prices brought about by operating LMFBRS.

11.1.2.1.4 Alternative Fission Breeder Systems

Several alternative breeder systems are discussed in Section 6. These systems are the light water breeder reactor (LWBR), the gas-cooled fast breeder reactor (GCFR), and the molten-salt breeder reactor (MSBR). All fission reactor systems have fundamentally the same environmental impacts as the LMFBRS, and do not offer any significant improvement in that respect. The conclusions reached in Section 6 regarding these three systems are discussed below.

Light Water Breeder Reactor

The light water breeder reactor (LWBR) concept offers several attractive features: an improvement in fuel utilization efficiencies of existing and future pressurized water reactors; an existing technological base; and the productive use of another fuel resource--thorium.

The fuel cycle of an LWBR goes through two distinct phases. During the first ten years of prebreeder operation, the reactor is fueled with available fissile fuel such as enriched uranium and fertile thorium. During this period, the thorium is converted to fissile U-233 until enough is accumulated to provide all the core and ex-core fissile inventory of this material. During the remaining 20 to 30 years of breeder operation, the reactor would be self-sustaining in fissile material using bred U-233. The only fuel supply required would be small amounts of thorium. Thus, once an increment of capacity reaches the self-sustaining breeding cycle, no further mining or enrichment of uranium would be needed for that increment of capacity. New LWBR plants replacing old LWBR plants could be started up directly as breeders using the fuel discharged from the retired plant. However, the LWBR will not produce a surplus of fissile fuel for use in additional reactors, as would be necessary for an expanding nuclear economy to be self-sustaining without requiring mining or enrichment of additional uranium.

By successively recycling the thorium, up to 50% utilization of the thorium resource* can be expected. During the ten-year prebreeder period, uranium resource utilization is comparable to that in present LWRs.

Each new increment of LWBR capacity would have to progress through the ten year pre-breeder phase. During this phase, somewhere between 1300 and 3000 tons of U_3O_8 would be mined and enriched to provide the fissile requirements for a 1000 MWe plant. Since a new LWBR replacing an old LWBR can continue the fuel cycle without the pre-breeder phase, an increment of LWBR capacity would never require additional natural uranium input to the cycle, no matter how many times the reactor is replaced. In contrast, a 1000-MWe LWR plant would require about 5200 tons of U_3O_8 over a 40-year operating life, and each successive LWR replacing it would consume new U_3O_8 at the same rate.

The energy production costs for the LWBR system based on present costs of U_3O_8 are estimated to be slightly higher than for present types of LWR plants of comparable size. The energy production costs of a nuclear power system are normally broken into three categories: capital costs; operating and maintenance costs; and fuel-cycle costs. On the basis of current information, it is reasonable to assume that the first two categories, which contribute about two-thirds of the total, would be the same for LWBR and PWR systems of the same capacity. The fuel cycle costs (based on present U_3O_8 costs), which are about one-third of the total, are higher in the LWBR system due to the features necessary to achieve breeding and use of recycled radioactive fuel in the core. However, if nuclear power is to be a major energy source in the future, all reactor cycles will of necessity eventually use recycled fuel. The difference in energy production cost is not expected to be a barrier to use of the LWBR when other resources become limited and the cost of U_3O_8 increases.

No valid quantitative fuel-cycle cost comparisons of large-scale LWBRs and LWRs can be made at this time. However, the fuel-cycle cost of LWBRs would be higher than LWRs until the cost of U_3O_8 increases above the present cost. In view of the uncertainty of future large-scale LWBR and LWR fuel-cycle costs, the value of U_3O_8 which would result in LWBR fuel-cycle costs equal to LWR fuel-cycle costs cannot be determined at this time.

*Fuel utilization depends upon the fissile inventory ratio and processing losses. A fissile inventory ratio slightly above unity would enable 100% utilization of the fertile material except for materials lost in processing, which can amount to 30 to 50% after many successive recycles.

The environmental cost of an LWBR operation would be the same as for a PWR of comparable capacity, except the LWBR would require mining of small amounts of thorium and much less uranium.

Gas Cooled Fast Breeder Reactor

The gas-cooled fast breeder reactor (GCFR) as an alternative fast breeder option will have utilization incentives similar to those of the LMFBR. The economic, resource, and environmental costs of the GCFR are expected to be comparable with those of the LMFBR. However, the GCFR is in the early stages of development, and it is expected to reach commercial introduction later than the LMFBR.

The GCFR will use the same mixed uranium--plutonium--oxide fuel cycle as the LMFBR. Therefore, the GCFR will produce the same benefits accruing to the very efficient use of uranium resource as the LMFBR. The GCFR is expected to have a higher breeding ratio than the LMFBR, but the LMFBR is expected to have a higher specific power because of the lower heat removal capability of the GCFR's helium coolant.

A major portion of the LMFBR program is concerned with the development of fuels, and the GCFR program will be able to utilize much of the work as spin-off technology. However, a GCFR has never been built. Important work will be required to develop core and fuel cladding designs suitable for the high-pressure helium environment of a GCFR. The GCFR will be able to utilize some technology developed for the HTGR, such as component and reactor vessel design. Additional work will be needed in the areas of GCFR safety and component design.

The costs and benefits of the GCFR should parallel very closely those expected from the development of the LMFBR because of the similarity in purpose, function, fuel cycle, and operation. The major difference other than plant design is the relative timing of commercial availability of the GCFR and the LMFBR. Based on past experience with other reactor development programs, the AEC feels that the GCFR will become commercially available about a decade later than the LMFBR. However, General Atomic Company (GAC) believes that adequate funding would allow the GCFR to be available within a few years of the LMFBR. GAC believes that the use of LMFBR and HTGR technology, along with a moderate research and development program, will be sufficient to proceed directly to a small (300 Mwt or larger) demonstration plant and then to a full-size (1500 MWe) commercial plant. The AEC believes the approach recommended by GAC to be one having higher risks than the

usual approach that the AEC has followed in its reactor development programs of proceeding through a series of test and smaller scale demonstration reactors to a reactor of commercial size.

In all important respects, the GCFR will have approximately the same environmental impacts as those associated with the LMFBR. Accordingly, the environmental impacts determined in other sections of this study for the LMFBR are generally applicable to the GCFR.

Molten-Salt Breeder Reactor

The molten-salt breeder reactor (MSBR) concept is based on the use of a circulating fluid fuel which is continuously cycled through the reactor and through an on-line fuel-reprocessing system. As presently envisioned, it would operate as a thermal spectrum reactor, utilizing a thorium--uranium fuel cycle. Thus, the concept would offer the potential for broadened utilization of the Nation's fuel resources by using the fertile material, thorium.

The MSBR is essentially in the initial research and development stage, and it appears that the MSBR would not be expected to have a significant role before the year 2000. Although the basic feasibility of operating a fluid fueled reactor has been demonstrated, a large amount of basic work is required to solve materials problems and to develop process systems to meet the unique characteristics of this system. If development efforts are successful and it is commercially introduced, the MSBR could meet a moderate part of the electricity demand some time after the year 2000. The conclusion reached in Section 6 is that MSBRs probably will not provide an alternative to the LMFBR in the time span of primary concern to this study.

Evaluating the economics of the MSBR is difficult because it is the least developed of all the reactor systems currently considered to have commercial potential. Earlier design studies estimated that MSBR power costs based on current uranium prices would be less than LWR power costs. This cost advantage would increase as uranium prices increase.

The environmental impacts resulting from construction and normal operation of an MSBR would likely be similar to those for an LMFBR plant of comparable size.

Imported Breeder Reactor Technology

Another alternative to the LMFBR being developed in the United States is the evolving LMFBR technology abroad. Several European countries are currently developing LMFBR power plants. Thus, importation of LMFBR technology is an alternative to the current U.S. LMFBR program.

The goal of a viable and competitive nuclear industry in the U.S. entails manufacturer involvement in the breeder reactor research and development program leading to commercial power plants. The base technology necessary to support large-scale deployment of the LMFBR involves the entire fuel cycle and power plant industry. The basic knowledge and trained personnel to build and operate plants, and to provide the full range of fuel-cycle services must be domestically available to provide the sound, reliable foundation for an LMFBR industry. This involvement can provide the mechanism for internal trade-offs which result in safe, economical, and environmentally acceptable LMFBR power plants.

There is no guarantee that other countries will develop breeder reactors based on a firm foundation of proven technology necessary for acceptance by U.S. utilities. Should foreign reactors be available, there is no assurance that the plants would be licensable under U.S. standards. If the U.S. were to rely solely on the prospect of importing breeder technology, the Nation could ultimately find itself in the vulnerable position of economic dependence so dramatically illustrated by the recent oil embargo.

11.1.2.1.5 Solar

As discussed in Section 6, there are a number of proposed methods of using solar energy. These include direct utilization, such as thermal conversion, photovoltaic conversion, and thermal energy collection for space conditioning, as well as indirect solar energy systems such as those based on wind and ocean thermal gradients. The solar energy reaching the surface of the United States exceeds the energy produced from conventional fuels by a factor of nearly 700. However, the portion of this energy that can be effectively utilized is limited by technical, economic, environmental, and social considerations.

The major drawback in the use of solar energy is the diffuse and periodic nature of sunlight. Considering nights, weather, seasons, atmospheric attenuation, and variations in latitude, the average rate at which solar energy reaches the surface of the U.S. is 17 w/ft^2 . Although certain areas of the United States are better

suited for solar conversion, large amounts of land would be required to meet present and future electrical demands through solar-to-electric conversion. For example, a 1000-MWe thermal conversion solar plant capable of operating at a 70% capacity factor would require about 10 square miles of land. Large amounts of land, especially in the Southwest, could probably be made available for this purpose, but a greater problem would be the manufacture and construction of the collection and conversion systems. The manufacture of the collectors, converters, and energy distribution equipment to cover large areas of land would require vast amounts of resources as well as the development of an industry to supply the equipment. The efficiency of solar systems must be high if land use is to be minimized. Estimates of the efficiency of solar-to-electric conversion systems vary from a low of 1 or 2% for the combustion of photosynthetic material to a high of 30% for a thermal conversion system.

As discussed in Section 6, cost estimates for solar conversion systems vary widely. For example, estimates for a solar-to-thermal conversion system vary from \$450/kWe to \$2000/kWe installed capacity for a system providing peaking capacity.

Solar systems large enough to meet total base and variable demand are estimated to have costs that could be five times as much as those previously given. With such a wide variation in predicted costs, it is impossible to make an accurate analysis of the economic competitiveness of solar power.

It was concluded in Section 6 that all proposed solar energy systems, with the exception of thermal collection for buildings, have poor prospects for economically competing with either coal or nuclear systems for at least several decades. The NSF/NASA Solar Energy Panel concluded that the most significant contribution of solar energy will be for the heating and cooling of buildings. The NSF/NASA Panel also estimated that 1% and 20% of electric demand could be met with solar-to-electric conversion in the years 2000 to 2020 respectively. The Panel's estimates have been adopted as the potential contribution of solar-to-electric conversion.

11.1.2.1.6 Geothermal Energy Sources

Geothermal energy may play an important role in meeting future electrical demand, especially in the western one-third of the U.S. The conversion of geothermal heat to electrical energy is less efficient than using the higher temperature and pressure steam produced in nuclear and fossil-fueled boilers, but the absence of fuel costs makes geothermal power attractive if geothermal reservoirs can be developed

economically. Geothermal energy also has alternative uses, such as the production of industrial heat or the desalinization of water.

As Section 6 discusses, there are several types of geothermal systems. Vapor-dominated systems, such as The Geysers which produce live steam, are rare and are not entirely prototypic of future geothermal developments. Liquid-dominated reservoirs are more common and some of these are already under commercial development. Liquid-dominated reservoirs produce a hot, corrosive, liquid brine which is used to produce steam or vapor to drive a turbine. Dry, hot rock systems are the most common, but development work to utilize these resources is just beginning.

The quantity of geothermal energy below the earth's surface in the United States is vast, but there is wide disagreement as to what extent this energy may be utilized in the coming decades. The Hickel panel has estimated that 75,000 MWe could be developed by the year 2000 with a moderate research and development program and that 395,000 MWe could be developed with an accelerated research and development program. The Department of the Interior estimates in the "Final Environmental Statement for the Geothermal Leasing Program," that 75,000 MWe will be produced geothermally by the year 2000.

The Bureau of Mines has made an even lower estimate of 40,000 MWe for the year 2000. The projected geothermal capacities adopted for this study are those proposed in "The Nation's Energy Future." The projected capacities were 80,000 and 200,000 MWe for the years 2000 and 2020, respectively, which is 6% of the projected demand for both of these years. A large number of potential geothermal sites have been identified in the western United States. However, the technology to economically extract energy from many of the sites has not been developed, and until this is done, it will be impossible to determine how much geothermal energy can be counted as a recoverable resource.

The major potential environmental impacts of the use of geothermal energy are in the general areas of surface and groundwater quality impairment as a result of fluid disposal, air emissions such as hydrogen sulfide, noise from drilling and steam venting during operation, uncontrolled blowouts, aesthetic impact, land subsidence from fluid withdrawal or reinjection, land use, and damage to vegetation and wildlife. The environmental impact of geothermal generation is largely restricted to the generating site and its immediate surroundings--a contrast with fossil- or nuclear-fueled generation, for which impacts occur at several locations (mines,

processing plants, disposal sites). The different types of geothermal systems present different environmental impacts. Because of the relatively pure fluid in the vapor-dominated reservoirs, the fluid-disposal problem is relatively small compared with that of the hot-brine systems, whose high salinity represents a potentially serious environmental impact. The environmental impact of hot-rock utilization has not yet been thoroughly evaluated and cannot now be fully defined.

11.1.2.1.7 Organic Wastes

As discussed in Section 6, the economics of using organic wastes for power generation have significantly improved in the past few years because of: (1) the rise in fossil fuel prices; and (2) the increasingly difficult problem of waste disposal. The limitation on the use of organic wastes for power generation is that there is simply an insufficient quantity of collectible material to make a large impact on energy supply. The Bureau of Mines has estimated that 136.3 million tons of potentially collectable organic wastes were generated in 1971. If all these wastes had been converted to electricity at the national average conversion efficiency of 32%, the power production for 1971 would have been 205 billion kWhr or nearly 13% of the national demand. The EPA has estimated that urban waste collection will increase at a rate of 3.4% per year until 1980. If the quantity of collectible wastes would increase by 2.4% per year until the year 2000, and if it were possible to utilize all collectible wastes for power production, wastes could produce 550 billion kWhr of power, or about 5% of the demand in the year 2000. After the year 2000, it might be expected that conservation measures would stabilize the amount of waste packaging materials and that, because of worldwide pressures on food, more grain would be consumed directly, thus reducing animal wastes. If collectable wastes held steady at the year 2000 level, they could supply only 2% of the year 2020 power demand. Complete utilization of organic wastes does not necessarily mean total conversion to power, because they could also be converted into synthetic petroleum.

11.1.2.1.8 Controlled Thermonuclear Fusion

Controlled thermonuclear fusion offers the possibility of virtually unlimited energy resources, because the deuterium contained in the oceans would serve as its fuel. Fusion reactors could also be fueled by breeding tritium from lithium, but even using this more limited resource, fusion could meet projected electricity demand for centuries.

A fusion reaction occurs in a fully ionized gas called a plasma. The central problem at present is to confine a reacting fusion plasma at conditions of density,

temperature, and confinement time sufficient to produce a self-sustaining fusion chain reaction. A controlled self-sustaining fusion reaction has yet to be achieved, but the AEC is supporting programs that are exploring two separate methods to reach this goal. Magnetic confinement techniques to produce a suitable plasma have been pursued since 1951, and currently, three different magnetic confinement concepts are being studied. A newer approach, using a pulsed laser to heat and compress a plasma to the necessary conditions, has been pursued since 1962. Both concepts may reach the important milestone of a controlled self-sustaining reaction by 1980. If this milestone is met, it may be possible to build a demonstration net-energy-producing fusion reactor in the 1990's and to achieve commercial introduction of a fusion reactor in the next century. Although scientific feasibility of a practical, controlled fusion system has not been demonstrated, the estimate from "The Nation's Energy Future" that 8% of the year 2020 electrical demand could be met with fusion power has been adopted as the potential contribution of fusion.

11.1.2.2 Alternative Strategies for Future Electric Generation Systems

Future electrical energy needs will be fulfilled by generating systems composed of various energy sources and conversion systems. The use of any particular strategy for the use of the available generating options depends on the energy demand and the relative costs of the options. As used here, the costs include both internal expenses reflected in the power cost and external, uncompensated expenses incurred as a result of environmental or human impacts.

Another important element of any strategy is the possibility of altering energy needs through conservation. As indicated in Section 6, there are a number of possibilities in the area of conservation. Reductions in electric energy demand are considered in the strategy alternatives which follow.

11.1.2.2.1 Strategy Based on Present Technology

If the Nation chooses to follow a strategy based on present technology (with anticipated improvements) to meet its future energy demand, the options available consist mainly of nuclear fission converter reactors, fossil-fueled power plants, and hydro-electric plants. The technological status and resource base for these systems is adequate to make this a feasible but not necessarily the most economic option through at least the first few decades of the next century.

An assumed distribution of electric energy production from the various conventional energy sources is shown in Table 11.1-2 for the years 2000 and 2020.

Table 11.1-2
DISTRIBUTION OF ENERGY PRODUCTION
(10¹² kWhr/year)

	Year	
	2000	2020
Nuclear	8.0	20.0
Fossil	2.1	7.1
Hydro	<u>0.5</u>	<u>0.5</u>
Total	10.6	27.6

The market penetration of nuclear plants has been limited to about 60% of the capacity. This assumption is consistent with the base case in the cost-benefit analysis in Section 11.2 with no LMFBR. In cases of free nuclear--fossil competition, nuclear plants would capture a larger fraction of the market on the basis of economics.

11.1.2.2.2 Strategy Based on Potential Energy Sources

If potential energy sources, such as solar, geothermal, organic wastes, and controlled fusion are included in the energy mix at levels estimated to be attainable under optimistic conditions, the estimated distribution of energy sources is shown in Table 11.1-3 for the year 2000, and in Table 11.1-4 for 2020.

As illustrated in Table 11.1-3, the potential sources might be capable of supplying up to 13% of the year 2000 base-case electricity demand, although it is by no means assured that such sources will be technically available and economically viable at that time. If it is assumed that conservation is effective in reducing the demand by 20%, the potential sources could account for about 16% of the reduced demand. The arbitrary (but conservative) assumption here is that energy conservation is applied only to conventional sources, and that the absolute contributions of other sources remain constant. Thus, conventional sources would be needed to produce 7.1 to 9.2 trillion kWhr and the required conventional capacity would be equivalent to about 1700 plants of 1000 MWe each. These would be primarily coal and nuclear converter reactors.

Table 11.1-3
ENERGY SOURCES FOR ELECTRICITY PRODUCTION
IN THE YEAR 2000 WITHOUT THE BREEDER

	With Base-Case Demand		With 20% Reduction By Conservation	
	Trillion kWhr	Percent of Demand	Trillion kWhr	Percent of Demand
Energy Demand	10.60	100	8.48	100
Energy Sources				
Potential				
Solar	0.21	2	0.21	2.5
Geothermal	0.63	6	0.63	7.4
Organic Wastes	0.54	5	0.54	6.4
Fusion	0	0	0	0
Subtotal	1.38	13	1.38	16.3
Conventional ^a	9.22	87	7.10	83.7
TOTAL	10.60	100	8.48	100

^aNuclear, coal, hydroelectric.

By 2020 (Table 11.1-4), energy sources might be capable of producing 20% of the electricity demand or, if conservation reduces total demand by 20%, the potential sources might provide 26% of energy generation. This would leave 16 to 22 trillion kWhr to be supplied from coal, nuclear converters, and hydroelectric; the required conventional generating capacity would be equivalent to 3000 to 4200 plants of 1000 MWe each. In the event that the total energy demand in 2020 were reduced 50% below the base-case projection, this same energy contribution by the potential system would provide 42% of the lower demand. This would leave about 8 trillion kWhr of electric energy to be generated by conventional sources.

Table 11.1-4
ENERGY SOURCES FOR ELECTRICITY PRODUCTION
IN THE YEAR 2020 WITHOUT THE BREEDER

	With Base Case Demand		20% Reduction		50% Reduction	
	Trillion kWhr	Percent of Demand	Trillion kWhr	Percent of Demand	Trillion kWhr	Percent of Demand
Energy Demand	27.6	100	22.1	100	13.8	100
Energy Sources						
Potential						
Solar	1.40	5	1.40	6.3	1.40	10
Geothermal	1.60	6	1.60	7.3	1.60	12
Organic Wastes	0.54	2	0.54	2.4	0.54	4
Fusion	2.21	8	2.21	10.0	2.21	16
Subtotal	5.75	21	5.75	26	5.75	42
Conventional ^a	21.85	79	16.35	74	8.05	58
TOTAL	27.6	100	22.1	100	13.8	100

^aNuclear, coal, hydroelectric.

It is noted again that the above figures make the very conservative assumption that the energy generated by potential systems is not reduced by the conservation measures, thereby causing the conventional sources to absorb all of the reductions. The more reasonable event to be expected is that all the energy sources would generate less energy in the energy-conservation cases, and that the reductions would be distributed more or less proportionately to all energy sources. This is the assumption that was used in deriving the energy consumption projections used in the conventional cost-benefit analysis, leading to a base case with 20 trillion kWhr generated by nuclear power in 2020. The strategy distribution of electric energy generation for nuclear and nonnuclear plants is shown in Table 11.1-5.

Table 11.1-5
BASE-CASE ENERGY SOURCE DISTRIBUTION
FOR ELECTRIC ENERGY GENERATION
(trillions of kilowatt hours)

	Year 2000	Year 2020
Nonnuclear	2.6	7.6
Nuclear ^a	8.0	20.0
Energy Demand	10.6	27.6

^aNuclear market penetration is held constant, with or without the LMFBF.

Cases corresponding to 20 and 50% reduction in total energy demand led to nuclear generation of 16 to 10 trillion kWhr, respectively, in the year 2020. Note that nonnuclear and nuclear generation were proportionally reduced by the corresponding electric energy demand fraction. This assumption is more representative than the restrictive assumption that energy conservation is applied only to conventional sources.

The nonnuclear energy source distribution shown in Table 11.1-5 includes fossil-fired plants, solar converters, geothermal plants, controlled thermonuclear plants, and plants fired by organic wastes. Analysis of market penetration on the basis of economics shows that nuclear fission converters have a competitive edge on fossil-fired plants. Thus, the major portion of the nonnuclear energy sources will probably be low-cost power plants using new technology. If suitable low-cost technology does not evolve, then nuclear sources will probably penetrate beyond the estimates in Table 11.1-5.

Plants generating electric energy from nuclear sources are represented in the cost-benefit analysis by LWRs, HTGRs, and LMFBRS. Nuclear plants are allowed to compete within the nuclear source market envelope, with or without the LMFBRS. Realistically, introduction of the LMFBRS decreases all nuclear-generated power cost and would probably increase the market penetration of nuclear power.

The nuclear fission converter reactors built through the year 2000 to meet the energy production shown in Table 11.1-5 would require about 5.5 million tons of U_3O_8 to be mined during their operating lifetimes of about 30 years. The total domestic uranium resources consisting of ores costing \$30/lb or less are estimated to be about 2.4 million tons of U_3O_8 . The supply of 5.5 million tons of U_3O_8 will, therefore, require mining of high cost ores with low uranium concentrations if large quantities of relatively high grades are not found. As discussed previously, this will lead to substantial increases in the cost of generating electricity, and will impose a heavy penalty in terms of occupational hazards of large-scale mining operations and the environmental impacts of the extensive mining and material processing operations. These impacts and hazards can be reduced in the near term and eliminated in the long term by the deployment of the breeder reactor.

As discussed in Section 11.1.2.1.4, there are several potential types of breeder reactors. Each type of breeder reactor has its particular advantages and disadvantages. The economic effects and environmental effects of the alternative breeder reactors are generally similar. However, the potential for early entry

into the nuclear power industry, the excellent heat-transfer properties of sodium, the low system pressure at elevated temperatures, and the good prospect for inherent safety and reliability were all major factors in the selection of the LMFBR for the priority U.S. breeder program and thus, the breeder reactor type examined in the cost-benefit analysis. Also, introduction of other potential breeders such as the GCFBR and MSBR would at best provide a negligible increase in benefits as they would be available when the advanced fueled LMFBRs are available and the system is close to fissile fuel self-sufficiency.

Thus, the system mixes selected for examination by the conventional cost-benefit methodology reflect estimates of market penetration which might optimistically be expected of the potential energy source. Also, the energy demands reflect energy conservation to an extent that many would consider to be optimistic, especially since it was assumed that this energy conservation would directly reduce electric energy demand, when in fact there may be strong motivation to substitute coal and nuclear-generated electricity for oil and natural gas wherever possible. The potential energy sources and energy conservation were not used as "alternative systems" directly within the cost-benefit model. They were, however, given their projected market share as a reduction in the demand left to be satisfied by the breeder and nonbreeder systems treated by the model. In this manner, the potential systems and energy conservation were granted an optimistically high share of the projected energy demand, irrespective of economic tradeoffs. It is possible that some of the potential energy systems would not be able to compete economically for a conservative approach, since it restricts the LMFBR economic competition to a reduced portion of the total electric energy market.

The following sections will discuss the environmental impacts and internalized costs of energy supply strategies aimed at meeting the fossil--nuclear portion of the electrical energy demand.

11.1.3 Environmental Cost-Benefit Analysis of the LMFBR-External Costs

11.1.3.1 Cumulative External Impacts of Alternative Strategies of Electrical Energy Supply

The unit-impact information pertaining to the external impacts (as opposed to internal costs included in the price) of electrical energy production (see Section 9) can be used to calculate effects for certain mixes of generation modes and fuel cycles in meeting future expanding demands for electricity. The general approach is to examine alternate strategies (mixes of fossil and nuclear plants) for supplying electricity

over the time interval 1974 to 2020. The number of strategies considered was limited relative to the large number of cases treated in Section 11.2. The considerations which tend to restrict the use of nuclear and fossil units and influence probable mixes are discussed in Section 11.1.3.

Alternative advanced systems such as solar, fusion, etc., have not been treated in this section, because their associated uncertainties are much greater. Impact coefficients are not known, the introductory timing is speculative, and the amount of load to be assigned to each is uncertain. This section was, therefore, limited to the three nuclear--fossil strategies described in Section 11.1.2.2.

Three expansion strategies were selected to determine the bounds of impacts to be expected from fossil and nuclear plant mixes. The mixes range from no new nuclear (reliance on coal) to large-scale reliance on the LMFBR. This selection should provide a basis for the comparison of impacts resulting from the selection of a basic energy system, including one which uses the LMFBR.

Though assessment of these impacts is subject to many uncertainties, the values calculated should indicate the general magnitude of effects.

The three basic system expansion strategies are as follows:

Case A. The LMFBR is assumed to be developed and widely deployed by the latter part of the 1970 to 2020 period. During the period beyond about the year 2000, essentially all new reactors constructed are LMFBRs. This case corresponds approximately to case 3 in the cost-benefit analysis in Section 11.2. The total system nuclear electrical capacity and its distribution according to plant type are shown in Figure 11.2-27.

Case B. It is assumed that the LMFBR is not developed, but that nuclear fission technology continues to be deployed in the form of LWRs and HTGRs. In this case, the LWR and HTGR provide the capacity which was supplied by the LMFBR in Case A. This case corresponds to Case 1 in the cost-benefit cases treated in Section 11.2. The mix of LWR and HTGR plants was selected by economic optimization, shown in Figure 11.2-25.

Case C. It is assumed that no additional nuclear plants are constructed beyond those now committed (1974). All of the new capacity committed beyond this date is assumed to be in the form of conventional coal-fired units. This case was not calculated in the cost-benefit studies.

In all these cases, the same total energy is being supplied, namely that amount assumed to be provided by nuclear plants in the base cases of the cost-benefit analysis. The impacts are calculated for the period 1974 to 2020, including commitments beyond 2020 to run all plants to end of life.

Since the impacts treated in this section have not been subjected to present-value discounting, the total planning period is divided into three intervals: mid-1974 to the year 2000; from year 2000 to 2020; and from 2020 to end of all plant lives. The total impacts are shown for each of these time periods, allowing the reader to weigh the time dependence of the relative impacts. Impacts for comparative "units" of electricity for each specific electric energy generating option considered was given in Section 9.

11.1.3.2 Cumulative Human Effects

The projected cumulative health and safety effects of the three cases are presented in Table 11.1-6, for both occupational and public population groups. These results indicate that if a commitment was made that all future plants would be fossil fueled (case C), the cumulative "external" impacts would be significantly greater than those associated with the nuclear-fueled mixes in either case A or B. As noted previously, this is a consequence of the very large-scale extraction and transportation activities required to support coal-fired electric generation. Some lessening of the magnitudes of these impacts will undoubtedly occur in the future, associated with technological changes in the form of increased automation of coal mining, handling, greater use of coal slurry pipelines, etc. The tables show relatively little difference in impacts of producing electricity from the LMFBR or from a combination of LWRs and HTGRs (compare cases A and B). Case A shows slightly smaller impacts, but the apparent reduction is not significant within the accuracy of the basic data.

11.1.3.3 Fuel Resource Requirements

Table 11.1-7 summarizes the cumulative fuel resource requirements for the three cases treated. The fuel requirements include forward commitments to support those plants which are operating in the years shown.

Table 11.1-6
CUMULATIVE HUMAN IMPACTS OF EXPANDING
ELECTRICAL ENERGY SUPPLY (1974-2020)

	Impacts Associated with Energy System Operation During 1974-2020			Impacts Associated with Energy System Operation During 2000-2020			Forward (Post-2020) Commitments Due to Plants Existing in Year 2020			Total Impacts Associated With Energy System Operation 1974-2020, plus Forward Commitments		
	Case A	B	C	A	B	C	A	B	C	A	B	C
Occupational Accidents												
Fatalities (thousands)	11	11	18	16	19	60	17	19	67	45	50	145
Nonfatal Injuries (thousands)	506	514	827	770	890	2645	809	940	2980	2065	2345	6452
Man-Days Lost (millions)	96	97	161	143	165	522	146	171	584	385	433	1267
Public Injuries in Fuel Transportation												
Fatalities (thousands)	5	5	9	8	8	31	8	8	35	21	21	75
Nonfatal Injuries (thousands)	12	12	20	17	17	68	20	20	76	49	49	164
Man-Days Lost (millions)	32	32	59	50	50	97	51	51	221	133	133	377
Coal Workers Pneumoconiosis												
Simple CWP (thousands of cases)	6	6	10	8	8	34	8	8	38	22	22	82
(millions of man-days lost)	6	6	10	8	8	34	8	8	38	22	22	82
Acute CWP (cases)	50	50	100	90	90	340	80	80	380	220	220	820
(millions of man-days lost)	0.3	0.3	0.6	0.5	0.5	2	0.5	0.5	2	1	1	5
Radiological Health Effects												
Occupational (thousands of malignancies)	1.0	1.0	0.350	3.3	3.9	0.320	3.9	4.7		8.2	9.6	0.67
(millions of man-days lost)	6	6	2	20	24	2	24	28		50	58	4
Public (malignancies)	14	15	5	42	54	1	48	72		104	141	6
(millions of man-days lost)	0.1	0.1	~0	0.3	0.3	~0	0.3	0.4		1	1	~0
Total Man-Days Lost (millions)	140	141	233	222	248	657	230	259	845	592	648	1735

Notes: Case A - with LMFBR; Case B - no LMFBR; Case C - no new nuclear. Calculated values are shown to several digits for comparison purposes only. All values have considerable uncertainties, and absolute accuracy should not be implied by numerical precision.

The most significant factor which emerges from the comparison of physical resource commitment is the much smaller fuel requirement when the breeder is included. The emphasis of the scale of fuel extraction becomes more significant when one considers the associated land disturbances.

11.1.3.4 Discussion of Overall Impacts

One of the principal advantages claimed for the LMFBR is that it helps conserve uranium resources. This advantage is shown on Table 11.1-7 by comparing the U_3O_8 requirement in case B (without the LMFBR) with that in case A (with LMFBR). The LMFBR reduces the amount of U_3O_8 committed through the year 2000 by about one million tons, and the commitment through the year 2020 is reduced by over 8 million tons of U_3O_8 .

If coal were selected as the primary fuel for electricity generation (case C), instead of nuclear fuel, it would be necessary to commit about 340 billion tons of coal to fuel the power plants through the year 2020. The total amount of coal in the United States recoverable by current technology is estimated to be about 400 billion tons (see Section 6).

The reduction in ore requirements associated with the use of nuclear fuels, and emphasized in the breeder case, has an attendant significant reduction in health hazards: occupational fatalities would be reduced by about 100,000; public fatalities in fuel transportation would be reduced by about 55,000; and total man-days lost would show a reduction in the range of one billion during the years from 1974 to 2020.

Table 11.1-7

FUEL RESOURCES COMMITTED FOR ELECTRICAL GENERATION
(INCLUDING CUMULATIVE USAGE AND FORWARD COMMITMENTS)

Case	Year 2000			Year 2020		
	A	B	C	A	B	C
Fuel Commitment						
Uranium (millions of short tons of U_3O_8)	4.4	5.5	0.8	4.4	12.7	0.8
Coal (billions of short tons)	32	32	97	90	90	337
Oil (billions of barrels)	9	9	9	9	9	9
Gas (trillions of standard cubic feet)	102	102	102	102	102	102

Notes: Case A - with LMFBR; Case B - no LMFBR; Case C - no new nuclear.

11.2.1 Introduction

A cost-benefit analysis of the U.S. breeder reactor program was performed as part of the Environmental Impact Statement. This analysis consisted of forecasts of the most probable development of the nuclear power economy over a planning horizon extending to the year 2020. The analysis showed that the liquid-metal fast breeder reactor (LMFBR) can produce substantial dollar benefits for the U.S. economy by providing low-cost electrical energy. Simultaneously, the amount of uranium ore and separative work required is substantially reduced, and, in fact, the major part of the dollar benefit is due to the lower demand for these items. Finally, the study showed that the introduction of the LMFBR will eventually allow the U.S. electrical power economy to become independent of possible shortages of mined uranium, or any other depletable fuel resource, and to provide essentially unlimited low-cost energy.

The basic model used in the cost-benefit analysis was a linear program with an objective function designed to minimize the total cost of electrical energy over the planning horizon. Within this model, power plants compete with each other for a share of the market based on their capital cost, fuel cost, and fuel supply. The linear program utilizes this competition to select a growth pattern which minimizes the total energy cost over the planning horizon. Over certain time periods, plant construction rates were sometimes specified, rather than allowing free competition. This was done in order to be consistent with other AEC studies--namely, WASH-1139, Nuclear Power 1973-2000. Also, when a new reactor type--such as the LMFBR--was introduced, the plant construction rate was initially limited by the rate of increase of new manufacturing capacity.

The principal difference between this cost-benefit study and previous cost-benefit studies is that the basic input data have appreciably changed. Fossil fuel costs, capital costs for nuclear and fossil power plants, the estimated cost of obtaining uranium ore from shale, separative work costs, and projected AEC research and development costs for the LMFBR program are all higher; finally, and of no less importance, LMFBR core designs have changed. Because of this, a new cost-benefit study was required for this Environmental Impact Statement.

11.2.1.1 Summary of Benefits

The dollar benefit and the development cost* associated with the LMFBFR program are shown in Figure 11.2-1. The benefit is simply the reduction in total power cost over the planning horizon from 1970 to 2020 obtained by introducing the LMFBFR, with future costs properly discounted using present value analysis. At a discount rate of 7.5%, the development cost for the LMFBFR program is approximately 5 billion dollars, while the benefit is 54 billion dollars for base conditions. When discounted at a rate of 10%, the development cost is still approximately 5 billion dollars, while the benefit is 19 billion dollars. In either case, the benefit is substantially greater than the development cost. The development cost is relatively insensitive to the discount rate, since this cost is incurred early in the planning period. However, the benefit is accrued throughout the planning period--particularly in the latter part--and hence is very sensitive to the discount rate. This is readily apparent when considering the undiscounted costs and benefits, which are about \$8.4 billion and \$1.65 trillion, respectively, for base conditions.

The benefit is due primarily to the lower nuclear fuel cost obtained by introducing the LMFBFR; particularly, by the reduction in the requirements for uranium ore and separative work capacity. This is illustrated in Figure 11.2-2. Without the LMFBFR, the cumulative U_3O_8 requirement to the year 2020 is 6.3 million tons, while the cumulative U_3O_8 requirement with the LMFBFR is 2.6 million tons. Furthermore, without the LMFBFR, U_3O_8 will continue to be mined at an ever increasing rate, while with the LMFBFR, the annual ore requirement becomes insignificant after about the year 2015.

Separative work requirements are also shown in Figure 11.2-2. Without the LMFBFR, an annual separative work capacity of 450 million separative work units (SWU) is required in the year 2020, while with the LMFBFR, the maximum annual separative work capacity requirement is only 95 million SWU. Also, separative work requirements continue to increase without the LMFBFR; with the LMFBFR, the annual rate of 95 million SWU is attained in the year 2000 and separative work requirements decrease continuously beyond the year 2000.

Finally, nuclear fuel costs in the year 2020 are shown in Figure 11.2-2. Without the LMFBFR, the light water reactor (LWR) fuel-cycle cost has increased to 6.4 mills/kWhr, exclusive of inflation. This is primarily due to rising uranium costs. Though not shown in Figure 11.2-2, the U_3O_8 cost in this case has risen to about \$100/lb. With the LMFBFR, the uranium-fueled LWR fuel-cycle cost is stabilized at about 3.0 mills/kWhr, and the LMFBFR fuel-cycle cost is 0.7 mill/kWhr. Indeed, it is just this

*All benefits and costs are in 1974 dollars unless designated otherwise.

DOLLAR BENEFITS FROM THE LMFBR
Figure 11.2-1

11.2-4

URANIUM ORE MINED
TO YEAR 2020
(MILLIONS OF TONS
OF U_3O_8)

WITH LMFBR

2.6

WITHOUT LMFBR

6.3

SEPARATIVE WORK CAPACITY
REQUIRED TO YEAR 2020
(MILLIONS OF SEPARATIVE
WORK UNITS PER YEAR)

95

450

NUCLEAR FUEL COSTS
IN YEAR 2020
(MILS/KWH)

LMFBR

0.7

LWR

3.0

LWR

6.4

INTERPRETATION OF LMFBR BENEFITS

Figure 11.2-2

difference in fuel-cycle costs that is directly responsible for the LMFBR dollar benefit. Without the LMFBR, the LWR total power cost is about 16 mills/kWhr in the year 2020, and so the fuel cost is about 40% of the total power cost in this case.

The information presented in Figures 11.2-1 and 11.2-2 is for an LMFBR introduction date of 1987 for base conditions. If the LMFBR introduction date is changed from 1987 to 1991, the cumulative U_3O_8 requirement would increase to 3.4 million tons, and the maximum annual separative work capacity required would increase to 140 million SWU. Note that this is a 30% increase in the amount of U_3O_8 required and about a 45% increase in the amount of separative work required. At a 7.5% discount rate the benefits decrease by about \$7 billion and at 10% by about \$3 billion. Hence there is a strong incentive to introduce the LMFBR at the earliest possible date.

An analysis of the reduction in the electrical power cost attributable to the LMFBR for base conditions by cost category is shown in Figure 11.2-3. Note that the benefits are obtained primarily from the reduction in the requirements for U_3O_8 and separative work.

A nuclear industry growth pattern that might be considered typical of those obtained in this study is shown in Figure 11.2-4. Figure 11.2-4 shows the reactor construction rate in units of 10^9 gigawatts (GW) per year as a function of time throughout the planning horizon. Note that the LWR is the primary power plant throughout the 1980's and into the 1990's. However, the LMFBR is being built at an increasing rate throughout the 1990's, and it becomes the predominant power plant in the late 1990's. A plutonium-fueled LWR emerges in the decade following the year 2010, and consumes the surplus plutonium from the LMFBRs. In this period, in fact, any low-cost plutonium-fueled reactor would be suitable--such as an LMFBR without a blanket.

11.2.1.2 Basic Input Data and Assumptions

A cost-benefit study which evaluates the relative merits of a long-range program requires estimates of future costs, demands, and availabilities. In this study, estimates were required for: the electrical energy demand, the U_3O_8 and separative work price, the nuclear plant capital cost, the available LMFBR core designs, and the discount rate. The values used in this study are discussed in the following paragraphs.

11.2-6

THE REDUCTION IN ELECTRICAL POWER COST PRODUCED BY THE LMFBR BY MAJOR CATEGORY DISCOUNTED AT 10%

Figure 11.2-3

11.2-7

PROJECTED NUCLEAR INDUSTRY GROWTH PATTERN

Figure 11.2-4

The current annual electrical energy demand in the U.S. is about 1.7×10^{12} kWhr, and the historical rate of increase has been about 6 to 8% per year--with even higher rates occurring in recent years. The future electrical energy requirement considered most probable in this study was based on a declining growth rate. The initial rate of increase was 7.8% per year, and this rate was assumed to decline continuously to 3.7% per year in the year 2020. The average rate of increase from 1974 to 2020 in this case was 6.2% per year, and the electrical energy requirement in the year 2020 was about 28×10^{12} kWhr. This projection, labeled "base" or reference case, is illustrated in Figure 11.2-5. Also shown in Figure 11.2-5 are three other projections used in this study. Each projection assumes a continuously declining electrical energy growth rate, with an initial rate of 7.8% per year. The projection labeled "large" assumes an electrical energy growth rate which declines continuously to 4.2% per year in the year 2020. The corresponding annual energy requirement in the year 2020 is about 34×10^{12} kWhr, which is 20% above the base value. The projection labeled "small" assumes an electrical energy growth rate which declines continuously to 3.0% per year. The annual energy requirement is about 22×10^{12} kWhr in the year 2020, which is 20% below the base value. The projection labeled "very small" assumes an electrical energy growth rate declining to 2.8% per year. The annual energy requirement is about 14×10^{12} kWhr in the year 2020, which is one-half the base value.

It is important to note that all the projections assume a declining growth rate, and hence the benefits described later in this report are not contingent upon a continuation of the long-term historical electrical energy growth rate.

In this study, approximately 30% of the annual energy requirement--which is approximately 40% of the operating capacity--was arbitrarily assigned to fossil, solar, geothermal, fusion, and other nonfission power systems. That is, fission plants were allowed to compete for only about 60% of the generating capacity. This assumption is considered conservative, because the arbitrary assignment of 40% of the generating capacity to other power systems cannot necessarily be justified on an economic basis.

The estimates of the U_3O_8 marginal price versus cumulative supply used in this study are shown in Figure 11.2-6. Three estimates were used: small, base or reference, and large. The small estimate corresponds to approximately 2-1/2 million tons of U_3O_8 available before the mining of shale is required, the base estimate corresponds to 4 million tons available before shale must be mined. The uranium resource estimates shown in Figure 11.2-6 are based on a continuous and systematic evaluation by

11.2-9

PROJECTED ELECTRICAL ENERGY REQUIREMENTS

Figure 11.2-5

11.2-10

MARGINAL PRICE OF U_3O_8 VERSUS CUMULATIVE SUPPLY

Figure 11.2-6

the AEC of data collected by both industrial organizations and government agencies. While they do not necessarily reflect the ultimate availability of uranium in the U.S., they do indicate the amount of uranium that can be reasonably inferred to be available using current information. The uranium prices developed are based on projected costs and the estimated fair rate of return on investment. They can be considered as the minimum price required to maintain a viable industry. Actual marketplace prices can be much higher depending on such factors as the supply-and-demand relationship, prices for competing sources of electric energy, and the number of major suppliers of uranium. Throughout this study, it was assumed that foreign demand for uranium would be approximately equal to foreign supply, and that the U.S. power economy would rely on uranium mined in the U.S.

The separative work price in this study was assumed to be constant at \$36/SWU. This assumption is conservative, since separative work prices will probably increase as private industry provides the additional capacity. The cost of separative work has already risen above the assumed \$36/SWU value.

The nuclear plant capital cost estimates used in this study are shown in Figure 11.2-7. The capital costs are in 1974 dollars, that is, inflation is excluded. The LWR capital cost was assumed to be \$420/kWe from 1974 to 1990, and \$368/kWe from 1990 to 2020. A plant size change from 1300 to 2000 MWe was assumed to occur in 1990, and the capital cost change in 1990 was produced simply by this change in plant size. The HTGR and LWR capital costs were assumed to be essentially identical throughout the study. The LMFBR was initially introduced at a capital cost of \$520/kWe, that is, at a cost differential of \$100/kWe with respect to the LWR. For the most probable case, the LMFBR-LWR capital cost differential was assumed to decrease linearly to about \$70/kWe in the year 1990. This decrease is attributable to the learning process associated with the introduction of a new plant type, that is, to the construction of similar plants in a repetitive manner which produces increased efficiency and reduces unit costs. In the year 1990, the size of the LMFBR was also assumed to increase from 1300 MWe to 2000 MWe, and the LMFBR-LWR capital cost differential was assumed to continue the linear decrease to a differential of zero in the year 2000. Beyond the year 2000, the LMFBR and LWR were assumed to have equal capital costs. Here, as with the uranium price projections, the plant capital cost projections do not reflect marketplace conditions, although capital prices are not expected to be as vulnerable as fuel prices to large changes from the projected costs.

Two variations of the LMFBR capital cost projections were considered; these costs are shown in Figure 11.2-7. The first variation assumed that the LMFBR-LWR capital

11.2-12

REACTOR CAPITAL COSTS VERSUS TIME

Figure 11.2-7

cost differential was \$50/kWe in the year 2000, and that this differential persisted until the year 2020. The second variation assumed that the LMFBR-LWR capital cost differential was \$100/kWe in the year 2000, and that this differential also persisted until the year 2020.

The characteristics of the LMFBR core designs used in this study are given in Table 11.2-1. Four design concepts were used: one with early oxide fuel, one with advanced oxide fuel, and two with advanced carbide core models. The early oxide was assumed to be available in 1987, the advanced oxide in 1991, and the advanced carbide models in 1995. The principal difference between the three core designs is that each one in sequence has a higher breeding ratio and a shorter doubling time.

The first design in the sequence, the early oxide, is based on the FFTF fuel assembly design. Two advances beyond FFTF technology were assumed: a fuel smear density of 90%, and an average linear power rating of 9 kW/ft. The breeding ratio for the early oxide design is 1.15 and the simple doubling time--including the effect of the out-of-reactor inventory--is 28 years. The advanced oxide design is based on a core design technology substantially beyond that of the FFTF. In particular, it assumes that the stainless steel swelling problem has been solved, and also that the conservatism in the FFTF fuel assembly design has been found to be unnecessary. The principal advances contained in this advanced oxide design are: a fuel smear density of 90%; an average linear power rating of 12 Kw/ft; a cladding thickness of 10 mils; a duct wall thickness of 60 mils; and a duct clearance of 40 mils. The breeding ratio for this design is 1.25, and the simple doubling time is about 12 years. Finally, and quite obviously, the advanced carbide core designs assume the development of a reliable carbide fuel. Though little is known about the behavior of a carbide fuel under actual LMFBR operating conditions, it is generally felt that a carbide core could be designed to produce a high breeding ratio. The breeding ratios of the carbide designs used in this study were 1.36 and 1.46, and the simple doubling time was about seven years.

Currently, LMFBR core design is in a state of transition. Design modifications which will produce a shorter doubling time are being examined. As irradiation experience is obtained in the FFTF, the feasibility of these modifications will be assessed, and also the conservatism inherent in the FFTF fuel design will be evaluated. Thus, it should be possible to substantially improve LMFBR performance characteristics beyond FFTF and the demonstration plant, indeed, it would be unreasonable to assume otherwise.

Table 11.2-1
LMFBR Design Characteristics

Characteristics	Early Oxide	Advanced Oxide	Advanced Carbide	
			Large Pin	Small Pin
Power (MWe)	1300	2000	2000	2000
Thermal Efficiency (%)	40	40	40	40
Introduction Date	1987	1991	1995	1995
Average Core Discharge Exposure (MWd/kg)	110	110	110	110
Average Blanket Discharge Exposure (MWd/kg)	6	6	6	6
Core Power Density (kW/kg metal)	182	221	120	243
Average Linear Power Rating (kW/ft)	9	12	19	19
Maximum Linear Power Rating (kW/ft)	16	18	31	30
New Yield Fissile Plutonium (kg/MWe-year)	0.141	0.247	0.381	0.303
Breeding Ratio	1.15	1.25	1.46	1.36
Simple Doubling Time ^a (year)	28.0	12.5	7.4	7.6

^aBased on a one year out-of-reactor time.

Finally, four discount rates were used in this study: 0, 5, 7-1/2, and 10%. The 10% rate was considered to be the reference value, and all the results obtained during the course of this study are reported at 10%. However, it is important to note that the study was performed in a deflated sense, that is, inflation was excluded when calculating future costs. Thus, the discount rate should be indicative of the long-term true cost of money--exclusive of inflation. Since a long-term real-money cost of 10% may be high, a discount rate of 7-1/2% may be more realistic. It has been suggested that an appropriate discount rate would be the cost of capital for the utility industry, which is about 5 to 6%. Others have, in turn, suggested that an appropriate discount rate, excluding taxes, for Federal Government research and development, is about 6%. Because of this, the dollar benefits in some cases are also reported at 7-1/2%.

11.2.1.3 Results

The results of the cost-benefit study are tabulated in summary form in Figures 11.2-8 through 11.2-11. Unless otherwise noted, the dollar benefits shown are discounted at a rate of 10%. Figure 11.2-8 shows the benefits obtained from the LMFBR as a function of the availability of U_3O_8 , the demand for energy, and the LMFBR introduction date. For the cases in this figure, the construction schedule for all nuclear plants was specified to the year 2000 in order to be consistent with WASH-1139 (1972). Beyond the year 2000, the nuclear plants compete for a share of the market on an economic basis. Three levels of U_3O_8 availability and energy demand are considered: small, base, and large. The nomenclature for all cases described in this section is identical to that in the previous section. Finally, three LMFBR introduction dates are considered in Figure 11.2-8: 1985, 1987, and 1991.

For the case in which the LMFBR is introduced in 1987 and the uranium supply and energy demand are the base projections, the LMFBR program produces a benefit of \$19 billion. If the uranium supply is large, the benefit is reduced to \$12 billion, while the benefit is increased to \$31 billion if the uranium supply is small. If the demand for energy should prove to be small, the benefit is reduced to \$14 billion, while the benefit is increased to \$26 billion if the demand for energy should prove to be large. Delaying the introduction date for the LMFBR reduces the benefits by \$1/2 to \$1-1/2 billion per year of delay, with the exact value depending upon the uranium supply and the energy demand. The most representative value is three-quarters of a billion dollars per year of delay.

*General Electric, Comment Letter 64, p. 2; P. S. VanNort, Testimony, pp. 336, 337.

11.2-16

LMFBR BENEFITS IN BILLIONS OF DOLLARS USING A SPECIFIED CONSTRUCTION SCHEDULE WITH A 10% DISCOUNT RATE.

Figure 11.2-8

SENSITIVITY OF DOLLAR BENEFITS TO VARIATIONS IN THE BASIC INPUT DATA
WITH A 10% DISCOUNT RATE FOR 1987 LMFBR INTRODUCTION

Figure 11.2-9

11.2-18

SENSITIVITY OF DOLLAR BENEFITS TO LARGE VARIATIONS IN ENERGY DEMAND AND LMFBR CAPITAL COST
WITH A SPECIFIED CONSTRUCTION SCHEDULE

Figure 11.2-10

11.2-19

SENSITIVITY OF DOLLAR BENEFITS TO LARGE VARIATIONS IN ENERGY DEMAND AND LMBFR CAPITAL COST
 WITH NO CONSTRUCTION SCHEDULE

Figure 11.2-11

The sensitivity of the benefit to other variations in the input data is illustrated in Figure 11.2-9. Six effects were considered: the effect of an increase in the LMFBR capital cost; the effect of an increase in the LMFBR spent fuel cooling period; the effect of removing the carbide core reactors from the study; the effect of a higher separative work charge; the effect of removing the nuclear plant construction schedule; and the effect of allowing free competition between nuclear and fossil plants. For all cases shown in Figure 11.2-9, the uranium supply and energy demand were the base projections, and the LMFBR was introduced in 1987. Thus, the results may be compared directly with the \$19 billion benefit given in Figure 11.2-8. Note that for all cases in Figure 11.2-9, other than the sixth case, the specified nuclear plant construction schedule to the year 2000 was used. This construction schedule limited LMFBR capacity to about 400,000 MWe, and HTGR capacity to about 100,000 MWe, by the year 2000. These limitations were based on results from separate AEC studies conducted to assess the realistic marketplace potential of the various reactor types, the interest of manufacturers in introducing new plant types, and similar factors.

An examination of Figure 11.2-9 shows the following. If the capital cost differential between the LMFBR and the LWR is increased from zero to \$50/kWe in the year 2000, the benefits decrease from \$19 to \$15 billion. If the cooling period for spent LMFBR fuel is increased from 120 to 365 days, the benefits are reduced by \$1 billion. If the LMFBR design with the carbide core is removed from the study, the benefits are reduced by \$1 billion. If the separative work charge is increased from \$36 to \$75/SWU, the benefits increase to \$29 billion dollars. If the specified nuclear plant construction schedule is removed, the benefits decrease to \$13 billion. If free competition is allowed between nuclear and fossil plants after the year 2000, the benefits increase to \$25 billion.

The effect on dollar benefits of very large changes in both the energy demand and the LMFBR capital cost are shown in Figure 11.2-10. For cases shown in previous figures, the parametric variations generally occurred singly, with all other parameters held to the values considered most probable. This is not true for the cases shown in Figure 11.2-10; here, the uranium supply, energy demand, and capital cost were allowed to vary simultaneously. The variation in uranium supply was identical to that considered previously, and the uranium supply is labeled as before: small, base, and large. In contrast, the variation in electrical energy demand is much larger than considered previously. The base value is again 28×10^{12} kWhr per year in the year 2020; however, the case of a very small demand of 14×10^{12} kWhr per year is also considered. In addition, the variation in LMFBR capital

costs is much larger than considered perviously. There is no base case differential between the LMFBR and LWR in the year 2000; however, a case of a very high differential of \$100/kWe is also considered. Note that this is a very pessimistic assumption, since it assumes that after 25 years of construction experience, the LMFBR capital cost still remains 21% higher than that of a competing nuclear power plant.

Benefits are presented in Figure 11.2-10 for discount rates of 10 and 7-1/2%. First, consider the results at 10%. A careful examination of the first five cases shows the following. If the uranium supply, energy demand, and LMFBR capital cost are the base projections, the benefit from the LMFBR program is \$19 billion, with a large uranium supply, the benefit drops to \$12 billion. If the LMFBR capital cost should prove to be very high, while the uranium supply is large and the energy demand remains at the base projection, the benefit from the program drops to \$5 billion, that is, about equal to the development cost; hence, there is little net loss or gain. If the energy demand should prove to be very small, while the uranium supply is large and the LMFBR capital cost remains at the base projection, the benefit is again approximately equal to the development cost. However, if the uranium supply is large, while the energy demand is very small and the LMFBR capital cost is very high, then the benefit is \$1 billion and a definite net loss occurs. It is important to note that a definite net loss occurs only for the case in which two large variations, both acting to the detriment of the LMFBR, occur simultaneously.

Finally, consider the case of a small uranium supply, that is, the last four cases in Figure 11.2-10. If the energy demand and LMFBR capital cost are the base projections, then the benefit from the program is \$31 billion. If the LMFBR capital cost is very high, the benefit is still \$24 billion. If the energy demand is very small, the benefit is \$10 billion. Even for the case where the energy demand is very small, while, simultaneously, the LMFBR capital cost is very high, benefits of about \$7 billion are realized.

Now consider the benefits computed at a discount rate of 7.5%. If the uranium supply, energy demand, and LMFBR capital cost assume the base projections, the benefit from the LMFBR program is \$54 billion. This is in contrast to a development cost of approximately \$5 billion. If the LMFBR capital cost should prove to be very high, while the uranium supply is large and the energy demand remains at the base projection, the benefit from the program is \$15 billion. If the energy demand should prove to be very small, while the uranium supply is large and the LMFBR capital cost remains at the base projection, the benefit is \$12 billion. However,

if the uranium supply is large, while the energy demand is very small and the LMFBR capital cost is very high, then the benefit is \$1 billion, and a definite net loss occurs. Again, it is important to note that the program produces a definite net loss only when two or more large variations, which are adverse to the program occur simultaneously; otherwise, the program produces a substantial net benefit.

Now consider the case of a small uranium supply. If the energy demand and LMFBR capital cost are the base projections, then the benefit from the program is \$78 billion. If the LMFBR capital cost is very high, the benefit is still \$60 billion. If the energy demand is very small, the benefit is \$28 billion. Even if the energy demand is very small and the capital cost is very high, the benefit is still \$19 billion.

A similar set of cases not using the construction schedule specified in WASH-1139(1972) is shown in Figure 11.2-11. Among other effects, removal of the construction schedule resulted in a projection that the HTGR, with capital and operating costs assumed for the study, completely captured the nuclear power market after 1990, when the LMFBR was not available. This unusual result does not appear realistic in view of current market trends. Again, note that the benefits are generally much greater than the development costs, and that simultaneous adverse assumptions are required to reduce them below the development costs.

The cumulative U_3O_8 and the maximum annual separative work requirement as a function of the uranium supply, the energy demand, and the LMFBR capital cost are shown in Figures 11.2-12 and 11.2-13. The cases are identical to those shown in Figure 11.2-10. The uranium supply variations considered are small, base, and large; the energy demand variations considered are base and very small; and the LMFBR capital cost variations considered are base and very high. Figures 11.2-12 and 11.2-13 illustrate two very important effects. First, if the LMFBR capital cost is the base projection, then the introduction of the LMFBR reduces the amount of U_3O_8 and separative work capacity required substantially. This is true, independent of the uranium supply or the energy demand. Second, even if the LMFBR capital cost is high, the introduction of the LMFBR generally reduces the amount of U_3O_8 and separative work capacity required substantially below the amount required without the LMFBR. Thus, whereas assumptions adverse to the LMFBR may substantially affect the dollar benefits, they generally do not affect the ability of the LMFBR to reduce the U_3O_8 and separative work requirements.

CUMULATIVE U_3O_8 REQUIREMENTS

Figure 11.2-12

11.2-24

MAXIMUM ANNUAL SEPARATIVE WORK REQUIREMENT

Figure 11.2-13

The reasons that ore and separative work reductions generally occur regardless of assumptions adverse to the LMFBR are demonstrated in Figure 11.2-14. This figure shows the construction rate by reactor type throughout the planning horizon for various cases. The total number of plants of each type built in each case is shown in parenthesis. Note that the total number of LMFBRs constructed is generally on the order of 2000, and that the effect of assumptions adverse to the LMFBR is simply a delay in time, rather than a reduction in the number built. The only exception is the case of a very high capital cost.

In addition to the sensitivity studies discussed above, a set of three cases was run to determine the variation in the economic benefits from the LMFBR as a function of LMFBR doubling time, that is, the time required for a breeder to generate enough fissile fuel to duplicate itself. The three cases were run using the base uranium ore supply, base energy demand, no construction schedule, and a 7.5% discount rate. The first case, which contained the early commercial oxide reactor as the only LMFBR, yielded a discounted benefit of \$14 billion. The second case, which contained both the early and advanced commercial oxide reactors, produced a discounted benefit of \$28 billion. The third case, which contained the two oxide reactors plus the carbide reactor, produced a discounted benefit of \$29 billion.

The results are plotted in Figure 11.2-15 as a function of the doubling time of the most advanced reactor contained in each case. The doubling time is the simple doubling time with the out-of-reactor inventory taken into account. The reprocessing losses were assumed to be zero. Figure 11.2-15 shows that if the doubling time is long, the benefits increase substantially as the doubling time is reduced, in fact, at the rate of approximately \$1 billion per year of doubling time. Hence, the economic incentive to improve a long doubling time is large. However, for a simple doubling time of less than 15 years, the curve is very flat. This indicates that the economic incentive for a simple doubling time of less than 15 years, or a compound doubling time of less than 10 years, is small.

Introduction of the LMFBR also leads to a net reduction in the total capital requirements associated with U.S. power generation. Because LMFBR capital costs were assumed to be higher than those of other plant types before the year 2000, an increase of about \$11 billion was calculated to be needed for installation of generating plants for base conditions. However, introduction of the breeder results in a reduction of over \$100 billion in facilities for uranium ore mining and milling, and of over \$60 billion in uranium enrichment facilities. This

REACTOR CONSTRUCTION RATE
Figure 11.2-14

11.2-27

LMFBR BENEFITS AS A FUNCTION OF THE DOUBLING TIME WITH A 7-1/2% DISCOUNT
RATE AND WITHOUT A CONSTRUCTION SCHEDULE

Figure 11.2-15

results in a net savings of about \$160 billion in cumulative capital requirements for the U.S. power economy.

Comparison of cumulative capital requirements with and without the LMFBR is shown in Figure 11.2-16.

The LMFBR not only provides low-cost power of itself, but because it eventually provides a source of low-cost fissile plutonium it permits nonbreeders to utilize this plutonium and themselves produce low-cost power. This synergistic effect of the breeder on system power costs is shown in Figure 11.2-17. In the case with no breeder (Curve 1) the initial lowering of power costs due to expansion and maturation of the nuclear industry is reversed as higher uranium prices drive system power costs upward. With the LMFBR available, power costs for the system are lowered considerably below those attainable without the breeder, and the low costs are maintained as the plutonium fuel cycle becomes dominant.

In summary, the LMFBR program conserves resources and produces substantial economic benefits for those cases considered to be the most probable. The effect of adverse assumptions is to reduce the economic benefit, however, they generally do not reduce the economic benefits below the development cost. The economic benefit is less than the development cost only when two or more large adverse effects occur simultaneously. It is also noted that the savings in terms of uranium ore and separative work capacity is generally less sensitive to adverse assumptions than the economic benefits. Finally, the LMFBR permits the electrical power economy to become independent of possible severe limitations in fuel resources and to have the potential for essentially unlimited low cost energy.

EFFECT OF LMFBF ON CAPITAL REQUIREMENTS
FOR U.S. POWER SYSTEMS

Figure 11.2-16

EFFECT OF LMFBR ON SYSTEM POWER COSTS
Figure 11.2-17

REFERENCES FOR SECTION 11.2.1

1. USAEC, "Cost-Benefit Analysis of the U.S. Breeder Reactor Program," Report WASH-1126, April 1969. USAEC "Updated (1970), Cost Benefit Analysis of the U.S. Breeder Reactor Program," Report WASH-1184, January 1972.

11.2.2 LMFBR Program Costs

The projected program costs associated with 1987 introduction of the LMFBR total \$8.4 billion; discounted at 10% to mid-1974, these costs are \$4.7 billion. Corresponding costs associated with 1985 introduction of the LMFBR are \$8.6 billion (\$4.8 billion at 10% discount), and for 1991, introduction estimated costs are \$8.7 billion (\$4.7 billion at 10% discount). Comparisons of costs for the three introduction dates are shown in Table 11.2-2. Also shown in the table are the estimated research and development costs for support of both the LMFBR and a parallel breeder reactor (PBR) concept. This option was not considered in the cost-benefit studies; LMFBR research and development costs are not changed by inclusion of a PBR.

Table 11.2-3 presents the projected research and development costs of the LMFBR Program through the year 2020 for 1987 introduction. Yearly estimates are shown for fiscal years 1975 through 1979. These are the current budget planning projections of the AEC for the LMFBR Program. The subtotal for the period 1980 through 2020 was projected assuming successful research and development programs and a viable, competitive nuclear industry existing at the time of commercial introduction of the breeder. Commercial introduction is defined as the time period over which a number of commercial-sized power plants become operational. A viable industry would include several reactor manufacturers and architect-engineers from whom interested utilities could solicit bids and select a power plant. A competitive industry would include a number of qualified and experienced vendors from whom selections could be made for the furnishing of major equipment items.

As a result of the continuing assessment of the Nation's civilian nuclear power program, the LMFBR program plan is being revised. The AEC plans to strengthen its development program to attain the capability of developing and testing large sodium components such as steam generators, heat exchangers, and pumps. A strengthened component development program, including the availability of a large-component test facility, should allow the industry to provide large near-commercial size plants with full commercial size components much sooner than previously contemplated. Early plant experience will be gained through operation of the FFTF, CRBR, and foreign LMFBRs. This adjusted LMFBR plan should further enhance the ability of the industry to design and build a number of large commercial plants for operation in sizeable numbers in the 1990's.

Specified assumptions used in projecting beyond 1979 for the Base case assuming 1987 LMFBR introduction are:

Table 11.2-2

SUMMARY OF ESTIMATED LMFBR PROGRAM COSTS
TOTAL COSTS FROM FISCAL YEAR 1975 (MID-1974 TO 2020)
BILLIONS OF DOLLARS (FISCAL YEAR 1975 DOLLARS)

	LMFBR Introduction Dates			
	1985	1987	1991	1987 with PPR ^a in 1994
I. AEC Costs				
LMFBR	6.6	6.5	6.8	6.5
Supporting Technology	<u>1.6</u>	<u>1.6</u>	<u>1.6</u>	<u>1.6</u>
Total LMFBR and Supporting Technology	8.2	8.1	8.4	8.1
Other Breeders	1.4	1.4	1.4	5.7
Nonbreeders	<u>0.7</u>	<u>0.7</u>	<u>0.7</u>	<u>0.7</u>
Total	10.3	10.2	10.5	14.5
Total LMFBR and Supporting Technology Discounted to 1974 at:				
0%	8.3	8.1	8.4	
5%	6.1	5.9	6.0	
7-1/2%	5.3	5.1	5.2	
10%	4.7	4.5	4.5	
II. Electric Utility Contributions to CRBR^b (\$260 Million)				
Total LMFBR Program Costs Discounted to 1974 at:				
0%	8.6	8.4	8.7	
5%	6.3	6.1	6.2	
7-1/2%	5.5	5.3	5.4	
10%	4.8	4.7	4.7	

^aParallel Breeder Reactor.

^bClinch River Breeder Reactor demonstration plant.

Table 11.2-3
DETAIL OF LMFBR PROGRAM COST PROJECTIONS (1975 thru 2020) LMFBR INTRODUCTION DATE 1987
(millions of fiscal year 1975 dollars)

	FY 1975	FY 1976	3 mos. Trans.	FY 1977	FY 1978	FY 1979	Subtotal 1975-1979	Subtotal 1980-2020	Total 1975-2020
<u>LMFBR</u>									
<u>R&D</u>									
FFTF	65	46	12	46	37	37	243	526	769
CRBR ^a	44	44	12	64	50	33	247	67	314
Support Facilities	43	47	13	60	63	63	289	613	902
Engineering & Technology									
Technology	52	53	15	57	60	63	299	588	887
Engineering	49	53	15	69	94	123	403	759	1162
<u>Cooperative Projects</u>									
CRBR ^a	21	73	5	155	160	140	554	200	754
NCBR ^b				5	18	64	87	189	276
<u>Capital Equipment</u>	19	17	5	23	24	26	114	201	315
<u>Construction Projects</u>									
FFTF	132	74					206		706
Plant Component Test Facility		5		9	41	110	165	203	368
Rad & Repair Eng. Facility				9	18	14	41	5	46
Advanced Fuel Lab				9	18		27		27
Fuels & Materials Exam Facility				23			23		23
Hot Reprocessing Pilot Plant				2	7	28	37	239	276
Miscellaneous Projects	15	18	3	20	28	17	101	91	192
Total LMFBR	440	430	80	551	618	718	2836	3681	6517
<u>Supporting Technology</u>									
<u>Safety</u>									
R&D	37	40	12	46	52	58	245	646	891
Equipment	4	4	2	4	3	4	21	49	70
<u>Construction</u>									
Safety Test Facility		3		9	18	46	76	108	184
Transient Reactor Safety									
Test Facility				11	9	7	27		27
Advanced Fuel Technology	12	15	5	18	23	28	101	352	453
Total Supporting Tech	53	62	19	88	105	143	470	1155	1625
TOTAL LMFBR & SUPPORT	493	492	99	639	723	861	3306	4836	8142

FOOTNOTES FOR TABLE 11.2-3

- ^aThe CRBR project has recently completed a major design, cost, and schedule review. The costs reflected here are consistent with the revised cost estimate of \$1.7 billion.
- ^bThe Near Commercial Breeder Reactor (NCBR) is not well defined except that it is expected to be made from large commercial size components. This size would be an extrapolation of 4 to 6 over the CRBR. The funds given here are a very rough estimate of Government assistance; however, a more precise estimate will be available as the nuclear industry approaches the commitment year for this project.

- (1) The FFTF continues operation into the early 1990's as the major fuel irradiation test facility in support of the LMFBFR fuel and materials development activities. Its operation extends beyond the 1987 introduction date due to the continued extensive work related to advanced fuels (advanced oxides, nitrides, carbides) and materials required to obtain as high a breeding ratio as possible.
- (2) Criticality of the CRBR is assumed in 1982 and completion of the demonstration period 1986, at which time it is expected that the facility will be turned over to TVA as a power producer.
- (3) Support Facilities
 - (a) The EBR-II and Hot Fuel Examination Facility are projected to complete their operations by the mid-1980's. The functions of these activities are picked up by similar facilities at Hanford.
 - (b) Upon completion of the physics program by the mid-1980's, the Zero Power Reactors (ZPPR, ZPR-VI, and ZPR-IX) will be decommissioned.
 - (c) The Plant Component Test Facility should become operational in the early 1980's and continue operation into the 1990's in support of testing large commercial-sized engineered sodium components.
- (4) Engineering and Technology

In the technology area, physics, fuels and materials, and chemistry programs will continue into 1980's in support of early LMFBFRs. The fuel recycle program, however, will continue into the 1990's to provide the necessary fuel reprocessing, refabrication, and shipping technology to the industry.

Large plant design activities, systems engineering work, and large component development work will continue into the 1980's and early 1990's in support of industrial efforts along these line to assure the economic competitiveness of the large target systems.
- (5) The Clinch River Breeder project will continue to be supported until completed and it is assumed that another cooperative project called the Near Commercial Breeder Reactor (NCBR) will be initiated by the nuclear utility industry in 1977. This project is assumed to be completed by 1986 and it is expected that government involvement will be substantively less than that required for the CRBR. It is also assumed that this plant will be 1000 MWe or larger and would contain commercial size sodium components.
- (6) LMFBFR construction

The major construction activities not yet underway include the Plant

Component Test Facility and facilities at the Hanford test site to adequately support the extensive fuel irradiation programs which will be using the FFTF. In addition, it is assumed that a hot fuel reprocessing pilot plant which includes an extensive fuel storage facility will also be authorized for construction and built by the mid-1980's.

(7) Other breeders

The Gas-Cooled Fast Reactor (GCFR) and Molten-Salt Breeder Reactor (MSBR) technology activities will continue into the early 1980's and will phase out approximately four years prior to the introduction of the LMFBR. It is assumed that by 1982-1983 there will be a high level of confidence that the LMFBR will be introduced and further work on alternatives and backups would not be necessary.

(8) Supporting breeder technology

The LMFBR safety research and development activities continue at a high pace through the 1980's in support of the licensing efforts for commercial plants. This activity continues into the 1990's but at a decreasing rate to a modest level of effort (\$5 million per year) through the year 2020. It is assumed that two major facilities, the Transient Reactor Safety Test Facility and the Safety Test Facility (STF), will receive construction authorization in the late 1970's for operation in the early and mid-1980's.

(9) Nonbreeders

The HTGR program and related work is continued through the 1980's and early 1990's in fulfillment of the Commission's commitment to assure HTGR fuel-cycle technology. Since it is expected that HTGRs will be a part of the U.S. power economy, a modest HTGR safety effort (\$2 million per year) is continued through the year 2020.

The funding projections for work being sponsored by the Commission relating to light-water reactor safety and the light-water breeder are not included in this study.

The NRDC has the following concerns about the LMFBR research and development program:*

Currently, the curve of estimated LMFBR Program expenditures as a function of time is diverging from the curve of the cumulative expenditures to date, even when using constant dollars. As long as this is occurring, AEC projections of additional program expenditures will understate the true cost and the ultimate expenditure ceiling will remain unknown.

*Comment Letter 38g, pp. 14-19.

It is significant that the AEC's projection of LMFBR expenditures exceeds a recent FPC estimate of the total R&D costs (to the point of commercialization) of all non-nuclear technologies, including coal gasification, solar (direct and indirect) and geothermal technologies, advanced steam cycles; MHD, fossil fuel effluent controls, and a variety of energy storage systems. A NSF/NASA Solar Energy Panel recommended in late 1972 that a 15-year program to develop all solar energy options would cost \$3.5 billion, roughly one-half the AEC's estimate of the LMFBR Program cost.

Such statements are misleading in that they fail to recognize the complexity of the undertaking and the many unknown factors involved. On the other hand, the LMFBR research and development cost projections include the costs of all known elements that are necessary to establish the LMFBR as a commercially and environmentally acceptable concept to achieve its full potential for natural resource conservation. When embarking on the development of a complex technology, such as the breeder, cost overruns and schedule slippages may occur. The LMFBR Program is not unique in that respect, however. Similar situations would be expected with any of the potential alternative energy sources.

The LMFBR Program is now moving quickly from the research phase into the hardware engineering phase and cost projections can be expected to be predictable. Program costs are expected to level off in the next few years and decrease rapidly thereafter. The LMFBR Program has been underway for over 20 years, notwithstanding the recent cost escalations and unexpected overruns being experienced, the research and development cost projections for this Program are much more reliable than research and development cost projections for alternative energy sources, which are for the most part in their infancy.

The NRDC questioned the detail in the LMFBR research and development cost projections stating that:*

...difficulties in estimating the validity of AEC's current projections of LMFBR R&D costs arise because the AEC consistently refuses to provide the public with a laundry list breaking down this budget by years and program component. It is also impossible to tell, for example, to what extent, if any, the AEC included in the 1978 Analysis, LMFBR safety research expenditures which will necessarily continue far beyond the commercial entry date as is the present case with respect to light water reactors.

To the (estimate) should be added an appropriate share of the 'General Support' items...considerable costs overruns, additional costs incurred as the commercial entry date slips beyond 1987 (which it undoubtedly will), probably, as mentioned above, the continuing safety program costs beyond 1987, and some major program components that are probably not included.

*Comment Letter 38g, p. 16.

With respect to the "major program components," NRDC states:*

It is doubtful whether (the advanced fuels development effort) is included in the...estimate" and "...a Safety Test Facility (STF) and an Excursion Test Facility (ETF)...are not to our knowledge included in the...estimate" and "Finally, to the (estimate) must be added the share of AEC-Regulatory and the AEC's Division of Reactor Safety Research which are identified with the LMFBR Program, and last but not least, a major fraction of the cost of a more stringent safeguard program.

Table 11.2-3 presents the cost projection breakdown by year and program component. As indicated in the assumptions enumerated previously, the AEC recognizes that commercialization will not mean the end to safety research efforts. Thus, while the commercial LMFBR will be developed and introduced in conjunction with industry as a safe concept, a continuing safety research program is expected for as long as the concept is commercial.

Funding for general support activities is not included in the cost projections, since such work is of generic interest to other nuclear and non-nuclear power plant concepts. This work includes power plant siting, dry cooling tower development, desalting, process heat, environmental studies, and safeguards activities. Because this effort would continue even if there were no LMFBR Program, it is not appropriate to include it as a part of the cost projections for the Program.

As indicated previously, a complex research and development undertaking which involves major advancements in the state-of-the-art may expect cost overruns and schedule slippages. Cost overruns and schedule slippages are, by their nature, impossible to predict accurately. Part of good program planning is to establish reasonable cost and schedule goals and to attempt to meet them.

Recent energy problems have highlighted the need for conservation of energy resources. This need has been reflected in the LMFBR Program with the inclusion of the Advanced Fuels and Materials development program. Although similar R&D efforts have always been contemplated as necessary to developing the full capabilities of the breeder and have been included in previous forecasts, an accelerated Advanced Fuels and Materials program is now an important part of the current forecast.

Also included in the projections are two safety development facilities, the Safety Test Facility and the Transient Reactor Test Facility.

*Comment Letter 38g, p. 18.

The cost of Regulatory activities for licensing and surveillance of LMFBRs is borne by the utilities as a normal cost of operation and hence is not included in the research and development forecast for the LMFBR.

Funding for safety research is included in the projections, as stated previously. The safety effort will be sufficient to ensure development and commercialization of a safe concept. The need to acquire an independent safety assessment capability to support Regulatory operations has been recognized by AEC. This is not appropriately included in the research and development cost projections, since it is independent of the Program and not necessary to support the development of the concept.

Funding for a materials safeguards program is included under a general support category, as noted above, and is not in the projected LMFBR program costs. As noted in Section 7.4, Safeguards, the safeguards problem will exist in the future with or without the LMFBR. It is expected that by the time the LMFBR has become commercially available, the routine safeguard procedures and practices established for the currently commercial reactors and their fuel cycles will provide most, if not all, the needed safeguards. The same comment is applicable to the timing and cost of development of radioactive waste disposal techniques.

In commenting on the draft EIS, the EPA* felt that the costs the private sector incurred in the development of the LMFBR should be included along with the AEC research and development costs for LMFBR. However, privately funded research and development was not included in the LMFBR Program research and development costs, since these costs are recovered through sale of nuclear plants, nuclear fuel or fuel cycle services. However, the projected contribution of utilities to the Clinch River Breeder Reactor demonstration plant has been included in the LMFBR Program costs as used in the cost-benefit calculations.

It should be noted that the brief history of nuclear power demonstrated the economic benefits and the return available from a relatively small research and development investment. The cost of developing the LWR over a 20-year period totals less than \$2.5 billion. Yet this investment has nurtured an industry, yet in its infancy, with current capital commitments of nearly \$100 billion and fuel commitments estimated at \$200 billion. The LMFBR investment can be expected to reap similar returns and in addition, to increase the return of the LWR investment.

*Comment Letter 53, p. 43.

11.2.3 Method of Calculation and Major Assumptions

The updated cost-benefit study compares power system costs for alternative systems. Calculations for this study were performed using a computer model designed to analyze electrical power systems using linear programming techniques developed at the Hanford Engineering Development Laboratories. The model represents all the electricity-generating companies or utilities as a single-minded company. The logic of the cost-benefit model as related to individual utility planning methods is discussed in Section 11.2.5.

11.2.3.1 Method of Calculation

The economic structure used in the model is shown schematically in Figure 11.2-18. In the discussion that follows, the numbers in parentheses refer to the numbered streams on Figure 11.2-18.

Evaluations of power costs required to meet a specified electric energy demand considered the following cash and material flows. The company supplies electricity (1) to the consumers. In return, the company receives a commensurate cash flow (2). To meet increased demands and to replace old plants the company builds new plants (3) and pays cash to the contractors (4), that is, capital investment in new facilities. The company uses fossil fuels (5) (in some of the cases considered) and pays cash to the suppliers (6). It also pays cash for operating expenditures, maintenance, taxes, and miscellaneous expenses (7). The company obtains fresh nuclear fuel and other fuel-cycle services (8) and pays cash in return (9). These services include fuel ore supply, conversion, enrichment, preparation, fabrication, transportation, chemical reprocessing, and waste disposal. The fissile fuel stockpile receives fissile material from reprocessed spent fuel and supplies fissile fuel to the fabricators (10). The cash flow to and from the stockpile represents credit for fissile material recovered from spent fuel, charges for fissile material used in fresh fabricated fuel, and storage charges associated with the building and maintenance of storage facilities (11). The credits and charges for fissile material are evaluated at the time of deposit or receipt based on the internal worth of the fissile material.

The electric generating company has the option of selecting any combination of available plants and fuels over the study period (1974-2020) that will enable it to meet the electrical energy demand of the consumers. The cost-benefit model selects the plant types as a function of time to minimize the power cost over the study period in constant dollars, present-valued, to mid-1974. All cash flows are evaluated in terms of constant 1974 dollars. Additionally, all expenditures are

COST-BENEFIT ANALYSIS ECONOMIC MODEL
Figure 11.2-18

present-valued by discounting them to mid-1974 at appropriate discount rates. The discounted cash flow method used in the model defines the cost of power (cash flow from consumers) so as to satisfy the following equation (numbers in parentheses refer to Figure 11.2-18):

$$\begin{aligned} \text{Total present worth of cash incomes (stream 2)} \\ = \text{Total present worth of cash outflows} \\ \text{(streams 4, 6, 7, 9, and 11).} \end{aligned}$$

For a fixed set of input variables (a case), the linear programming model selects a unique plant-building program (a reactor mix) that minimizes the right-hand side of the equation and thus minimizes the total, present-valued power cost.

The discount rate used to determine the present worth of all cash flows was 7.5% in the Draft Statement. As explained in Section 11.2.3.2, the Final Statement reports the base case results at a 10% discount rate in response to comments on the Draft Statement.

Each power cost calculation depends on a projected electrical energy demand as a starting point. The base total energy demand and the base electrical energy demand are discussed in Section 11.2.3.3. The electrical energy demand projection is essentially an extrapolation of current trends. Energy input to electric energy generation is projected to grow from 25% (1970) to 65% (2020) of the total energy demand. Cases which considered only nuclear power plants were limited to 60% of the capacity required to meet the projected electrical energy demand. Most cases (i.e., without nuclear-fossil competition) assume that 40% of the electric energy plant capacity demand is satisfied by non-nuclear plants and that non-nuclear sources in addition provide 75% (1970) to 35% (2020) of the total national energy demand.

Within the framework of an assumed electrical energy demand, the cost-benefit model selects a schedule of generating plants. Each plant follows a predetermined, life-time capacity curve, as defined in Section 11.2.3.4. When only nuclear plants are considered, all plants were assumed to be base-loaded. For the cases assuming competition between nuclear and fossil plants, both base-loaded and load-following capacity curves were used. The two types were proportioned (about 60% base-loaded) to give an overall central-station capacity factor of 0.64 for the system.

The linear program successively alters the variables in the equation which determines the present-worth cash flows until a system is found which represents the minimum present-worth power cost over the study period (1974-2020). Plant selection is

based strictly on the need to supply new demand and to replace retired plants. If the model did not have appropriate build schedule constraints, it may select a plant mix which is impractical. For example, if a new type of plant is very economical, the model may choose to build only the new plant type, but the selected build schedule may outstrip the tool-up capacity of industry. Introduction constraints, defined in Section 11.2.3.5, attempt to provide practical limits to new plant construction. For most of the cases considered, AEC projections of nuclear capacity by plant type given in WASH-1139(72) were followed until the year 2000. Penetration of the HTGR after the year 2000 was limited, as discussed in Section 11.2.3.5, to account for anticipated manufacturing and economic limits.

Calculations covered the time period January 1, 1974 through December 31, 2019. Thus, the linear program selected plant build schedules for each biennium from 1974 to 2020. Forward costs for reactors built prior to 2020 were calculated through the remainder of their 30-year life. Thus, the total power cost for plants required to meet the electrical power demand (within the nuclear penetration limit) to 2020, including operating costs through 2050, was minimized in terms of the mid-1974 present worth. This procedure of operating plants to the end of their normal lives is in keeping with standard utility practices in the evaluation of alternatives. The mass balance and reactor performance data for all reactor types are given in Section 11.2.3.6.

The economic benefits associated with the LMFBR are defined as the reduction in the Nation's electric power costs due to inclusion of the LMFBR in the power system. These gross benefits can be calculated as the difference between two cases which differ only in the exclusion and inclusion of the LMFBR. Net benefits are those calculated by subtracting the LMFBR program costs from the gross benefit. Projected costs for the LMFBR program are described in Section 11.2.3.7. The costs for safeguarding nuclear facilities and fuel materials (as given in Section 7.4) were not included as internal costs. Subsequently, the safeguard costs for each case were computed and the benefits calculations were adjusted to reflect the somewhat larger safeguard costs associated with the LMFBR.

Comparisons of benefits from alternative systems are often based on the cost-benefit ratio. As used in this study, the cost-benefit ratio is defined as the ratio of the net discounted benefit to the discounted LMFBR program cost. An additional criterion, the internal rate of return, has been included in the Final Statement in response to comments on the Draft Statement. The rate-of-return on the programs investment is computed by a trial-and-error process which iterates over a range of

discount rates until the discounted programs cost are identically equal to the discounted benefits over the study period. The rate-of-return analysis somewhat understates the impact of actions far in the future, since the forward costs of plants operating between the end of the study period (2020) and the end of their life has not been included.

The cash flow items contributing to the "busbar" power costs computed in this study include all costs which are directly dependent on the choice of generating plant type. Cost of transmission and distribution are relatively independent of the generating plant type. The busbar cost items represent a large amount of input data for each plant type. The input parameters used in the study are based on extensive study and on data from Government agencies, utilities, reactor manufacturers, architect-engineers, and firms engaged in fuel-cycle operations. In many instances, the projected costs are higher than those used in previous LMFBR program cost-benefit studies. These higher costs are due partly to general escalation from the earlier base years to mid-1974, and partly to real cost increases in some segments of the industry. The costs included in the study are:

- (1) costs of uranium and thorium ore used, based on projections of ore availability as a function of price (11.2.3.7);*
- (2) capital costs of steam power plants, as a function of date of introduction (11.2.3.8);
- (3) operating and maintenance costs for these plants, including costs of heat rejection and--for those cases where fossil-fueled plants were included--costs to fly-ash and sulfur-oxide removal (11.2.3.9);
- (4) cost of fabricating and reprocessing nuclear fuels (11.2.3.10), and cost of fossil fuels (11.2.3.12);
- (5) cost of uranium enrichment (11.2.3.11);
- (6) costs of shipping fresh, recycled, and spent nuclear fuels (11.2.3.10);
- (7) cost of storing plutonium and U-233 fuels recovered from spent reactor fuels (11.2.3.10); and
- (8) costs of investment financing and insurance (11.2.3.2).

*Numbers in parentheses refer to sections in this document containing descriptive material.

11.2.3.2 Discount Rate

The choice of an appropriate discount rate for use in benefit-cost analyses has been the subject of many debates and has caused the generation of a large volume of writings and testimony. Professional disagreement still exists, but the most accepted position in the Federal Government is that the discount rate should be based on the opportunity cost of displaced private spending.¹ This concept, simply expressed, is that if the Government undertakes a project, the return to society should be equal to what the private sector could have generated through an equal investment. The widespread difference of thought as to the actual value of the discount rate is demonstrated by noting the different views.

In commenting on the draft Environmental Impact Statement (EIS), the position expressed by the Natural Resources Defense Council (NRDC) is that "a much better standard for social rate of discount . . . is the before tax rate of return to capital in the entire private sector. This rate measures the productivity of resources which will be drawn away from the private sector if the breeder program continues."* A similar viewpoint by the Environmental Protection Agency (EPA) is "the appropriate rate of return is the deflated rate of return for all private businesses."** Thus, NRDC believes "it is reasonable to require the benefit to cost ratio to be favorable at rates of discount existing in private industry (15-20 percent per year, before tax),"† and EPA proposes "an acceptable range of discount rates of 10% to 15%."††

On the other hand, a number of economists and consulting firms have argued for a discount rate in the range of 5-8 percent. For example, a recent analysis² on the economic incentive for the Fast Breeder Reactor conducted by representatives of Commonwealth Edison Company, General Electric Company and Harvard University utilized a discount rate based on the social rate of time preference (SRTF) for present worthing the cash flows associated with utility expenditures. The SRTF measures society's assessment of the social worth of future consumption as an alternative to current consumption. The analysis used constant dollar discount rates of 4% and 6%. In addition, the Joint Economic Committee has expressed the view that projects which displace specific private investments, such as the public production of many research and development outputs, should be evaluated by the rate of return prevailing in the sector from which the specific investment is displaced.³ In the case of the LMFBR, the Government is doing investment for the electric utility sector. Therefore, one

*Comment Letter 38g, p. 6.

**Comment Letter 53, p. 31.

†Comment Letter 38g, p. 7.

††Comment Letter 53, p. 32.

may contend that the rate of return prevailing in the electric utility sector could be used as the discount rate. It has also been argued that the R&D investment substitutes for that in the reactor manufacturing industry and that the higher rates of return prevailing in that industry should be considered. Although some reactor manufacturing industry investment may be displaced, it is likely that the Government investment stimulates, rather than displaces, investment by that industry sector.

There are several other issues which create difficulties for measuring the discount rate. Some of these issues are:

1. The treatment of inflationary influences on observed interest rates.
2. The role of risk and uncertainty in public investment decisions and interest rate policy.
3. The treatment of taxes in future benefits.
4. The use of the investment sector versus all sectors of the economy in measuring foregone opportunities.

This Environmental Impact Statement uses a basic discount rate of 10 percent based on the preferences of the Office of Management and Budget (OMB) and other organizations and individuals. The OMB, through the issuance of OMB Circular No. A-94 Revised, states that the discount rate of 10% represents an estimate of the average rate of return on private investment, before taxes and after inflation. It should be remembered that OMB has established this rate to achieve a uniformity of practice for all agencies during the budgetary allocation process only and does not state that this rate represents the true discount rate for each and every Government investment decision.

In the draft EIS, a basic discount rate of 7.5 percent was used, following the same logic that OMB had used in establishing an estimate of the uniform rate for all Federal agencies. The one major point where a difference existed was the use of an after-tax discount rate. The principal purpose of selecting the 7.5 percent after-tax discount rate was to provide a consistent comparison with the two previous benefit-cost studies for the LMFBR. In both of those studies, which received the approval of OMB, the after-tax discount rate method was applied to the calculations. The use of an after-tax rate is equivalent to a higher discount rate measured on a before-tax method as illustrated by the following discussion.

The concept of the before-tax discount rate is expressed by Professor William Baumol:

For the company to get 5 percent, it would have to produce a yield of 10 percent out of its productive process, since 50% of its earnings go into taxes. As a result, any resources withdrawn from the corporate sector would involve a loss of a 10-percent earnings in the productive sense, earnings of goods produced for society and, therefore, the resources should only be reinvested in a Government project if there they could produce 10 percent.⁴

When one applies the before-tax rate, one must measure the future benefit stream in terms of real productive earnings produced for society which includes the earnings necessary to meet the tax obligations associated with that production. In effect, taxes are included in calculation of the benefit stream.

However, Professor Morton Kamien has testified that:

Unless allowance is made for the difference between before-tax and after-tax returns in evaluating government projects, the overall yield on productive resources will not be maximized. The adjustment called for can be made either by raising the interest rate used for discounting or by calculating benefits after taxes. The latter alternative seems preferable, because it focuses attention on who the recipients of the benefits will be.⁵

When one uses the after-tax rate, one must measure the future benefit stream in terms of earnings after tax obligations have been removed from the benefits. This yields a smaller benefits stream than in the previous example along with the use of a lower discount rate.

Therefore, it was decided to emphasize the 10 percent after-tax discount rate in presenting the results and conclusions of the study. The after-tax rate was chosen in an effort to ensure that we used a base discount rate that was conservative regarding the attitude on this matter of those government agencies directly concerned with this study. The comments from EPA stated that "the rates of return measured by AEC are net of taxes levied on the corporation, net of tax levied on the bondholders, and even net of the retained earnings taken out for reinvestment before profit distributions are made."* This observation is factually incorrect. The rates of return are net of taxes levied on the corporation only.

This study also uses discount rates after taxes of 0, 5, and 7.5 percent per year. This variation provides a sensitivity analysis of benefit-cost ratios as related to the selection of an appropriate discount rate. It is hoped that the discussion

*Comment Letter 53, p. 31.

provided in this section informs the reader about the different viewpoints regarding the problems in choosing a discount rate and will help the reader to weigh the results and conclusions presented in this study.

For illustrative purposes related to the rate of return in the electric utility sector and for other computational uses in this study, an examination of the cost of capital for the electric utility sector is made. A review of average electric utility financing practices with emphasis on calendar year 1972 was conducted and is presented in Table 11.2-4. In 1972, debt financing accounted for 53.6% for electric utility financing. The remaining 46.4% of equity financing was comprised of 11.8% financing through preferred stocks and 34.6% through common stocks. The interest rate on new debt financing in 1972 was 7.5% before taxes and 5.8% after taxes, preferred stocks paid dividends of 6.8% and the return on common stock equity was 11.5%. The weighted average for new electric utility financing in 1972 was 8.8% before taxes and 7.73% after taxes. The rate of inflation for construction in the electric utility industry for 1972 was about 12% for labor and about 6% for material. The average rate of inflation for the Nation was 3.2% in 1972 and 5.3% in 1973. Hence, a deflated after-tax discount rate for the utility cost of capital is about a couple of percentage points below the inflated value of 7.73% after taxes.

The cash flow method of accounting used in the calculations for this study does not use fixed charge rates, but instead calculates the cost components normally included in these rates. Fixed charge rates derived from the calculations, while not directly associated with the discount rate for the present value aspect of the calculations, are given in Tables 11.2-5 and 11.2-6.

Table 11.2-4
AVERAGE 1972 ELECTRIC UTILITY COST OF CAPITAL (%)

	Fraction	Long-Term Average		New Financing	
		Before Taxes	After Taxes	Before Taxes	After Taxes
Debt	0.536	5.8	4.2	7.5	5.5
Preferred Stock	0.118	6.2	6.2	6.8	6.8
Common Stock	<u>0.346</u>	<u>11.5</u>	<u>11.5</u>	<u>11.5</u>	<u>11.5</u>
Weighted Average	1.000	7.82	6.96	8.80	7.83

Table 11.2-5
FIXED CHARGE RATE ON DEPRECIABLE CAPITAL (%)

Weighted Average Cost of Money	8.8
Sinking-Fund Depreciation	0.76
Federal Income Tax	1.71
State and Local Taxes	2.43
Interim Replacements	0.35
Property Insurance	<u>0.25</u>
Total	14.30

Table 11.2-6

FIXED CHARGE RATE ON NONDEPRECIABLE CAPITAL (%)

Weighted Average Cost of Money	8.8
Federal Income Tax	2.98
State Income Tax	0.29
State Revenue Tax	<u>0.70</u>
Total	12.77

REFERENCES FOR SECTION 11.2.3.2

1. "Economic Analysis of Public Investment Decisions: Interest Rate Policy and Discounting Analysis," A Report of the Subcommittee on Economy in Government of the Joint Economic Committee, U.S. Government Printing Office, Washington, D.C., 1968, page 12.
2. Dr. T. R. Stauffer, Harvard University; R. S. Palmer, General Electric Co.; H. L. Wycoff, Commonwealth Edison Co. "An Assessment of the Economic Incentive for the Fast Breeder Reactor," to be published.
3. Ref. 1, p. 15.
4. "The Planning-Programming-Budgeting System: Progress and Potentials," Hearings Before the Subcommittee on Economy in Government of the Joint Economic Committee, (September 14, 19, 20, and 21, 1967), U.S. Government Printing Office, Washington, D.C., 1967, page 166.
5. Ibid., page 149.

11.2.3.3 Electric Energy Demand

Future energy requirements projected with the assistance of an econometric model based on estimates of population and economic growth are given in Table 11.2-7.

Table 11.2-7
NATIONAL ECONOMIC ENERGY FORECAST

	1970	1980	1985	2000	2020
Population (millions)	205	228	240	271	307
GNP (constant 1958 billions of dollars)	724	1141	1360	2300	4291
Total Energy Demand (Btu x 10 ¹⁵)	67	99	117	195	359
Gross Energy Inputs to Electric Utilities (Btu x 10 ¹⁵)	17	30	40	97	235
Gross Inputs to Utilities as Percent of Total Energy	25	30	34	50	65

Projections of total energy consumption and energy inputs to the electrical sector were made on the basis of their historical relationship to the real Gross National Product (GNP). As a basis for the GNP estimates, the E-series population projection of the Bureau of the Census was used.¹ This population projection takes into account the recent sharp decline in fertility (average number of births per woman upon completion of childbearing) and the drop in birth expectation of young wives during the past five years. It assumes that fertility will decline so that the population would reach a stationary level in approximately 70 years, providing there is no net immigration of population. The size of the work force was estimated from information on the historical population in the 18 to 64 age group. The per annum productivity increase per employee was examined and a rate of 2.6% was chosen as representative of the long-term rate of change in productivity and used to project the GNP.

The total energy projection was obtained by assuming that total energy demand will continue to grow in relation to GNP much the same way it has in the past twenty-five years. This assumption implies that the economy will become more efficient in the utilization of energy, continuing the long-term historical trend. Technological changes and shifts to more efficient production processes and energy utilizing devices are an explanation of this phenomenon.

This projection of total energy demand can be compared with other reported results, as requested by comments.* The Ford Foundation energy policy report² used a 3.4% per year growth based on a rate approximating the average for 1950 to 1972 and obtained 185 quadrillion Btus in the year 2000 for this "historical growth" scenario. While the model used in the cost-benefit analysis did not use a single energy growth rate, the resulting energy growth rates predicted by the model were 4.0% for 1970 to 1980, 3.5% for 1980 to 2000, and 3.2% for 2000 to 2020. The higher growth rate for the present decade would appear to be quite consistent with the energy growth rate of 4.5% experienced during the period 1965 to 1970.

The Ford Foundation report describes two other scenarios besides the "historical growth" scenario: a "technical fix" scenario with a growth rate about half as high as a historical rate, and a "zero energy growth" scenario. Their report makes it clear that it is not intended that any one of these scenarios be considered a prediction or recommendation.³ "The alternative futures, or scenarios, are based on different assumptions we have made about the energy growth patterns our society might adopt for the years ahead, and the policies and consequences that each would entail They are not predictions, but a tool for rigorous thinking. We do not advocate one option over the other but present each for comparative analysis by the reader."

A survey of Energy Consumption Projections for the U.S. Senate Committee on Interior and Insular Affairs⁴ lists the results of several forecasts of total energy consumption for the year 2000. Some of these forecasts were made as early as 1960, while the latest forecasts were made in 1971. The ten forecasts ranged from 135 to 213 quadrillion Btus. The Bureau of Mines forecast listed in the survey⁴ was given as a range from 166 to 239 quadrillion Btus, depending on alternative contingencies of energy use.

Projections of energy consumption based on historical data are not intended as recommendations or predictions for the future. What must be identified, however, are the possible energy requirements that the Nation might encounter so that decisions can be made in the near future that will allow us to protect our options for the distant future. Society will have to evaluate the implication of increases in energy consumption at historical rates and will have to decide whether the consequences of such growth are desirable. The selection of a desirable rate of energy growth, and society's ability to achieve it, will depend upon many factors, including the

*Comment Letters: J. C. Sheppard, 21, p. 3; Chauncey Kepford, 25, pp. 8, 12, 16, 24; Atlantic Richfield Co. International, 11, pp. 1-2; R. W. Freedman, 32, p. 2; NRDC, 38g, pp. 55-62; NRDC, 38i, pp. 9-10.

technological options available, as well as the impact that the desired rate will have on the economy and on the environment. The analysis of cost vs benefit centered around a case based on historical projection seems most prudent for this purpose.

The projection of energy inputs to the electrical sector was obtained by assuming that electrical energy input requirements also would continue to grow in relation to GNP much the same way that it has in the past. The projection of energy inputs to the electrical sector was converted to kilowatt-hours on the basis that electric utilities would continue to add more efficient generating units and, therefore, that the average energy inputs needed to produce a kilowatt-hour would gradually decline for the total U.S. utility system. Total installed capacity requirements were determined from the electrical projections and the historical level of average plant utilization by all utilities.

In contrast to the 2000 million kilowatts of electric generating capacity for the U.S. in the year 2000 reported in WASH-1139(72),⁵ a higher level of 2200 million kilowatts was projected, in good agreement with the case B projection of WASH-1139(74).⁶ The differences in these two projections result primarily from differences in the models used to project total energy demand and the assumption about the efficiency of energy use in the generation of electricity. The earlier WASH-1139 projection extrapolated the total energy consumed per capita to the year 2000 which, when combined with the Bureau of Census Series D projection of population growth, yielded a total energy demand of 143 quadrillion Btu. It was further assumed that the energy consumed in production of electricity would decrease from 10,300 to 8,500 Btu/kWhr from 1970 to 2000. The projection used for the cost-benefit analysis follows the approach of WASH-1139(74) in which the total energy demand was correlated with GNP, and GNP was projected using the Bureau of Census Series E population growth projections. The energy consumed in the production of electricity was assumed to decrease from 10,300 to 9,600, rather than the 8,500 Btu/kWhr assumed in the earlier projection. The fraction of total energy used to generate electricity and plant capacity factors were essentially the same in both projections.

Other approaches to projecting the electrical power growth have been considered. The total electrical consumption increased from the period 1950 to 1970 at an average rate of 8.0%/year.⁷ Using the base of 1.53 trillion kWhr in 1970, this growth rate would result in a consumption rate of electrical energy of 15.5 trillion kWhr in 2000 and 71.8 trillion kWhr by 2020. The required energy input to meet this electrical energy consumption is not only much greater than the projection in Table

11.2-8, but exceeds the total energy demand projection in the year 2020 by a factor of 2.

Cochran⁸ describes work by Searl in which the U.S. electrical energy demand was represented as a linear function of GNP, using data from 1947 to 1969. Using Searl's expression and extrapolating it to the year 2000 results in an estimated electrical energy demand of 6.5 trillion kWhr for a 4.0% growth rate in GNP and 5.5 trillion kWhr for a 3.5% growth rate. This latter number is to be compared with 10.6 trillion kWhr equivalent to the 97 quadrillion Btus projected in Table 11.2-8 for gross energy input to electrical utilities.

Chapman, Tyrell, and Mount⁹ have identified elasticity factors for electricity price, population, income, and gas price based on past variations in electricity consumption versus these parameters. Using these parameters and various assumptions about population growth and the increase in cost of electricity, they conclude that the probable electric consumption rate in 2000 will be in the range of 1.9 to 4.6 trillion kWhr and, in some cases, the rate of growth has turned negative by that time. The rate of electrical consumption was 1.7 trillion kWhr in 1972.

Six other projections of utility electric power generation in the year 2000 are given in the Survey of Energy Consumption Projections.¹⁰ These range from 4.5 to 10.8 trillion kWhr.

The Federal Power Commission (FPC) recently made projections to the year 2000 resulting in an estimated consumption rate of 11.1 trillion kWhr.¹¹ A current update of the 1970 FPC Power Survey using four load growth projections results in estimates ranging from 6.1 to 12.3 trillion kWhr for the year 2000. The Interior Department has also made projections of the electrical growth through the year 2000 and obtained 9.0 trillion kWhr.⁷

Several comments have been received on the level of electrical energy demand used in the cost-benefit analysis. Some of the commenters* felt that energy conservation and rising fuel costs give rise to the possibility of zero energy growth which would significantly alter the cost-benefit ratio. For example, EPA has commented** that:

*Comment Letters: Chauncey Kepford, 25, pp. 16-27; B. J. Smernoff, 26, p. 28; Hamilton Treadway, 15, pp. 3-4; Atlantic Richfield Co. International, 11, pp. 1-2; R. W. Freedman, 32, p. 2; John Huber, 60, pp. 1-2; R. I. Goldsmith, 1 P 20, p. 1; EPA, 2 P 15, p. 1; NRDC, 1 P 9, p. 2; G. I. Rochlin and J. P. Holdren, 55, p. 2; NRDC, 38g, p. 1; Minnesota Pollution Control Agency, 39, p. 2.

**Comment Letters 53, pp. 72-75; 2 P 15, p. 1.

Since higher electricity prices plus energy conservation measures could easily result in a reduction in the annual electricity growth rate of 2%, 3%, 4%, or more, the "low" electricity demand case in the AEC sensitivity analysis is not appropriate....In our opinion, this projection model is less useful than several other available models which do include prices as an explicit independent variable. For example, this model does not reflect rising consumer price indices over the last six months which show utility rates leading the inflationary spiral along with food and gas prices....Given the importance of the electrical capacity projections, EPA believes that in the final EIS, the AEC should include a detailed description of its projection model and defend it relative to the much different results obtained from other models, or use the range of projections from other models as the basis for "high-low" sensitivity analysis.

Similarly, NRDC has commented*:

The AEC has selected a set of assumptions which generates a very high demand scenario which is beneficial to the LMEBP primarily through a more rapid utilization of low cost uranium resources. The AEC could have projected electrical energy demand versus real GNP directly rather than projecting total energy versus real GNP, then using the arbitrary assumption that electrical consumption will grow from 25 percent of total energy in 1970 to 65 percent in 2020....As noted....above the AEC's electrical energy production doesn't factor in price elasticity. The AEC presents no supporting argument for its claim that electrical energy prices will not increase faster than the "general price level." ...Furthermore, with the rapid increases in utility rates recently, we doubt that the AEC could defend this assumption. We believe it to be incorrect.

Any projection model used to estimate electrical energy growth depends directly on the continued relevance of the parameters selected. Also, the projections must be tested against the larger framework in which it is used. The electrical energy projections used here are consistent with the previously described projections of population, Gross National Product, and total energy demand. As fossil fuels become harder to find, develop, and extract, energy prices could increase faster than the general price level. As a result, electric energy demand may not grow as rapidly as projected as the economy shifts toward more efficient end-use devices and production techniques. At the same time, it is possible that greater emphasis will be put on use of indigenous resources. One result could be that the shift to electricity will continue, perhaps at a greater rate than projected, even if a smaller total energy demand occurs. The advent of the breeder with its associated low fuel costs may prevent the consumer price of electricity from increasing more rapidly than the general price level as the breeder displaces fossil plants with

*Comment Letter 38a, pp. 56-57.

their high fuel costs in utility systems. As a result, the demand for electrical energy could increase greatly and it may be that electrical energy will be needed to perform many more tasks in the economy than it does today. The substitution of electricity for other energy forms, combined with new uses for electricity, have been important factors in its rapid rate of increase and, with the impending exhaustion of U.S. oil and gas resources, these factors should continue to be extremely important.

It was assumed in the base case of the cost-benefit analysis that 10.6 trillion kWhr of electricity would be required by the year 2000. This reflects our belief that electricity would continue to substitute for other forms of energy in areas of current energy use and that new cases would be found for it in the future. In order to reflect the uncertainty in total energy demand and consequent electrical demand, the cost-benefit analysis has been performed over a range of +20 to -50% of the base case electrical demand. The resultant electrical energy requirements were therefore assumed to range between 7.1 to 11.7 trillion kWhr in the year 2000, and between 13.8 to 33 trillion kWhr in the year 2020.

The fraction of the total electrical generating capacity required to produce the projected electric energy demand assigned to nuclear power was about 60% over the period of 1985 to 2020. The forecast of national electric generating capacity is given in Table 11.2-8. The high and low energy projections used in the cost-benefit analysis were assumed to directly affect the capacity projections for each type of power plant. Accordingly, each power-producing segment of the capacity projection was changed by whatever fraction the energy projection changed.

Table 11.2-8
NATIONAL ELECTRIC GENERATING CAPACITY FORECAST
[millions of kilowatts (electrical)]

Year	IC/Ct ^a	Hydro ^b	Nuclear	Fossil and Other	Total
1985	71	97	260	486	914
2000	150	150	1200	700	2200
2020	250	210	3300	2130	5890

^aInternal combustion and combustion turbine.

^bHydro includes pumped storage installations.

REFERENCES FOR SECTION 11.2.3.3

1. U.S. Department of Commerce, Bureau of the Census, Current Population Reports: Population Estimates and Projections, Demographic Projections for the U.S., Series P-25, No. 476, February 1972. -- Population Estimates and Projections, Illustrative Population Projections for the U.S.: The Demographic Effects of Alternate Paths to Zero Growth, Series P-25, No. 480, April 1972.
2. "Exploring Energy Choices," A Preliminary Report of the Ford Foundation's Energy Policy Project, Washington, D.C., 1974.
3. Ibid, p. 39.
4. "Survey of Energy Consumption Projections," prepared at the request of Henry M. Jackson, Chairman, Committee on Interior and Insular Affairs, U.S. Senate, U.S. Government Printing Office, Washington, D.C. (1972).
5. "Nuclear Power, 1973-2000," AEC Report WASH-1139(72) (December 1, 1972).
6. "Nuclear Power, 1973-2000," AEC Report WASH-1139(74) (February 1974).
7. Walter G. Dupree, Jr., and James A. West, "United States Energy through the Year 2000," U.S. Department of the Interior (December 1972).
8. Thomas B. Cochran, "The Liquid Metal Fast Breeder Reactor," Resources for the Future, Inc. (1974).
9. Diane Chapman, Timothy Tyrell, and Timothy Mount, "Electricity Demand Growth and the Energy Crisis," Science 178: 703-708 (1972).
10. Op. cit., p. 42.
11. "Oil and Gas Input Issues," Hearings before the Committee on Interior and Insular Affairs, U.S. Senate, January 10, 11, and 22, 1973, p. 629. See also Table 2.1-12, Section 2.1.3.4, Volume I, AEC Report WASH-1535.

11.2.3.4 Capacity Factors for Generating Plants

In normal utility practice, certain plants--usually those with the lowest incremental costs of power generation, are designated as "base-load" plants. These plants operate essentially at full capacity, except for outage requirements, during the time they are so designated. Others, designated as "load-followers," operate at less than full capacity, retaining some reserve capability for use at peak demand periods. Other facilities--older or specifically designated steam plants, gas turbines, hydroelectric plants, pumped storage units, and the like--operate at low plant factor as peaking plants.

For use in the calculations, two types of plants were considered--base-loaded and load-following. For purposes of the calculations, any given plant was assigned to one of the two categories upon introduction, and was constrained to follow the characteristics of that plant type throughout its life. In reality, a plant may be shifted from one operational mode to another, to meet changing conditions in the situation faced by a utility.

The capacity-factor history curves, shown in Figure 11.2-19, depict the average annual capacity factor of "typical" steam power plants under base-load and load-following conditions. The assignment of newly introduced plants to these curves is made in such proportion that the integrated annual average capacity factor for all central-station plants in the system is approximately 0.64. This value is in substantial agreement with utility experience in overall central-station capacity factors. The operation of other facilities at lower capacity factors (hydroelectric and pumped storage units, gas-turbine peaking plants, etc.) reduces the net capacity factor for a typical utility to about 52 to 54%.

11.2.3.5 Constraint on Reactor Capacity Introduced

From 1974 until about 1982, the penetration of nuclear plants into the U.S. power economy can be predicted with reasonable certainty. Only those plants which are currently committed for construction can be built during that time period. However, projection of electric generating capacity by plant type after 1982 must be based on the relative potential of all viable plant types. For reasons of local economic advantage, local fuel preference or improved technology, fossil fuels are likely to remain a factor to some extent in electric power production through the year 2000.

Other non-nuclear sources of power generation, including solar and geothermal energy, are expected to come increasingly into use in the latter part of the 20th

LOAD HISTORY CURVES ASSUMED FOR CENTRAL STATION POWER PLANTS
Figure 11.2-19

century. However, neither solar nor geothermal energy appears likely to develop into a major energy source within the time frame of this study. The application of geothermal and solar energy appears likely to be limited to favorable geographical areas. Solar energy applications in this century are likely to be restricted to individual residential uses, since central-station power generation has numerous technological and economic hurdles to overcome. If central-station solar-energy generation is ground-based, extensive energy storage facilities would be required to meet overnight demand and demand over prolonged periods of poor weather. Practical and economic energy storage devices for this purpose have not been developed. Utilization of satellite technology could bypass this need, but would require extensive technological advances and may be inordinately expensive. Geothermal energy appears economically attractive in limited geographical areas where thermal zones in the earth's crust are near the surface. As a general source for electrical generation, however, the extraction of geothermal energy appears expensive and technically difficult.

At some point in the future--possibly early in the next century, thermonuclear fusion may be utilized for generating electrical power and may become the predominate source of energy for electrical generation in the more distant future. Although the scientific feasibility of controlled thermonuclear fusion has yet to be established, the current emphasis being placed on fusion development will probably provide solutions to the technical problems now apparent in this field; the utilization of fusion for energy generation may become technically and economically feasible early in the 21st century.

The potential growth rates or extent of penetration of fusion-powered generation, or of geothermal or solar power, into the national power economy are difficult to estimate; technical and economic assessments have a much higher degree of uncertainty than is the case with fission reactors. However, to allow for the potential utilization of these technologies in future years, a portion of the total capacity demand (amounting to about 40% over the study period) has been assumed to be fulfilled by generation from fossil fuels, fusion, and the other technologies. Except for a few cases to test the comparative nuclear--fossil economic potential, nuclear fission energy was assumed not to supply any generation within this block. In all instances, except for a 50% reduction in electric energy demand, the projection for unconventional energy sources (solar, geothermal, organic wastes and fusion) is within the non-nuclear projection in the cost-benefit analysis.

The projections in Table 11.2-8 indicated an "envelope" of nuclear penetration into the power economy. The cost-benefit analysis assumes that various types of nuclear plants compete economically within the limitations of the nuclear penetration projections. Nuclear penetration would increase under conditions of unconstrained competition with fossil-fueled generating plants, as indicated by previous AEC studies* and industry opinion.** Free competition among fossil and nuclear plant types was assumed for several cases to allow comparison with previous studies.

For most of the cases considered, AEC projections of nuclear capacity by plant type given in report WASH-1139(72) were followed until the year 2000. Eight additional cases were formulated to study projections recently published in report WASH-1139(74). Projections in report WASH-1139(74) assume the developing LMFBR industry will experience early growth slower than indicated in report WASH-1139(72). The slow LMFBR growth rates are projected on the basis of comparisons with the early LWR industry. However, LWR history is not entirely analogous to the potential growth of the LMFBR industry.

For instance, five commercial LWR plants were constructed within five years of initial operation of the Shippingport prototypic installation in 1957. In reflecting on that experience, construction of a comparable, or larger, number of LMFBRs over a similar period of time appears both feasible and reasonable. From the viewpoint of utilities, the electrical demand of 1981 will be many times larger than extant in 1957, and the desire for new and improved technology will accordingly be stronger. From the viewpoint of reactor manufacturers, the risk in technological changes should be much less in proceeding from an LWR to an LMFBR than in moving from no nuclear power station experience to Shippingport. By 1981, a technological base of well over 24 years, during which 100 U.S. nuclear power stations will have been constructed, will be available to the LMFBR industry, whereas no base existed in 1957. Furthermore, much of that manufacturing capability can also be transferred in the current and future period from the prior LWR industry to LMFBR construction with little modification.

Without proper constraints, the linear program might choose to build new plants at a rate which exceeds industry growth capabilities. Thus, introductory constraints

*USAEC, "Cost Benefit Analysis of the U.S. Breeder Reactor Program," Report WASH-1126, April 1969. USAEC, "Updated (1970), Cost Benefit Analysis of the U.S. Breeder Reactor Program," Report WASH-1184, January 1972.

**General Electric, Comment Letter 64, p. 5.

are required for LMFBRs and HTGRs to simulate the tooling-up of the nuclear industry for production of new plant types. For those cases in which introduction constraints are limiting, they were applied as follows:

Two HTGRs, some 2000 MWe, are currently committed for operation in the 1980-81 biennium. In the following biennium, 4000 MWe maximum were allowed; in following periods, the HTGR capacity could not exceed twice the capacity of the preceding biennium. Only one LMFBR is permitted in the year of introduction. With several potential vendors, a maximum of 8000 MWe of LMFBR capacity was permitted in the next biennium, with the maximum new capacity in each following biennium limited to twice the capacity of the preceding biennium.

In the years past 2000, breeder and nonbreeder plants compete within the assumed nuclear envelope. The HTGR penetration was limited to 25% of the nonbreeder portion of this envelope in acknowledgement of the established competitive position of LWRs. A set of cases was defined and analyzed which contains a sensitivity analysis for cases where there are no constraints on the HTGR/LWR mix after 1985. The 28 cases provide a basis for analyzing the effects of removing the HTGR constraint after 1985, except for the initial introduction constraint discussed previously. The objective of the cases is to demonstrate the effects of removing the post-1985 constraints on HTGR, and similarly LMFBR capacity growth. The influence of the uranium price schedule was delineated by running half the cases using the optimistic uranium supply assumption. The constraint on the HTGR capacity growth was removed with and without the LMFBR constraint. The cases additionally considered were: (1) a 50% reduction in the year 2020 energy demand, (2) a constant \$100/kWe capital cost differential for the LMFBR throughout the study, (3) free competition among nuclear and fossil plants. The details of the assumptions and results of the cases are contained in Section 11.2.3.

The HTGR penetration constraints in the base cases are founded on the basis that one vendor offers HTGRs now and it is unlikely that additional reactor manufacturers will offer the HTGR in the near future. The EPA and NRDC* questioned the basis for the HTGR constraint, citing the potential incentive for utilities to purchase the HTGR, and thus the incentive for other vendors to offer the HTGR. However, several factors should be noted regarding the feasibility of vendors other than General Atomic Corporation (GAC) delivering HTGRs much earlier than year 2000.

*Comment Letters 53, p. 36; 38, 38g, pp. 51, 65-75.

- (1) The HTGR penetration to the year 2000 in the nonbreeder cases is in good agreement with the vendor's (GAC) own estimate.
- (2) The capital investment required for a second vendor to enter the HTGR nuclear Steam Supply (NSSS) market would be in the range of hundreds of millions of dollars, perhaps as much as \$500 million. In the 1980's, the present LWR NSSS manufacturers probably would be starting to get a good return on their investment and if the utilities did not indicate a strong preference for the HTGR, they might be reluctant to make the investment required to be able to offer HTGRs.
- (3) GAC investment in the HTGR may be billions of dollars by the time the first large commercial HTGRs are available in the 1980's and, consequently, their offering prices for HTGR may be optimized to enable them to recoup their investment as quickly as possible without inducing competition. In other words, their pricing policy, even if the HTGR is much less costly than LWRs, may be to maintain themselves as the sole HTGR supplier by making the HTGR only mildly competitive.

The EPA and NRDC* also indicated that the linear program in the cost-benefit model had been forced to "buy" uneconomical LMFBRs, by utilizing the AEC WASH-1139 report projections. Capacity of LMFBRs following initial commercial entry is limited, not supplanted, by the use of the WASH-1139(72) projections. If the linear program selected plants strictly on an economic basis, the early LMFBR capacity would increase much faster.

"Negative benefits" reported in the Draft Statement as occurring in the early years of LMFBR operation have been shown to be an artifact of the means of calculation. They are associated, not with the LMFBR, but with the means by which the calculations account for forward costs of LWRs, considered separately, in an LWR-LMFBR economy (see Section 11.2.3.3.5). In fact, the LMFBR provides benefits from the year of introduction onward. Test calculations performed assuming availability of only the "early commercial" oxide-fueled breeder first introduced show that this LMFBR model alone will provide a small benefit.

11.2.3.6 Mass Balance and Reactor Performance

The mass balance and performance data for all reactor types included in this analysis were completely revised from those used in previous studies. The new data are based on actual design and performance data for modern reactors and on projected

*Comment Letters 38g, pp. 73-74; 53, p. 36.

data for advanced reactor types supplied by vendors. All data were thoroughly analyzed and cross-checked to assure consistency and comparability. They include LWR mass balances for six different fuel-cycle options, HTGR data for six such options, and four LMFBR designs, including a breeder fueled with U-235.

The LWR designs represent varying options of uranium and plutonium fueling, plus one design specifically optimized for production of plutonium. The LWRs to be introduced prior to 1990, of 1300-MWe capacity, have design features consistent with today's Emergency Core Cooling System (ECCS) mitigation procedures. The 2000-MWe units to be introduced in 1990 and later are assumed to incorporate design solutions to ECCS problems, have improved performance features.

The six HTGR variations also feature varying fuel cycles involving U-235 and plutonium enrichment. They also are assumed to be available in two capacity ranges (1300 and 2000 MWe) for pre-1990 and post-1990 introduction. Apart from the secondary effects caused by reactor size, there is no difference in the fuel-cycle characteristics of the 1300- and 2000-MWe HTGRs.

Four different models of LMFBRs are used in the study. The first, an "early commercial" 1300-MWe oxide-fueled breeder, is assumed to be in operation prior to 1990. This is basically a scale-up of current FFTF and LMFBR demonstration plant concepts, with a relatively low breeding ratio of approximately 1.20. For some sensitivity studies, a 2000-MWe version of this plant was also assumed.

The second LMFBR type, an "advanced oxide" breeder, of 2000-MWe capacity, is assumed to be available for operation in 1991. This reactor, featuring a breeding ratio of 1.25, is a high-performance oxide breeder; problems of fuel swelling and of irradiation damage to cladding are assumed to have been solved for this design.

The third LMFBR design used in the study is a carbide-fueled reactor, of 2000-MWe capacity, assumed to be available for operation in 1995. Two designs are considered; one of a relatively small diameter fuel pin with a breeding ratio of 1.34; the other of a large fuel pin diameter (0.361 in.), with a breeding ratio of 1.46. Further details on LMFBR plutonium fuel core design development are given in Appendix A of Section 11.

A fourth LMFBR design, fueled with U-235 was assumed in the analysis to be available for introduction in cases where shortages of plutonium inhibited breeder penetration of the power economy. Both the uranium-fueled design and the LWR

type optimized for plutonium production were assumed to be available as supplementary plutonium sources if economically feasible.

Characteristics of the various reactor types used in the study are summarized in Table 11.2-9.

11.2.3.7 Uranium Cost Versus Supply

11.2.3.7.1 U.S. Uranium Supply

The current AEC assessment of U.S. uranium resource availability and of future consumption rates is described in Sections 6A.1.1.2, 6A.1.1.8, and 6A.1.1.9. For convenience, Table 11.2-10 and Figure 11.2-20 are included in this section, although the same information appears in Section 6.

Table 11.2-10
ESTIMATED U.S. URANIUM RESOURCES

U ₃ O ₈ Cost up to: \$/lb	<u>Cumulative Thousands of Short Tons of U₃O₈</u>		
	Reserves	Potential	Total
8.00	280	450	730
10.00	340	700	1,040
15.00	520	1,000	1,520
30.00	700	1,700	2,400

Table 11.2-10 summarizes known reserves plus estimated potential (i.e., as yet undiscovered, but thought to exist) resources of conventional sandstone uranium ores in the U.S. The AEC evaluates domestic uranium resources in terms of estimated recovery costs as a function of ore grade. The relationship between cut-off cost ranges and U₃O₈ content for a typical western sandstone deposit may be seen by referring to Figures 6A.1-4 and 6A.1-5 in Section 6. Thus, the dollar figures displayed in Table 11.2-10 are production cost cut-offs, not the prices that buyers will pay. Until recently, U₃O₈ prices have been less than \$8 per pound, but market prices are now rising rapidly.¹

Figure 11.2-20 displays estimated quantities of uranium occurring in U.S. sandstones, shales, and granites, as well as in seawater. There is a large gap between the uranium content of conventional sandstone ores (700 to 2100 ppm) and the highest grade shales (60 to 80 ppm), and a corresponding gap in estimated recovery costs. Uranium from these shales, estimated in 1960 to be recoverable at \$40 to 50/lb of

Table 11.2-9
TYPICAL REACTOR CHARACTERISTICS ASSUMED IN COST-BENEFIT ANALYSIS

Reactor Design	Plant Net Thermal Efficiency (%)	Earliest Date of Availability	Fuel	Equilibrium Fuel Exposures (MWd/Tonne)	Specific Power (MW/Tonne)	kg/!We-Year			Plutonium Simple Doubling Time (Years)	Net U ₃ O ₈ (Tonnes/!We-Year)	Net Separative Work (SWU/!We-Year)
						Net Yield Fissile Plutonium	U-233	Net Consumption U-235			
LWR											
Nonrecycle	33.0	1970	Enriched uranium for 30 years	32,000	37.3	0.228		0.851		0.211	148
Full Plutonium Recycle	33.0	1986	Fully enriched plutonium in depleted uranium for 30 years	32,000	37.3	-0.377		0.062		0 ^a	0
Intensive Plutonium	33.0	1980	Enriched uranium for 30 years with intensive plutonium production configuration	15,000	23.6	0.460		1.016		0.253	179
HTGR											
Annual Refueling	38.5	1980	Highly enriched U-235 startup, U-233 recycle	81,500	76.6	0.001	0.050	0.404		0.110	103
Semiannual Refueling	38.5	1984	Highly enriched U-235 startup, U-233 recycle	66,000	69.0	0.001	0.050	0.370		0.101	95
Plutonium Recycle	38.5	1986	Plutonium fuel in thorium carbide	199,000	249.2	-0.715	0.125	-0.003		0	0
LMFBR											
Early Oxide	40.0	1987	Plutonium-fueled oxide	110,000-Core 6,000-Blanket	53.0	0.141		0.011	28	0 ^a	0
Advanced Oxide	40.0	1991	Plutonium-fueled oxide	110,000-Core 6,000-Blanket	72.0	0.247		0.010	12.5	0 ^a	
Advanced Carbide (small diam pin)	40.0	1995	Plutonium-fueled carbide	110,000-Core 6,000-Blanket	60.0	0.303		0.013	7.6	0 ^a	
Advanced Carbide (large diam pin)	40.0	1995	Plutonium-fueled carbide	110,000-Core 6,000-Blanket	46.9	0.381		0.012	7.4	0 ^a	
Advanced Uranium Oxide	40.0	1991	Uranium-fueled oxide	110,000-Core 4,500-Blanket	72.0	0.507		1.637		0.372	327
Advanced Uranium Carbide	40.0	1995	Uranium-fueled carbide	95,000-Core 8,600-Blanket	60.0	0.598		1.629		0.359	312

^a Uses uranium from tails stockpile.

11.2-69

* 700 - 2100 ppm

ESTIMATES OF URANIUM AVAILABILITY FROM GEOLOGICAL FORMATIONS AND OCEANS IN THE U.S.

Figure 11.2-20

U_3O_8 (cost),² would likely cost in excess of \$90/lb of U_3O_8 under current circumstances (see Section 6A.1.1.9), thus implying sales prices over \$100/lb of U_3O_8 . It is noteworthy that due to the low concentration of uranium in the shales, the energy density of coal and shale are about the same when only converter reactors are available.

One reviewer* of the Draft Statement expressed doubt that the aforementioned gap in uranium-content ores is real. Future exploration may uncover uranium resources in the 70 to 700-ppm range, but judging from the information on-hand, such resources will not be found in the western sandstone type of deposit. The current information on other types of uranium mineralization does not suggest the existence of significant quantities** of uranium in this, or other, concentration ranges. Thus, in postulating and examining the cases used in this cost-benefit analysis--including a possible requirement for 10 million tons of U_3O_8 over the next 50 years--it has been necessary to accept the conventional and shale resources as the only ones available to meet the postulated requirement.

The AEC fully appreciates that the pivotal question vis a vis the rapid development of the breeders is the prospect for finding additional uranium resources with grades of ore that are higher than that in the shales. Consequently the AEC is undertaking a national uranium resource evaluation to better understand the prospects for expanding U.S. uranium resources. In this program, initiated in 1973, the country has been subdivided into 20 regions which will be studied individually by geologic teams. Forty-two subareas have been identified for more intensive study. Teams will gather data from industry and government and generate new information by sampling, airborne surveys, geochemical surveys, and drilling. They will seek out and delineate geologic environments known to be favorable for the occurrence of uranium considering the geology of known uranium districts in the U.S. and other countries, including low-grade types of deposits. The studies will also indicate the needs for further investigation and will provide guidance to industry for future exploration efforts.

The primary method of quantifying potential resources that may be present will be by comparison of a number of favorability factors in the study area to those present in known uranium areas. Additional assessment techniques will be employed and research will be conducted on improving assessment methodology. An evaluation of the State of New Mexico employing the Delphi technique, which involved some 36 experts, was completed recently and others are planned.

*G. I. Rochlin and J. P. Holdren, Comment Letter 55, attachment, p. 3.

**The figures in Table 11.2-10 include about 90,000 tons of U_3O_8 expected to be recovered as a by-product of phosphate rock and copper ore processing by the year 2000.

A preliminary national appraisal is scheduled for completion by the end of 1975. A more comprehensive evaluation is scheduled for 1980. Interim reports will be published as the study proceeds.

11.2.3.7.2 Assumptions Used in the Cost-Benefit Analysis

The uranium supply and price projections used in this study are given in Table 11.2-11. These cases cover a likely range of possibilities considering current knowledge of U.S. resources, the degree of exploration accomplished in the U.S., and exploration and production limitations. Revisions to these projections are likely to be necessary as resource assessment and exploration proceed.

Case A (Base Case)

This projection is based on the following assumptions:

- (1) Reserves and additional resources at various cutoff costs are as estimated by the AEC.
- (2) Rapidly increasing demand and rising prices will cause part of the production from resources in each cost category to be sold at higher prices than would be required by production costs. Thus, some resources in the \$8 cost cutoff category will be sold at well above the equivalent prices.
- (3) Further exploration will only slightly increase \$8 resources (reserves plus potential). The incremental resources at higher costs, \$8 to \$15 to \$30 per pound will increase to about double present estimates.
- (4) Erosion of higher cost resources will occur during mining of lower cost material, but these losses will be offset by subsequent discovery of additional higher cost material over and above the additions described in assumption 3.
- (5) Availability of production from resources will be restricted by the lead times required for exploration and construction of production facilities and by the production level feasibility limitations. Production rates from a particular category of resources will increase to a peak then tail off gradually over many years.
- (6) Production of uranium as a by-product of phosphoric acid and copper production will start in 1975, and aggregate about 90,000 tons of U_3O_8 through the year 2000 and about 200,000 tons through 2020.
- (7) Production from the Chattanooga shales, which contain several million tons of uranium, will be needed to fill annual requirements during the

Table 11.2-11
 PROJECTED U_3O_8 PRICE-QUANTITY RELATIONSHIPS
 (prices: 1974 dollars per pound of U_3O_8)

Cumulative Supply (Million Tons U_3O_8)	Case A (Base Case)	Case B	Case C
0	8	8	8
1	13	10	16
2	21	14	45
3	30	18	90
4	60	25	110
5	80	40	120
6	100	50	130
7	110	60	135
8	120	70	145
9	125	75	150
10	125	80	155

Note: The values given above are particular points on a continuous curve. For example, when the cumulative supply reaches a level of 5 million tons of U_3O_8 the price of U_3O_8 for case A has reached \$80/lb. Intermediate values can be interpolated.

2000 to 2010 decade and beyond. Lower cost production from the higher grade, more easily minable shales could amount to one million tons of U_3O_8 and will be available at \$60 per pound of U_3O_8 . Additional quantities will require higher costs, up to \$125 per pound of U_3O_8 .

- (8) Foreign demand will approximate available foreign supply. Net U.S. imports will be minor.
- (9) All prices are in 1974 dollars.

Case B (More Optimistic)

This case was developed using the same assumptions as for case A, but with the following, more optimistic, modifications:

- (1) Present \$8 resources will be expanded about 50%. Resources in the \$10 to \$15 increment will double, and resources at \$15 to \$30 will triple.
- (2) Uranium will be produced from Chattanooga shale at prices ranging from \$50 to \$80 per pound because of more advanced production technology and open-pit mining.

Case C (Pessimistic Estimate)

This case is based on a present estimate of resource availability with Case A assumptions modified as follows:

- (1) Resources up to the \$30 cutoff will expand by about one-fourth.
- (2) Some loss of current \$15 and \$30 per pound resources will occur during mining of the lower cost resources contained in the same deposits.
- (3) Initial Chattanooga shale production would be available at around \$80 per pound, but prices would increase to around \$150 per pound because of environmental control requirements, less favorable mining conditions, and difficulties in attaining the high mining and milling rates required.

The Case C assumptions and the corresponding U_3O_8 prices of Table 11.2-11 correspond most closely with the information and assessments on hand today. Nevertheless, the somewhat more-optimistic Case A has been selected as the base case for this study, on the basis that it is reasonable to expect the discovery of significant quantities of additional sandstone ores in the U.S., beyond those already included in Table 11.2-11, as exploration progresses. Case B may be, however, overly optimistic in the assumption for conventional uranium availability and on prices of uranium from shale, although not everyone would agree with this optimism.

Indeed, several reviewers of the Draft Statement take issue with the uranium resource and price assumptions used in the cost-benefit analysis,* claiming that AEC estimates of uranium resources are low and price estimates are high, tending to exaggerate the importance of early commercial introduction of the breeder. NRDC suggests the existence of more than 13 million tons of uranium in sandstone ores at a cut-off recovery cost of \$15/lb of U_3O_8 .** Noting that the AEC estimate of 1.5 million tons of U_3O_8 in the same category (see Table 11.2-10) is largely located, or expected to be found, in the known producing areas--which constitute no more than 10% of the land areas in which sandstones are found, NRDC postulates that the AEC estimate "...represents less than 10% of the ultimate domestic uranium resources in this type of geologic formation...." The same argument is made with respect to ores in the \$15 to \$50/lb cost categories.†

The weight of available evidence does not support the NRDC assumptions and resulting estimates, or the contentions of others who believe that very large quantities of sandstone ores exist and will be found. Geologic information and experience indicate that the present producing areas, which were located over a decade ago, are, geologically, the most favorable for uranium. Thus, prospects for finding large deposits of relatively high-grade uranium ores in other areas evidently are not of the highest order. In spite of considerable exploration in other areas over the past decade or so, no new uranium deposits comparable to the producing areas have been found. Moreover, exploratory drilling in recent years, while considerable, has not been adding sufficient uranium to the known reserves to keep up with the demand expected of few years hence.

In fact, there is a relatively new body of professional judgement indicating that the AEC estimates of sandstone uranium resources may be high. As part of the National Uranium Resource Evaluation program, the AEC recently asked for the individual evaluation of 36 highly qualified geologists in respect to uranium occurring in the San Juan Basin of New Mexico.³ This is the most important uranium producing area in the U.S. and one of the largest in the world. Of the 1.7 million tons of (undiscovered) estimated potential resources shown in Table 11.2-10, 740,000 tons are considered, in AEC estimates, to occur in the San Juan Basin. By contrast, the 36 individual estimates averaged 450,000 potential tons of U_3O_8 . The median of the estimates (18 estimates were below and 18 estimates were above) was 150,000 tons.

*Comment Letters: J. J. Barker, 14, p. 1; B. J. Smernoff, 26, p. 25; NRDC, 38b, pp. 5-33; NRDC, 38i, p. 5; G. I. Rochlin and J. P. Holdren, 55, p. 1 and attachment; NRDC, 38g, pp. 46-53.

**Comment Letter 38g, p. 48.

†Comment Letter 38g, p. 49.

Four estimates were above one million tons and 12 were below 100,000 tons. The AEC estimate is, therefore, well in the higher end of the range.

In view of the tenor of comments made in the previously identified comment letters, it is of some importance to emphasize that uranium exploration in the U.S. has been one of the most intensive and extensive search activities for native metals to date. Considering the large land area made up by the 50 states and the depths to which deposits have been found (4000 ft), it is hardly possible to consider exploration complete. Nevertheless, a large body of information exists.

The AEC resource estimates have been based on a more or less continuous and systematic evaluation of information collected in the field by government and industry personnel since the earliest days of the atomic energy program. In addition, there has been a growing insight into how and where uranium was concentrated into minable deposits by natural process in the geologic past. Thus, while the AEC estimates do not identify the ultimate availability of indigenous uranium, they do reflect those amounts of uranium that reasonably can be inferred from available information. Considerable information on the outlook for uranium supply and on requirements has been published in the last year or so. The major reports of interest are listed among the references for this section.⁴⁻¹³

In this context, it seems at least prudent to give serious consideration to the possibility that the ultimate availability of uranium from conventional areas will not be far removed from the currently estimated amounts, as is done in this Statement. In the matter of U_3O_8 sales prices vs supply, this Statement unquestionably errs on the low side of reality. The construction of Table 11.2-11 started with market prices in effect at the time, but does not reflect the more recent rapid escalation in prices¹ in the U.S. market. On this basis, the pricing assumptions made in the cost-benefit analysis are very conservative. This factor must be considered in judging the end results of the analysis.

The advent of lasers and a rapidly developing laser technology has enhanced the possibility of developing commercial-scale processes for the separation of uranium (and other) isotopes, at low cost and high separations efficiency, through the mechanism of selective photon excitation of molecules. Section 6A.1.1.2.4, "Potential Effect of Advanced Enrichment Processes on Resource Conservation," provides a discussion on laser isotope separation. Although that section speculates on the impact the laser process might have on uranium resources, it was thought

it would be appropriate to also examine its impact in the framework of the cost-benefit analysis. Therefore, some cases were run in the cost-benefit analysis to indicate the impact of a hypothetical "ultimate" laser process, assumed to be available after 1990 which offered 100% efficiency in isotope separation. Results of these cases are described in Section 11.2.4.2.7.

REFERENCES FOR SECTION 11.2.3.7

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2. Mineral Beneficiation Laboratory, Columbia University, "Recovery of Uranium from Chattanooga Shale - Final Report," Report RMO-4013, Office of Technical Services, Department of Commerce, Washington, D.C., September 1960.
3. AEC News Release No. 665, Grand Junction Office, Grand Junction, Colorado, June 25, 1974.
4. U.S. Atomic Energy Commission, Office of Planning and Analysis, "Nuclear Power 1974-2000," Report WASH-1139(74), U.S. Government Printing Office, Washington, D.C., February 1974.
5. U.S. Atomic Energy Commission, Division of Production and Materials Management, "Survey of United States Uranium Marketing Activity," Report WASH-1196(74), U.S. Government Printing Office, Washington, D.C., April 1974.
6. U.S. Atomic Energy Commission, Division of Production and Materials Management, "Nuclear Fuel Supply," Report WASH-1242, U.S. Government Printing Office, Washington, D.C., May 1973.
7. U.S. Atomic Energy Commission, Division of Production and Materials Management, "Nuclear Fuel Requirements and Resources," Report WASH-1243, U.S. Government Printing Office, Washington, D.C., May 1973.
8. U.S. Atomic Energy Commission, Directorate of Licensing, "Environmental Survey of the Nuclear Fuel Cycle," Report WASH-1248, Washington, D.C., November 1972.
9. U.S. Atomic Energy Commission, Grand Junction Office, "Statistical Data of the Uranium Industry," Report GJO-100(74), P.O. Box 2567, Grand Junction, Colorado, January 1974.
10. U.S. Atomic Energy Commission, Grand Junction Office, "Uranium Exploration Expenditures in 1973 and Plans for 1974-5," Report GJO-103(74), P.O. Box 2567, Grand Junction, Colorado, April 1974.
11. U.S. Atomic Energy Commission, "Potential Uranium Resources in the Western United States," Report GJO-104(73), P.O. Box 2567, Grand Junction, Colorado, May 1973.
12. U.S. Atomic Energy Commission, Grand Junction Office, "Nuclear Fuel Resources Evaluation," Report GJO-105(73), P.O. Box 2567, Grand Junction, Colorado, May 1973.
13. U.S. Atomic Energy Commission, Grand Junction Office, "Production Capability of the U.S. Mining Industry," Report GJO-106(73), P.O. Box 2567, Grand Junction, Colorado, May 1973.

11.2.3.8 Capital Costs

The estimated capital costs used in the study are shown in Table 11.2-12, and the results from detailed analysis leading to these estimates are presented in Table 11.2-13.

These estimates were made by the Studies and Evaluation Group of the Oak Ridge National Laboratory utilizing to a great extent information developed by United Engineers & Constructors and reported in WASH-1230, volumes I through V. The investment cost studies for LWR and fossil plants (volumes I through IV) have been recently updated to include all environmental and safety-related costs in effect since the date of the original studies. The study for HTGRs (volume V) was only recently completed and includes these costs. The CONCEPT computer code¹ was used to adjust these reference cost estimates to mid-1974 and to scale costs to the larger unit sizes. The CONCEPT code was designed primarily for use in examining average cost trends in capital costs, displaying the important elements in the underlying cost structure, determining the sensitivity to technical and economic factors, and providing reasonable long-range projections of costs on a consistent basis. Factors significantly affecting plant investment costs include size of unit, local construction and skilled labor rates, the utility's cost of money, and the heat rejection mode selected.

Two-unit plants with two different unit sizes are presented as a basis for these estimates. The 1300-MWe units were chosen to represent the average size of power plants built up to 1990. After 1990, it was assumed that the average plant size would increase to 2000 MWe. Although it is reasonable to expect further increases in unit size to occur, the rate of increase is uncertain and may be limited by undetermined constraints; therefore, the unit size was held constant at 2000 MWe after 1990.

11.2.3.8.1 Discussion of the Plant Capital Cost Estimates

The LWR capital cost for a plant sold in 1974 for on-line operation in 1981 is \$420/kWe in 1974 dollars or approximately \$565 in 1981 dollars. As a test of the credibility of this number, sale prices for LWR plants have been taken from the Nuclear News Buyers' Guide and evaluated. Generally the prices for plants sold across the country and scheduled for operation in 1981 ranged from slightly under \$500/kWe to slightly over \$600/kWe; thus the LWR estimate is in good agreement with actual contract prices reached in the marketplace.

Table 11.2-12
POWER PLANT CAPITAL COST ESTIMATES^a
(1974 dollars)

Power Plant Type	Capital Costs, \$/kWe					
	1974	1980	1985	1990	2000	2020
LWR (1300 MWe)	420	420	420	420		
LWR (2000 MWe)				368	368	368
LWR Pu producer (derated) (1300 MWe)	464	464	464	464		
(2000 MWe)				380	380	380
HTGR (1300 MWe)	419	419	419	419		
HTGR (2000 MWe)				367	367	367
LMFBR (1300 MWe)			520	487		
LMFBR (2000 MWe)				438	368	368
Coal-Fired Fossil (1300 MWe)	346	346	346	346		
Coal-Fired Fossil (2000 MWe)				316	316	316

^aGround rules for the above estimated were:

Environmental Systems	All plants use natural-draft evaporative cooling towers. Coal plant has wet limestone scrubber sulfur-oxide removal systems.
Plant Net Efficiency, %	LWR: 32.0 HTGR: 37.5 LMFBR: 40.0 Coal: 37.0
Plant Location	Hypothetical Middletown site
Construction Period	7-1/2 years for the first nuclear unit; 6 years for the first fossil unit. Second unit is one year later for nuclear and fossil.
Cost Basis	Mid-1974 dollar values. Interest during construction is included in capital cost. No escalation beyond mid-1974.
Interest Rate	7-1/2%/year compounded.

Table 11.2-13

DETAILED BREAKDOWN OF PLANT CAPITAL COSTS
(millions of dollars)

	2600 MWe (two units)				4000 MWe (two units)			
	Coal-Fired	HTGR	LWR	LMFBR	Coal-Fired	HTGR	LWR	LMFBR
<u>Direct Costs</u>								
Land and Land Rights	1	1	1	1	1	1	1	1
Physical Plant								
Structures and Site Facilities	81	141	126	130	112	199	178	184
Reactor Plant Equipment	239	208	204	383	352	269	264	490
Turbine Plant Equipment	175	206	221	180	247	291	311	254
Electric Plant Equipment	48	63	73	67	58	82	95	89
Miscellaneous Plant Equipment	7	13	10	12	9	15	12	14
Subtotal (Physical Plant)	550	631	634	771	778	856	860	1031
Spare Parts Allowance	4	4	4	6	5	6	6	8
Contingency Allowance	37	43	43	49	52	58	58	66
Subtotal (Physical Plant)	591	678	681	826	835	920	924	1105
<u>Indirect Costs</u>								
Construction, Facilities, Equipment and Services	44	37	37	44	60	48	48	57
Engineering and Construction Management Services	47	95	95	113	65	126	127	149
Other Costs	20	30	30	35	27	39	39	44
Interest During Construction	197	248	248	299	277	333	333	396
Subtotal (Indirect Costs)	308	410	410	491	429	546	547	646
Total Costs								
Millions of Dollars	900	1089	1092	1318	1265	1467	1472	1752
Dollars per Kilowatt	346	419	420	507	316	367	368	438

The HTGR cost estimate from the CONCEPT code is \$419/kWe, essentially the same as that for the LWR. No significance should be implied by the \$1/kWe difference between this and the \$420/kWe for LWRs. Detailed cost analyses performed by ORNL resulted in no observable significant difference in total cost of the HTGR and LWR.

Using similar cost estimating techniques as were used for the LWR and HTGR, along with data obtained from reactor manufacturers and an engineering firm, ORNL has estimated the capital cost for an early commercial LMFBR at \$507/kWe or about 25% higher than the nonbreeder reactors. This estimate has been adjusted to \$520/kWe for this study, giving an initial capital cost differential of \$100/kWe.

Estimated costs for all plants undergo a reduction in 1990 when it is assumed that the size of the generation unit increases from 1300 to 2000 MWe, as indicated previously. While the larger plant costs were obtained from the detailed CONCEPT code procedures, it is to be noted that these are in good agreement with numbers that are developed by the scaling formula where the scaling factor is 0.7, a commonly used number in industry.

Dr. C. Kepford,* in his comments to the Draft Statement states

...it [referring to Table 11.2-12] assumes initial costs which are lower by a considerable margin than today's estimated costs. For instance the estimated costs to complete the Limerick Station in Pennsylvania are about \$550 per kilowatt. This is significantly higher than the \$420 figure in the table. Similarly, for Fulton Generating Station, an HTGR, the projected costs by the owner, Philadelphia Electric Co., are \$645 per kilowatt, over 50% higher than that estimated for an HTGR. I suggest that \$800 per kilowatt would be initially a conservative estimate of its** capital cost...

The costs presented in Table 11.2-12 are in terms of mid-1974 dollars, as are all other costs used in the cost-benefit study, and do not include allowances for escalation either during the construction period or to other time periods. Escalation from start of construction to commercial operation at rates of 6 to 7%/year will add about 30% to the estimated cost, for a total of approximately \$540/kWe which agrees with the Limerick estimate. Applying the same rationale of escalation to the year of plant operation for the HTGR estimate gives an approximate plant cost slightly under \$600/kWe, this being in fair agreement with the Fulton Station value. Likewise, escalating the LMFBR estimate to a 1985 start-of-operation results in a value of approximately \$825/kWe.

*Comment Letter 25, p. 29.

**Though not specifically identified in the comment letter, it is believed that Dr. Kepford is associating this number with the LMFBR.

With reference to changes in the plant capital costs in the time period 1974 to 2000, the LWR, HTGR and coal-fired plant estimates remain constant except for the reduction that takes place in 1990 when the size of the units is increased from 1300 to 2000 MWe. The LMFBR costs reduce by approximately 6% from 1985 to 1990, and further by 16% from 1990 to 2000, these being in addition to the reduction for the size increase in 1990.

Many comments* were presented regarding the changes (or absence of changes) in plant capital costs from 1974 to 2000. The National Resources Defense Council (NRDC) summarizes their comments in this area as follows:

...since the 1970 analysis there is no new evidence that argues for the inclusion of a learning curve to decrease the LMFBR capital cost over time. Indeed, actual cost trends suggest the contrary will be the case. Moreover, there is certainly no valid argument to support increasing the LMFBR learning rate from 5 percent per decade to 16 percent per decade, while reducing the LWR and HTGR learning rates to zero, and there is no valid argument for starting the LMFBR learning rate at the date of commercial introduction rather than five, ten or even 16 years later.

The Environmental Protection Agency (EPA) also comments to the effect that it has reservations about the degree of optimism embodied in the AEC position of learning associated with the LMFBR, pointing out also the difference in the learning approach from that previously adopted by ORNL,² specifically, that capital costs (in constant dollars) continue at the same level for ten years after introduction of a given reactor type.

Other reviewers also take similar issue with the learning effects assumed.

Dr. Kepford comments

...and history suggests that whatever the cost is, it will not decrease with time, but will drastically increase.

Mr. Barry Smernoff of the Hudson Institute comments

...one cannot be confident that LWR's have settled down on an economic learning curve.... There is little reason to believe that the estimate of \$520/KWe for 1300 MWe LMFBR's in 1985, dropping to \$487/KWe in merely five years...is correct...

*Comment Letters: Chauncey Kepford, 25, p. 29; B. J. Smernoff, 26, pp. 17-20; NRDC, 38g, pp. 10-11, pp. 19-50; EPA, 53, pp. 56-59; John Huber, 60, p. 3.

This assumption in no way is substantiated and seems to disregard the likelihood that LWR technology would not remain constant,...

The foregoing comments can be summarized into the following issues: (1) the application (and degree) of learning assumed for the nuclear reactor system considered in this study; and (2) the inconsistency with a previously published doctrine² covering, in this case, the application of learning to the LMFBR costs upon commercial introduction.

With reference to the first issue, examination of LWR cost trends indicate that the price of the nuclear steam system has remained relatively constant over the past several years, exclusive of escalation. This has occurred in spite of the cost additions resulting from increased environmental and safety concerns. Thus, it is concluded that the effects of learning and scale of industry operations in the manufacture of nuclear components have led to reductions in some areas of LWR plant costs. These reductions have, unfortunately, been offset by even larger cost increases arising from environmental and safety-related requirements, which increased the scope of work involved in plant construction. In addition, general inflationary cost trends have led to increasing current-dollar costs. The continuation of these LWR trends into the future is uncertain. However, the LWR industry is considered to have reached a relatively mature level. Current LWR cost estimates include all presently implemented environmental and safety requirements and reflect experience gained during the construction of about 23,000 MWe of nuclear capacity as of January 1, 1973, and the planning and construction underway for an additional 80,000 MWe of capacity to be completed by 1980.

In addition, it is anticipated that future changes required for LWR plants will affect other nuclear plants in a similar manner, and some changes (e.g., thermal discharge limits) would also affect fossil plant costs. The cost effect of possible future changes in safety and environmental requirements has not been estimated, since the nature of the changes is not known. However, the AEC is continuing to develop more accurate cost estimates through activities by the national laboratories, through contracts with architect-engineers, and by consultations with reactor equipment manufacturers and utilities. As these activities progress, the reference plant cost estimates will be updated as needed.

For purposes of the cost-benefit study, it was assumed that any effects from continuing learning or design changes would make little change in the relative cost

of LWR plants. It is recognized that the absolute costs of LWR plants may increase or decrease in the future, due to escalation and the changing requirements discussed above. However, this assumption states the belief that those undefined changes will not alter the cost position of the LWR relative to other plant types. Therefore, to provide a reference cost base, the projected LWR capital costs were based on zero learning beyond the plants being ordered for operation in 1981. Capital costs for the other plant types were estimated relative to this reference base.

As mentioned previously, the AEC has sponsored detailed cost studies for both the LWR and HTGR plants. These studies showed no significant difference in the total cost of HTGR and LWR plants. The design characteristics and plant features were examined to determine if there were inherent differences which would tend to cause future HTGR costs to follow a different trend than that assumed for the LWRs. Although the large commercial HTGR is at an earlier stage than large commercial LWRs, it is subject to the same environmental and safety regulations, and its development has benefited from the developmental process which LWRs have undergone. It was concluded, therefore, that a reasonable assumption would be to hold the HTGR and LWR capital costs equal throughout the time span considered. This assumption still gives the HTGR a competitive advantage in power costs, since it is projected to have lower fuel costs than LWRs. Because of this, it might be concluded that there exists no great marketplace incentive for HTGR capital costs to ever become substantially lower than LWR capital costs.

In addressing the issue as to what appears to the reviewers to be extremely rapid decreases in LMFBR costs, specifically 6% in 1985 to 1990 and 16% in 1990 to 2000, it is the AEC position that these are not unreasonable. Further, if the learning effect is examined on a classical basis,* the cost reduction from \$520/kWe to \$487/kWe for the 1300-MWe LMFBR is equivalent to a 98% learning curve, assuming that ten units are placed in operation in this time period. In addition, the cost reduction from \$438/kWe to \$368/kWe for the 2000-MWe LMFBR is equivalent to a learning curve slightly under 98%, assuming that 210 units are placed in operation from 1990 to 2000. The composite learning curve for both 1300- and 2000-MWe units, including the decrease in cost in 1990 due to cost-size scaling is just under 96%. Thus, the learning curve assumed for the LMFBR is extremely conservative in comparison with typical values of 80 to 90% learning curves applicable to many

*It has been established by empirical studies that as a general rule the logarithm of the cost of a product is a decreasing linear function of the logarithm of the number of units that have been produced. For example, a 90% learning curve is one in which the unit cost is reduced by 10% whenever the number of units produced has been doubled.

industries. This conservative approach is acceptable, since the learning curve being used here applies to reductions in the cost differential for the LMFBR, and not to the total cost change.

With reference to the issue that the LMFBR should show no learning for the initial ten years after its introduction, it is the AEC's position that the conditions in the LWR industry in 1971 when this conclusion was reached are different from those existing today for the LMFBR. For instance, the conditions that plagued the LWR industry just prior to 1971 and related to changes in scope of work resulting from additional environmental and safety related requirements, new quality assurance provisions, schedular delays, construction cost increases, etc., which increased the cost of the LWR to the extent that any learning effects were obscured are already, to a great extent, factored into the LMFBR cost estimates. Thus, the gross learning that takes place in the LMFBR upon its commercial introduction, though offset to some extent by cost increases that today are not evident, is predicted to result in a small net learning effect as reflected in the cost estimate.

It should be emphasized also that the LMFBR is not a totally new power system, in the sense that nuclear fission is totally different from combustion, but rather one that is closely related to the LWR. The basic principles of design, construction, and operation of the LMFBR are similar to those of the LWR. It is acknowledged that some features of this advanced reactor--temperature and pressure of operation and some materials of construction--are different, but these can be viewed as modifications to the existing reactor system rather than features of a plant utilizing an entirely new principle of energy production.

It is noted, also, that much of the LWR experience, including its expert staff, its ways of doing business, its use of nuclear industry standards on design and manufacture of product, and its manufacturing facilities and skills will be applied in all probability to this program.

In summary, following their review of the Draft Statement, many organizations and individuals took issue with the learning approach used in the power plant capital cost estimates. However, in considering all factors and utilizing the expertise in the area of cost estimating developed at ORNL with some assistance from reactor manufacturers and an architect-engineer, it is the AEC's position for this study that:

- (1) The LWR capital costs (in 1974 dollars) will remain fairly constant in the period 1974 to 2020 for units of equal size and siting conditions.

- (2) The HTGR capital costs will be rather close to the LWR costs.
- (3) The LMFBR costs will show some reduction due to learning starting with its introduction and at a rate which is reasonable in terms of the number of units produced.

Further discussions on the LMFBR capital costs and justification for their reduction are presented in a later section.

11.2.3.8.2 Relative Power Plant Costs

LWR and Fossil

Capital costs for this study are considerably higher than those used in the 1970 study. Costs since then have increased about 70% for both LWR and fossil plants. The increased costs reflect changes which have occurred in the marketplace. They result from escalation of construction costs, from added quality requirements, and from additional equipment required to comply with more stringent regulations pertaining to safety and environmental impact. However, as of this time period, large-sized LWRs (about 1000 MWe) are being operated, and, from this experience, an established history for LWR costs and a firm basis for estimating their present and projected costs are developing.

Fossil plants in the study were represented by coal-fired plants. Recent events have served to confirm the indications of longer-range trends to the effect that coal will be the dominant fuel for fossil-fuel-fired power generation. Recent increases in oil prices, natural gas shortages, and increasing demand for both uses other than boiler fuels make it unlikely that either oil or gas will play significant roles in commercial power generation in the future.

Previous discussions have indicated that the LWR, in the opinion of the AEC, has reached a mature stage and further overall plant cost increases (in terms of 1974 dollars) will not be large. There will be increases in some areas, but reductions in others, and the net effect will be a leveling of the total plant costs.

The areas that have experienced and may continue to show cost increases are essentially common to all plant types, and, consequently, the relative cost position of nuclear and fossil-fueled power plants still favors nuclear. This is a consequence of the much lower fuel-cycle costs of nuclear power plants.

An LWR plant that was specially designed for increased plutonium production was included in the mix of available nuclear power plants. Plutonium production was increased by refueling at a lower burnup, specifically about 15,000 MWD/ton instead of about 33,000 MWD/ton, and by using a tighter core lattice to harden the neutron spectrum. The tighter lattice required that the core power density be reduced due to a lower heat removal capability. This resulted in an increased cost per kilowatt electrical for this type of LWR. The 1300-MWe unit had about a 10% increase (relative to the standard LWR) of \$44/kWe which decreased to \$12/kWe for the 2000-MWe unit.

LWR and HTGR

While detailed cost studies of the LWR and HTGR indicated that the total direct costs were about the same for both plants of the same size, distribution of the costs differed somewhat, and the following enumeration considers the differences for the major cost accounts.

- (1) Structures and improvements: HTGR costs were higher primarily due to higher costs of the reactor service building which houses the fuel storage facility.
- (2) Reactor plant equipment: The cost of the prestressed concrete reactor vessel (PCRV) and associated equipment and internals of the HTGR is greater than that of the reactor pressure vessel and internals for an LWR of comparable size. This leads to a higher total HTGR cost for these components even though the engineered safety features for the HTGR are fewer in number and costs.
- (3) Turbine plant equipment: The higher energy steam produced in the HTGR plant leads to smaller turbines and higher thermal efficiency, relative to the LWR plant and results in lower HTGR turbine costs.
- (4) Electric plant equipment: The costs of electric plant equipment are lower for the HTGR primarily due to differences in design and higher thermal efficiency, which results in smaller auxiliary loads, and therefore smaller and less costly equipment compared to the LWR.
- (5) Miscellaneous plant equipment: These costs are slightly higher for the HTGR plant.
- (6) Indirect costs: All the indirect costs including the cost of engineering, construction management, field supervision, quality assurance, construction facilities and equipment, operator training and general administrative expenses are about the same for HTGR and LWR plants of comparable size.

- (7) Interest during construction: Since the total of the costs for the HTGR is about the same as for a comparable size LWR, the cost of interest during construction will be about equal for the two plant types.

These factors of design and cost differences are expected to continue to influence the future relative costs of HTGR and LWR power plants, although both plants will undoubtedly show improvements in design and costs. Thus, the capital costs of HTGR and LWR plants are expected to be about equal throughout the period of this study.

LMFBR and LWR

The early commercial LMFBRs will have capital costs approximately \$100/kWe higher than the LWRs when introduced into the nuclear industry in approximately 1987. This cost differential decreases after introduction, to reflect improvements in design and construction features and progression to larger unit sizes, to a zero cost differential in the year 2000.

The decrease in the differential in costs is believed to be readily achievable due to the inherent favorable features of LMFBRs which would lead to lower capital costs in a mature industry. These features are:

- (1) Low pressure system making possible in-plant and system-design simplification;
- (2) Improved reactor performance achieved by going to large unit sizes;
- (3) Absence of major physical restrictions to building very large units;
- (4) Smaller core and building sizes per unit of capacity;
- (5) High thermal efficiency with lower heat rejection requirements;
- (6) Ability to shop fabricate essentially all the reactor plant equipment including the reactor vessel.

Consistent with the above, plans have been developed which emphasize specific programs of cost reduction for many plant systems and components. Some of the specific milestone advancements identified in these plans are as follows:

- (1) For the early commercial LMFBRs (i.e., advancements accomplished in going from the Clinch River Demonstration Plant to approximately 1987)
 - (a) Relocate primary pump from hot leg to cold leg of primary system in order to minimize pipe size.

- (b) Simplify and improve designs of other heat transport systems as intermediate heat exchanger, steam generator, secondary pumps, and valves.
 - (c) Improve auxiliary systems design.
 - (d) Improve refueling system design for more efficient refueling operations, and also for reduction in reactor vessel size from that adopted for the CRBRP.
 - (e) Improve performance of reactor core through use of vented fuel, low-swelling structural alloys, larger assemblies, taller core, and higher fuel volume fraction.
- (2) For the competitive commercial LMFBR (i.e., advancement in the period 1987 to early 1990's).
- (a) Utilize components developed for the earlier commercials and upgrade the design concept of three loops for the 1300- to 1500-MWe early commercial unit (450 to 500 MWe per loop) to a concept of four loops for the 2000-MWe commercial unit (with same loop size).
 - (b) Reduce reactor containment diameter through either floating components or primary loop bellows; also reduce component compartmentalization leading to smaller reactor building size.
 - (c) Eliminate intermediate heat exchanger; adopt double-wall primary steam-generator concept.
 - (d) Simplify systems, reducing duplication of equipment.
- (3) For the mature commercial LMFBR industries (i.e., beyond the early 1990's):
- (a) Promote simplification of nuclear standards and industries' familiarization with these standards.
 - (b) Improve manufacturing techniques.
 - (c) Take advantage of multiple plant effects.

The cost trends for the LMFBR and the cost differentials between the LMFBR and the nonbreeders presented in Table 11.2-12 assume the advancements as indicated above in moving from the demonstration stage to the early commercial and then to the economically competitive commercial era. The assumed rate of improvement is not large, reducing costs by 22% and the differential by \$100/kWe over the 13-year period from 1987 to 2000. During this same period, the LMFBR industry is projected to progress from the early commercial stage to installations of about 370 GWe of LMFBR capacity.

NRDC* questions the elimination of the intermediate heat-exchanger system and the adoption of the primary steam generator concept.

The AEC fully realizes that the intermediate loop serves as an important safety feature. Sodium and water react violently upon contact. The intermediate loop isolates the steam-generator from the primary sodium-coolant loop preventing the possibility of this reaction from taking place in the primary loop, thereby reducing the probability of loss of primary loop integrity. A steam leak into the primary sodium loop could result in severe pressure transients or loss of coolant flow in or loss of coolant from the reactor core....If the intermediate loop were eliminated, the steam generator would still have to have double-walled tubing to reduce the probability of steam leaks into the sodium. At the April American Nuclear Society - Fast Reactor Safety Meeting, Dr. J. F. Petit of CEA-France, reported that his country had studied the possibility of eliminating the intermediate loop and discarded the idea for reasons of economics, aside from the safety question.**

The generally accepted approach being considered in the elimination of the intermediate heat exchanger is to adopt the double-walled primary heat-exchanger concept. This provides the same degree of safety to the system in that two walls still separate the primary system sodium and the water. However, reliability of the total heat-transport system has been improved through simplification of the system, elimination of major components and auxiliary systems, and reduction in length of piping, number of fittings, etc. Detailed cost calculations taking into account the increased cost of the primary steam-generator concept, and also the decreased costs associated with the elimination of the intermediate heat exchanger and related costs as reduced size of the overall system and plant, indicate that significant savings (15 to 20% of total plant cost) can be realized.

There seem to be no inherent reasons for LMFBF plants to be more expensive than LWRs or HTGRs. Some industry sources (both U.S. and foreign) argue that the LMFBF may ultimately be cheaper to build than the LWR, primarily due to the low primary and secondary system pressure and high thermal efficiency of the sodium system.

For example, at the 1974 American Power Conference, a paper by the General Electric Company³ stated:

Because commercial LMFBFs have not been built, their future actual cost is uncertain. Conceptual design work indicates that in principle they

*Comment Letter 38g, pp. 26-27.

**Dr. J. F. Petit of CEA-France, Session on Fast Reactor Safety Needs, American Nuclear Society--Fast Reactor Safety Meeting, Beverly Hills, California, April 2, 1974.

should not cost much more than today's LWRs once initial first-of-a-kind costs in the early plants are past and an LMFBR equipment industry is in place.

An earlier paper by General Electric⁴ presented similar arguments and reached similar conclusions:

Despite the difficulty of establishing precise cost-technology, cost-size, and cost-multiple-plant relationships, sufficient effort has been conducted to establish the fact that these three ingredients...will be sufficient to establish a competitive LMFBR cost.

Some indications of the learning from first-of-a-kind to early commercial plant costs are given in another paper.⁵ Discussion presented stated that the fourth-of-a-kind plant cost was judged to be competitive with LWRs.

The French⁶ also have made recently some noteworthy comments on cost improvements in their program -

31. Investment costs

All under-mentioned costs are to be understood without intercalary interest, nor fuel.

-Studies start from PHENIX datum, now well known, and pass through an estimation of SUPER-PHENIX cost, which become more and more precise as project goes on; then studies lead to valuation for future commercial plants.

These valuations are compared with costs of LWR plants, at the same power level and the same date, in order to examine if fast breeders are able to find their own place from economic point of view only, without taking into account their fundamental interest as for utilization of natural resources of uranium.

-From PHENIX cost, it has been withdrawn, first supplementary costs due to prototype feature of the plant, then gains obtained by dimensions effect growing from 250 to 1200 MWe. Result for SUPER-PHENIX is 1,670 millions of F. F., i.e. 1,440 FF/KWe (\$335/KWe).

-For future 1200 MWe plants, two factors has been taken into account; scale effect, more and more tangible as number of plants grows, and technical progress, influence of which, clear for LWR's at their current development stage, will be clear moreover for plants only at their beginnings yet.

Results of detailed study show that, from the first plant to the sixth one, it may be expected a cost-decline 20 to 30%, which gives 1,000 to 1,150 FF/KWe (235 to 270 \$/KWe), with a supplementary decline of 10% if two plants are erected in the same site.

11.2.3.8.3 Summary Review of Comments

Comments expressed by reviewers of this section of the Statement tended to fall into four general categories:

- (1) Extra capital costs will be accrued by LMFBRs because of additional safeguards and safety hardware and plant expenses.*
- (2) Capital costs are too low initially.**
- (3) Learning effects of the LMFBR are optimistic both from the standpoint of "when-started" and rate of improvement as compared to learning effects assumed for the LWR and HTGR.[†]
- (4) Capital costs need further review.

With reference to Comment 1, the LMFBR estimate given in Table 11.2-24 reflects the cost projections of many safety-related items. These have been incorporated in this reactor concept resulting from the manner of its development, that is the progression from the FFTF, to the CRBRP, and then to early commercial plants in which safety and reliability of operation were emphasized either more strongly or equally as strong as other objectives of low plant cost, improved fuel systems, etc. It is recognized, however, that there will be additional costs because of additional safety and environmental related items. Some provisions for this have been included in the use of the \$100/kWe differential rather than \$87/kWe as projected by the actual cost estimates. Other additions will be offset by normal cost improvements in plant and component design and manufacture as discussed previously. Finally, some cost additions will be generic, affecting equally all reactor systems with no change in the cost differential of the LMFBR with its competing nuclear system.

With respect to Comments 2 and 3, it is felt that this has been covered in the foregoing discussion.

With reference to Comment 4, the AEC has performed a rather extensive review of its capital cost position. It has done this with the assistance of personnel from the ORNL Studies and Evaluation Group and Hanford Engineering Development Laboratory. Consultations with reactor manufacturers and engineering firms have been held, and suggestions from these consultants have influenced the assumptions and values which were used.

*Comment Letters: Chauncey Kepford, 25, pp. 10, 11; B. J. Smernoff, 26, p. 21; NRDC, IP-7, p. 9.

**Comment Letters: Chauncey Kepford, 25, p. 29; B. J. Smernoff, 26, pp. 17-20; NRDC 38, pp. 10-11, EPA, 53, pp. 54-59; John Huber, 60, p. 3; General Electric, 64, p. 3; SIPI, H-18, pp. IV.2-4. SIPI, Testimony, pp. 314, 315.

†Comment Letters: Ebasco Services 18, pp. 5,6; T. B. Taylor, 37, pp. 5,6.

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2. H. I. Bowers and M. L. Myers, Estimated Capital Costs of Nuclear and Fossil Power Plants, Oak Ridge National Laboratory, ORNL-TM-3243 (Mar. 5, 1971).
3. R. S. Palmer and K. H. Horst, "Cost Targets for Commercial LMFBR's," American Power Conference, April 28--May 1, 1974.
4. J. Barnard et al., "Development of the Commercial Breeder," General Electric Co., Nuclear News, 15(12): 30-36 (December 1972).
5. L. A. Feathers, "Realizing the Potential of the Breeder," General Electric Co., paper presented at the 1973 American Power Conference, Chicago, Illinois.
6. R. Carle, J. Megy, J. Fedoe, and J. Villeneuve, "Future Programs and Plans for Prototype and Prospects for Commercial Fast Reactors (CFR's)," paper presented at the BNEC Conference on Fast Reactor Power Stations, March 11-14, 1974.

11.2.3.9 Plant Operating and Maintenance Costs

Operating and maintenance costs used in this study for the various types of plants involved are shown in Table 11.2-14. These cost estimates were made by the Studies and Evaluations Group of Oak Ridge National Laboratory in the same series of studies which resulted in the previously discussed estimates of plant capital costs. These estimates are derived from an analysis of the costs of operation of typical modern fossil- and nuclear-fueled plants, and were extended to projected future plant types by means of the CONCEPT and ORCOST computer codes.

In accordance with utility accounting practice, the operating and maintenance costs are presented in two categories: fixed costs, which are incurred by an operating plant independent of capacity factor; and variable costs, which are proportional to the amount of energy generated. The two cost categories are used in this fashion in the computer model.

All the cost items are higher than in the 1970 study--as might be expected for wage-intensive costs such as these. A significant increase in fossil-fueled plant costs, however, results from the addition of sulfur removal systems. Operating and maintenance costs for these systems and the disposal costs of ash and sulfur-removal by-products, form the major portion of fossil-fueled plant operating and maintenance costs. Higher costs of staffing a fossil-fueled plant, as well, stem primarily from sulfur-removal operations and fuel handling.

The increased maintenance costs associated with sodium systems are primarily responsible for the higher operating and maintenance costs of LMFBRs as compared with other nuclear plant types. As with capital costs, these costs might be expected to decrease with time, through "learning effects" and improved equipment designs. However, no credit was taken in the study for any such decrease.

The costs levied against nuclear plants include nuclear insurance premiums, assessed at a flat fee, and nuclear licensing fees, which are based on the thermal rating of a plant.

11.2.3.10 Fuel-Cycle Component Charges and Times Required for Fuel-Cycle Steps

The systems analysis model utilizes unit costs for each component of the fuel cycle including chemical preparation and isotopic enrichment of raw materials, fabrication of fuel, conversion, and chemical reprocessing which have been computed based on fuel mass flows for the entire life of each nuclear plant considered. The code

TABLE 11.2-14

ASSUMED ANNUAL OPERATION COSTS FOR PLANTS IN STUDY
(costs in thousands of dollars at 80% plant factor)

	1300-MWe Units* (Introduced Before 1990)				2000-MWe Units* (Introduced 1990 and Later)			
	LWR	HTGR	LMFBR	Fossil (coal)	LWR	HTGR	LMFBR	Fossil (coal)
<u>Fixed Costs</u>								
Staff	2240	2240	2240	2,400	2480	2480	2480	2,700
Fixed Maintenance	4770	4770	5840	10,270	6600	6600	7400	14,250
Insurance	580	580	580	0	580	580	580	0
Fees	290	240	230	0	450	370	350	0
Administration and General	<u>1080</u>	<u>1080</u>	<u>1080</u>	<u>1,450</u>	<u>1420</u>	<u>1420</u>	<u>1420</u>	<u>2,140</u>
Total Fixed Costs	8960	8910	9970	14,120	11,530	11,450	12,230	19,090
<u>Variable Costs</u>								
Variable Maintenance	2380	2380	2920	5,270	3290	3290	3700	7,870
Supplies and Miscellaneous	1410	1410	1650	1,440	1840	1840	2040	1,990
Limestone, Ash, and Slurry Disposal	<u>0</u>	<u>0</u>	<u>0</u>	<u>19,000</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>29,750</u>
Total Variable Costs	3790	3790	4570	25,710	5130	5130	5740	39,610

*Two units per plant.

used (FUELCO) is applicable to power systems in which the number of power plants installed is changing with time, and several different kinds of reactors are used. The effective unit costs for a given process in the fuel cycle are thus a complex function of the extent of penetration of the various reactor types into the power economy.

Historical trends in fuel-cycle costs have varied from those predicted in earlier studies. Fuel reprocessing costs are higher than those predicted, whereas fuel fabrication costs are lower.

For the current study, therefore, present and projected fuel-cycle costs were evaluated based on an analysis of the individual processes involved and on consideration of vendor-supplied data. The costs of fuel-cycle operations for LWR and LMFBFR plants were calculated by the FUELCO code, using cost coefficients based on the analyses performed. For HTGR fuels, vendor-supplied data were used directly. Table 11.2-15 shows some cost elements of the fuel cycle used in the study.

The shipping costs of fresh and spent fuel were estimated based on data accumulated in other AEC studies. Fresh fuel shipping costs ranged from \$1/kg for U-235 enriched fuel, to \$5/kg for plutonium fuels and \$6/kg for U-233-enriched HTGR fuels. Spent fuel shipments were assumed to be \$7/kg for LWR fuel, \$50/kg for HTGRs, and \$38/kg for LMFBFRs.

Storage costs for bred fuels were considered in the current study for the first time. Based on an analysis of trends in these costs, storage charges for fissile plutonium were taken at \$500/kg-year, and for U-233 at \$600/kg-year.

The times associated with various steps of the fuel cycle, as used in the study, are shown in Table 11.2-16. These times were checked for consistency with the fuel mass balances of the various reactor types involved and with normal industry practice.

11.2.3.11 Uranium Enrichment (Separative Work)

Uranium-fueled reactors utilize fuel which is enriched in the fissionable isotope U-235. The concentration of U-235 in such fuels is several times greater than the concentration found in uranium ore. Uranium is presently enriched in gaseous diffusion plants operated by the Federal Government. The gaseous diffusion process forces uranium hexafluoride gas (UF_6) by a pressure differential through permeable tubes. The molecules with U-235 atoms diffuse slightly more readily than the molecules with U-238 atoms. When this process is repeated, the UF_6 increases in

Table 11.2-15

FABRICATION AND REPROCESSING COSTS
(1974 DOLLARS) GENERATED WITH FUELCO

Reactor Type	Fabrication (including fuel preparation) (\$/kg)		Reprocessing (including conversion) (\$/kg)	
	Initial ^a	2020	Initial ^a	2020
LWR (U-235 fueled)	60	31	94	41
LWR (Plutonium recycle)	155	47	102	43
HTGR (U-233 fueled)	225	147	215	85
HTGR (U-235 fueled)	200	115	215	85
HTGR (Plutonium fueled)	760 ^b /225	147	215	85
LMFBR (oxide)	239	105	92	73
LMFBR (carbide, large diameter fuel pin)	80	41	75	73
LMFBR (carbide, small diameter fuel pin)	150	100	75	73

^a1974 for LWR and HTGR; 1987 for LMFBR oxide; 1995 for LMFBR carbide.

^b18.8% plutonium enriched for initial core.

Table 11.2-16

FUEL CYCLE TIMES (DAYS)

	LWR			HTGR				LMFBR		
	Enriched Uranium	Depleted Uranium	Plutonium Recycle	Enriched Uranium	Thorium	U-233 Recycle	Plutonium Recycle	Enriched Uranium	Depleted Uranium	Plutonium Recycle
Fabrication (Including Pre-fabrication)	219	80	52	199	65	25	52	252	90	48
Fresh Fuel Shipping	10	10	10	34	34	34	34	10	10	10
Preirradiation Storage	30	30	30	30	30	30	30	30	30	30
Postirradiation Storage	150	150	150	90	90	90	90	120	120	120
Spent Fuel Shipping	32	32	32	34	34	34	34	21	21	21
Reprocessing	30	30	30	40	40	40	40	25	25	25
Ship to Storage (Stockpile)	30	30	30	30	30	30	30	30	30	30

11.2-98

concentration of fissionable U-235. The measure of the effort expended in the plants to separate a quantity of uranium into a portion enriched in U-235 and a portion depleted in U-235 is the separative work unit (SWU). As shown in Figure 11.2-21, one SWU converts 2.35 kg of natural uranium feed material to 1.35 kg of tails and 1 kg of enriched uranium respectively. The number of separative work units required to produce enriched uranium for fuel for any specific nuclear power plant is related to the amount and concentration of the feed material and the tails concentration. The amount and concentration of enriched uranium required is determined by the types of reactors in a system and the requirements of each reactor types. Natural uranium feed has a nominal concentration of 0.7% U-235. The tails concentration in this study is determined by balancing the trade-off between feed material cost, separative work cost, and the resultant enriched uranium cost. Thus, as uranium costs increase, the tails assay is decreased; less feed material and more separative work are required per unit of enriched uranium product.

Charges for separative work are set to cover capital costs of the enrichment facilities and the costs of electrical energy required for plant operation. The projection of a constant \$36/SWU enrichment charge was selected as a reasonable constant dollar projection which would provide conservative estimates of LMFBR benefits. (The LMFBR has no separative work requirements per se, and reduces the separative work requirements of the system in which it is in by breeding and using fissionable plutonium.)

Recently, the Atomic Energy Commission announced an increase in the basic separative work charge to \$44.25/SWU, effective in December 1974.* Further increases may occur, even on a constant-dollar basis, depending on the circumstances under which additional enrichment capacity is introduced by industry or Government. Sensitivity cases were run at \$75/SWU to cover the potential range of such increases.

Developing technology may reverse the potential of increased enrichment charges using current technology. Gas centrifuge enrichment may reduce the costs of enrichment. Enrichment utilizing laser separations technology has an even greater theoretical potential for reduced enrichment costs. These concepts are discussed in Section 6A.1.1.2.

Feasibility and practical application of advanced enrichment technologies are uncertain. Thus, the process efficiencies and costs are difficult to estimate.

*Nuclear Industry, pp. 10-11, June 1974.

SEPARATIVE WORK UNIT
Figure 11.2-21

However, for comparison purposes, cases were run which assumed a hypothetical enrichment technology capable of 100% efficiency with a charge of \$5/kg of feed uranium.

11.2.3.12 Fossil Fuel Costs

Most of the calculations in the present study assumed that nuclear energy growth was confined within an "envelope" of capacity commitment defined by other studies. Other means of generation, including fossil fuels, were extraneous to these calculations, and fossil fuel costs assumptions had no effect.

For check calculations, however, free marketplace conditions were assumed in which nuclear and fossil fuel options competed. For these calculations, a review of fossil fuel costs used in previous studies was made, and cost assumptions were updated.

The contribution of fossil fuels to future production of electric power was represented entirely by coal in this study; oil and gas do not appear to have a significant role in power generation in the future.

In 1972, the average cost of coal to U.S. utilities was 38.2¢ per million Btu; coal cost projections given in the Draft Statement were based on the 1972 costs. However, in the biennium 1971-1972, the average price of coal increased from 31.1 to 38.2¢ per million Btu, an average of 10.8% per year. Subsequently, the Federal Power Commission reported that in March 1974, the average price of coal climbed to 60.8¢ per million Btu.* Currently pending legislation for regulation of strip mining appears likely to trigger additional cost increases not considered in the estimate used in the study. (A higher coal cost would increase the calculated breeder benefits for those cases assuming nuclear--fossil competition.)

Because of this rapid increase in coal costs, the cost projections used in the study were updated to those shown in Table 11.2-17.

The average cost of coal to U.S. utilities is estimated to increase from 65.1¢ per million Btu in 1974 to 81.4¢ per million Btu in 2020, in 1974 dollars. Using an average heat content of 11,750 Btu per pound of coal (23.5 million Btu per ton), this is equivalent to coal costs of \$15.30 to \$19.13 per ton. In the 1970 LMFBR cost-benefit study, a long-term average price of \$8.00 per ton was used.

*Electrical Week, p. 8, July 15, 1974.

Based on historical data on the national and regional use of coal by utilities, coal costs were distributed into ten cost ranges; within each cost range, coal was assumed to be available to supply a specified percentage of the total central-station electric generation. These cost distributions are indicated in Table 11.2-17.

The projections assume that the extremely rapid rise in coal costs during the past few years will be substantially moderate in future years. Coal costs are estimated to increase, in 1974 dollars, at a rate of about 1% per year until the year 2005, and to remain constant thereafter. Even this updated estimate of coal costs may prove to be low in future years, however, if a premium price is established for coal based on demands of future gasification and liquefaction processes.

Table 11.2-17
 PROJECTED COAL COSTS
 (costs in cents per million Btu)

Cost Category	Percent of Generation	1974	1980	1985	1990	1995	2000	2005	2010	2015	2020
1	13.6	30.7	33.0	34.6	36.0	37.1	37.9	38.0	38.0	38.0	38.0
2	6.7	44.3	47.5	49.9	52.0	53.6	54.7	55.2	55.2	55.2	55.2
3	10.2	48.3	51.3	54.4	56.6	68.4	59.5	60.2	60.2	60.2	60.2
4	10.9	52.3	57.3	60.6	62.7	64.5	65.8	66.4	66.4	66.4	66.4
5	8.4	59.0	63.4	66.6	69.3	71.4	72.2	73.6	73.6	73.6	73.6
6	11.6	66.1	71.0	74.5	77.6	80.0	81.6	82.4	82.4	82.4	82.4
7	11.5	73.3	78.6	82.7	86.1	88.6	90.4	91.4	91.4	91.4	91.4
8	9.3	82.9	88.2	92.6	96.5	99.4	101.4	102.4	102.4	102.4	102.4
9	9.1	94.1	101.1	106.2	110.6	113.9	116.2	117.4	117.4	117.4	117.4
10	8.7	115.5	124.5	130.9	136.2	140.2	143.0	144.0	144.0	144.0	144.0
Generation Weighted Average		65.1	70.1	73.6	76.6	78.9	80.5	81.4	81.4	81.4	81.4

11.2.4 Results of Updated Cost-Benefit Study

Results of the updated LMFBR cost-benefit study indicate that introduction of the LMFBR as a commercial producer of electricity will result in significant benefits due to the overall lowering of generation costs. Calculations indicate that these benefits will be realized over a wide range of projected future conditions in the U.S. power economy.

The benefits calculated for the breeder are due in large part to the savings in mining and enrichment of new uranium which would otherwise be required for operation of other nuclear plant types. The savings in fuel-cycle costs greatly outweigh the higher capital and operating costs projected for the LMFBR.

11.2.4.1 Range of Parameters Considered

The main focus of the updated 1973 cost-benefit study was centered on the base assumptions and projections for the U.S. power economy, as discussed in Section 11.2.3. However, a large number of calculations were made to explore the effects of variation in the assumed parameters, and to estimate the range of parameters over which LMFBR benefits would extend.

In the Draft Statement, calculations were included for 40 cases, covering base conditions and evaluation of changes in what were considered to be the major parameters. Four of these cases, initially included to indicate that some inflationary effects were still associated with a 7.5% deflated discount rate, if that rate were based on utility financing, were deleted in response to comments from reviewers of the Draft.

Comments on the Draft Statement received from EPA, NRDC, and others* requested that the sensitivity calculations address a wider range of parameter variations, and that the synergistic effects of simultaneous changes in two or more variables be investigated. In response to these comments, 36 new cases were added to the study. Moreover, four cases were added to explore the effects of increases in costs of separative work, bringing the total number of cases considered to 76.

The values of major parameters which were selected for the base case calculations, and the ranges of these values considered in sensitivity calculations, are summarized in Table 11.2-18.

*Comment Letters: EPA, 53, pp. 28, 49-51; NRDC, 38g, p. 12; B. J. Smernoff, 26, pp. 1, 16. Hearings Record Letter 18, pp. IV. 2, 4, 12.

Table 11.2-18

RANGES OF CONDITIONS CONSIDERED IN COST-BENEFIT STUDY

Parameters	Base Value Selected	Alternate Values Considered
Electrical Energy Demand (Ref. Figure 11.2-22)	Increased to 27.6×10^{12} kWhr in 2020	2020 value varied by $\pm 20\%$, -50%
Total Nuclear Capacity (Ref. Figure 11.2-23)	Increase to 1200 GW by 2000; to 3300 GW by 2020	Varied proportionately to energy projection; nuclear--fossil competi- tion assumed for some cases
Uranium Availability (Ref. Figure 11.2-24)	Three million tons under \$30/lb; max cost \$125/ lb. Four million tons available before mining of low-grade ore is needed	(1) 4.3 million tons under \$30/lb; max cost \$80/lb (2) 1.5 million tons under \$30/lb; max cost \$155/lb
Separative Work Costs	\$36/SWU	(1) \$75/SWU (2) Estimate made of effects of high-efficiency laser separation @ \$5/kg of feed uranium
Unit Capacity Assumed	(1) 1300 MWe to 1990 (2) 2000 MWe after 1990	
Capital Cost Differential (1) HTGR-LWR (2) LMFBR-LWR	Equal \$/kWe \$100/kWe at introduction; linear decrease to parity in 2000	(1) Linear decrease to \$50/ kWe in 2000 (2) Constant \$100/kWe
Spent Fuel Cooling Time Before Shipping (1) LWR (2) HTGR (3) LMFBR	150 days 90 days 120 days	365 days
LMFBR Introduction Date	1987	1985, 1991
LMFBR Model Availability	(1) Early commercial oxide fueled (doubling time, 28 years) (2) Advanced oxide fueled (doubling time, 12.5 years); available 1990 (3) Carbide fueled (doubling time, 7.6 years); available 1995	Assumed not available in some check calculations Assumed not available in some cases

Table 11.2-18 (cont'd)

Parameters	Base Value Selected	Alternate Values Considered
Capacity Constraints Imposed HTGR	(1) Before 2000: per WASH-1139 (72) (proportionately increased when breeders absent) (2) Post-2000: 1/3 of LWR capacity (nonbreeder cases only)	(1) Per WASH-1139 (74) (2) Unconstrained Unconstrained
LMFBR	(1) Pre-2000: per WASH-1139 (72) (2) Post-2000: unconstrained	(1) Per WASH-1139 (74) (2) Unconstrained
Discount Rate	(1) 10%	(1) Undiscounted (2) 5% (3) 7-1/2%

ELECTRIC ENERGY PROJECTIONS USED IN STUDY

Figure 11.2-22

NUCLEAR CAPACITY PROJECTIONS ASSUMED IN STUDY

Figure 11.2-23

URANIUM PRICE-AVAILABILITY SCHEDULES
ASSUMED FOR STUDY

Figure 11.2-24

Most of the sensitivity calculations in the study involve conditions or combinations less favorable than those selected for the base case; only a few involve conditions modestly more favorable. Circumstances more favorable to the LMFBR than the base-case assumptions are fully as likely to occur as are the less favorable conditions. However, calculations using base conditions produced an acceptably high--and conservative--level of benefits. Thus, while some cases were calculated assuming more favorable conditions to establish trends of benefits, it was felt to be more appropriate in the sensitivity calculations to concentrate on investigation of the LMFBR's ability to produce benefits under combinations of adverse conditions.

11.2.4.2 Details of Benefit Analysis

The method of calculating LMFBR economic benefits was described in Section 11.2.3. Using a given set of input parameters to represent conditions affecting the nuclear power economy, the computer model discussed in Section 11.2.3.1 selected a mixture of nuclear plant types to meet projected energy demands. The model optimized this mix of plants to achieve minimum total costs of electrical energy generation for all plants installed from 1974 up to 2020. Discounted and discounted costs of generation were calculated. For the same set of conditions, duplicate calculations were made, with and without availability of the LMFBR. In the sensitivity studies,^o the scheme of calculation was repeated for differing input conditions.

11.2.4.2.1 Composition of the Nuclear Power Economy

Typical scenarios of nuclear plant commitment which resulted from these calculations are shown in Figures 11.2-25 through 11.2-29. Figure 11.2-25 shows (in solid lines) the LWR-HTGR mix which evolves under base conditions without availability of the LMFBR. In those calculations, the HTGR capacity prior to the year 2000 was limited to the capacity defined in WASH-1139 (72);* after the year 2000, HTGR capacity was limited to 25% of the (nonbreeder) nuclear capacity. Also shown in Figure 11.2-25 (in dotted lines) is the plant mix which evolves if, after the initial introductory years, no constraints are placed on HTGR penetration except those of economics and fuel availability. Figure 11.2-26 shows the corresponding annual rates of nuclear plant introduction for the constrained and unconstrained cases.

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*USAEC, "Nuclear Power 1973-2000," WASH-1139 (72), February 1973.

COMPOSITION OF THE NUCLEAR POWER ECONOMY WITHOUT THE LMFBR

Figure 11.2-25

ANNUAL RATES OF NUCLEAR CAPACITY ADDITIONS WITHOUT LMFBR
Figure 11.2-26

COMPOSITION OF THE NUCLEAR POWER ECONOMY WITH LMFBR
Figure 11.2-27

ANNUAL RATES OF NUCLEAR CAPACITY ADDITION WITH LMFBR

Figure 11.2-28

EFFECT OF LMFBR INTRODUCTION DATE ON NUCLEAR SYSTEM COMPOSITION

Figure 11.2-29

As discussed in Section 11.2.3, the application of constraints to HTGR capacity in the base case is believed to provide a reasonable projection of future nuclear capacities. Removal of the constraints results in a significant increase in calculated HTGR capacity, primarily as a result of the high costs of uranium ores in the latter years of the study.

Calculated capacities in the unconstrained case infer a total commitment of the U.S. nuclear industry to the HTGR after about 1990--about 8 to 10 years after the first 1100-MW HTGR goes on line. In turn, all reactor manufacturers would need to establish manufacturing basis for HTGRs by about 1980.

Figure 11.2-27 shows the base mix of nuclear plants when the LMFBR is present. In this case, removal of constraints has only a small effect on the composition of the mix. The breeder consistently displaces both LWRs and HTGRs, with or without application of HTGR constraints. Further, LMFBR capacity increases at near-maximum rates (set by system capacity requirements) even when constraints are applied.

Annual rates of addition for these cases are shown in Figure 11.2-28. The irregular shape of the curve representing LWR capacity results from the change in LWR fuel-cycle usage occasioned by introduction of the breeder. After about the year 2000, no more reactors (LWR or HTGR) are introduced that require new uranium for fuel. Some 25 years following breeder introduction (about 2008 to 2015), surplus plutonium becomes available. Plutonium-fueled LWRs are then introduced to use this surplus fuel.

Figure 11.2-29 compares the plant mix resulting from 1987 introduction of the breeder with those which occur with breeder introduction date of 1985 and 1991. Varying the year of LMFBR introduction affects the HTGR capacity of the system only slightly. However, considerable differences in LWR capacity result during the interval from 1990 to about 2015. Corresponding differences thus arise in the consumption of newly mined uranium.

Cases in which nuclear and fossil plant types were allowed to compete for inclusion in the national power economy resulted in the compositions shown in Figures 11.2-30 and 11.2-31. These curves reflect two sets of assumptions. In the first set, HTGR (and LMFBR) capacity had constraints applied; in the second set, nuclear capacities were unconstrained. Competition between nuclear and fossil plants was allowed

EFFECT OF NUCLEAR-FOSSIL COMPETITION ON
NUCLEAR SYSTEM CAPACITY WITHOUT LMFBR

Figure 11.2-30

EFFECT OF NUCLEAR-FOSSIL COMPETITION ON
NUCLEAR SYSTEM CAPACITY WITH LMFBR

Figure 11.2-31

after 1982, the earliest reasonable date for addition of nuclear capacity beyond that now committed.

In all cases studied, nuclear--fossil competition resulted in expansion of nuclear capacity at the expense of fossil-fueled plant capacity.

11.2.4.2.2 Composition and Variation of Benefits

Introduction of the breeder under base conditions, in 1987, is calculated to provide undiscounted benefits of \$1.65 trillion, in 1974 dollars. This represents a 25% reduction in total power generation costs for the nonbreeder case. In the latter years of the study, the breeder provides up to 37% reduction in costs. The benefits discounted to mid-1974 at 10% are \$19.4 billion; at 7.5% discount the benefits are \$53.9 billion, and at 5% discount they are \$156.4 billion.

Capital costs of the LMFBR at the time of its commercial introduction were estimated to be \$100 per electrical kilowatt greater than LWRs and HTGRs (e.g., \$130 million greater for a 1300-MWe plant). The capital cost differential was assumed to decrease with time until parity with LWRs and HTGRs was achieved in the year 2000. Maintenance and operating costs for breeders were estimated to range 8 to 14% above those for an LWR of the same size and capacity factor. However, these added capital and operating costs, as well as increased costs of fuel fabrication and reprocessing, were outweighed by an overall reduction in fuel-cycle costs, yielding a lowered total cost of power generation. The relative cost changes leading to the benefits are indicated in Table 11.2-19.

Rate of Accrual of Benefits

The accrual of benefits from LMFBR introduction is shown as a function of time in Figure 11.2-32, for 1987 introduction (comparable curves are shown for introduction in 1985 and 1991). This figure shows the net change in total power system costs produced by introduction of the breeder. The values indicated at any point on the curve include consideration of costs and energy revenue associated with continued operation of all plants operating at that time to the end of their service lives. In each case, benefits begin to accrue in the year the breeder is introduced, and the accrual continues continuously throughout the study period.

Earlier calculations, which were reported in the Draft Statement, indicated a slight deficit in the early years of breeder operation. Further analysis has shown that the indicated deficit was an artifact introduced in the calculation of

Table 11.2-19

FACTORS CONTRIBUTING TO LMFBR BENEFITS--1987 LMFBR INTRODUCTION

(based on costs discounted at 10 and 7.5% to mid-1974)

Factor	Net Cost Change with Breeder (Billions of Dollars)			
	10% Discount	7.5% Discount	5% Discount	0%
Plant Capital Outlay	+2.0	+2.8		
Plant Operation	+1.8	+3.7		
Fuel Purchases, Uranium	-16.6	-43.9		
Fuel Purchases, Thorium	(negligible)	-0.1		
Separative Duty Costs	-6.5	-16.3		
Fuel Fabrication	-0.3	-0.6		
Fuel Reprocessing	<u>+0.2</u>	<u>+0.5</u>		
Total Cost Change	-19.4	-53.9	-156.4	-1654.8

ACCRUAL OF BENEFITS FROM LMFBR INTRODUCTION
Figure 11.2-32

forward costs (costs to end-of-life) of LWRs in the breeder cases, and that the deficit was fully accrued prior to introduction of the breeder.

In the nonbreeder case, LWR fuel-cycle options are selected by the computer model such that a balance develops between those plants generating plutonium and those using it as a fuel. In cases assuming the availability of the LMFBF, this balance must be modified to include the plutonium required for introduction of the breeders, and the plutonium surpluses generated by breeders in later years. In the calculations, the computer model must choose from among only a few LWR fuel-cycle options, and the fuel-cycle history of a given plant is set at the time of its selection. Thus, in establishing plutonium balances involving the breeder, the model may (and usually does) select a different mixture of fuel-cycle options for LWRs, several years in advance of the breeder introduction date, than would be selected in the nonbreeder case. (In real life, where the loading of a plant can be varied at each charge-discharge operation, this variation in the fuel-cycle mix several years prior to breeder introduction would not necessarily occur.)

When the forward costs of this pre breeder plant mix are compared with those for the optimum, nonbreeder case, they usually are seen to be higher--since they represent a departure from the economic optimum for the nonbreeder case, and since in these calculations they are considered separately from the breeders with which they are actually associated with later in life. Adding to this difference is the effect on fuel-cycle costs of the differing values of plutonium as calculated by the model. In the nonbreeder case, the costs of new uranium increase rapidly after the year 2000. The economic value of LWR-produced plutonium as a fuel, being related to the cost of enriched uranium also increases as the uranium price rises. When introduction of the breeder is assumed, uranium costs remain at much lower values, thereby holding down the corresponding price of plutonium. Furthermore, the breeders produce a surplus of plutonium in the later years of the study. Consequently, the economic value of plutonium from LWRs in this case is much lower than that in the nonbreeder case.

Thus, the deficit as shown in the Draft Statement appears to be caused by the manner in which forward costs for breeder-associated LWRs are calculated, and would not be expected to occur in real life. Supplementary calculations outside the computer model corrected the benefit accruals to provide the curves shown in Figure 1.2-32.

Range of Variation of Benefits

Any analysis of the Nation's power system requires consideration of a large number of variables, many of whose values are set by marketplace conditions, and are thus subject to change under external influences. Prediction of the impact of economic factors involved in electricity generation up to 50 years in the future introduces a large degree of uncertainty. To minimize this uncertainty, the parameters characterizing a power system and its components must be carefully evaluated, and supplementary calculations must be made to assess the differences which could be introduced by changes in the more important parameters.

The projected base values of study parameters are believed to be those likely to occur over the period covered by the study. These values were selected based on extensive study and on data from government agencies, utilities, reactor manufacturers, architect-engineers, and firms engaged in fuel-cycle operations. However, because of the uncertainties inherent in these predictions, a large number of cases were run to calculate the effect on benefits if future conditions differ from those projected.

Investigations were made of the effects of variations in: (1) introduction date of the breeder; (2) the availability--price relationship of newly mined uranium; (3) electrical energy demand; (4) relative capital cost differences between LMFBRs and other plant types; (5) the postirradiation cooling time assumed for LMFBR fuels; (6) availability of carbide-fueled LMFBRs; (7) availability of the HTGR, and introduction constraints applied to HTGRs and LMFBRs; and (8) the assuming of economic competition among nuclear-and fossil-fueled plant types. Several calculations were made to test the combined effects of coincident changing of two or more parameters. In addition, the effects on estimated LMFBR benefits of alternate AEC projections² of nuclear power growth were investigated. These sensitivity studies are fully as important as the base calculation of benefits, since they indicate the range of conditions over which the projection of benefits is valid.

Figures 11.2-33 and 11.2-34 indicate the range of variation in benefits as indicated by the calculations. Figure 11.2-33 shows the scope of these changes, ranging from a more than doubling of the base benefits to a near negation of benefits for combinations of the least favorable assumptions of conditions. The price and availability of uranium, one of the most important variables of the study, is parameterized in the figure.

- (a) Increased energy demand: 20% above "probable" demand in 2020
 (b) Reduced energy demand: 20% below "probable" demand in 2020
 (c) Greatly reduced demand: 50% below "probable" demand in 2020
 (d) LMFBR capital costs remain \$50/kw above LWR costs after 2000
 (e) LMFBR capital costs remain constantly at \$100/KWe above LWR costs

BENEFITS VARIATION WITH CONDITIONS

Figure 11.2-33

BENEFITS VARIATION: PLANT MIX AND FUEL-CYCLE
PARAMETERS (1987 LMFBR INTRODUCTION)

Figure 11.2-34

Figure 11.2-34 shows the effect on benefits of changing assumptions, composition of the power system, availability of carbide fuels, and various fuel-cycle parameters. For 1987 introduction of the breeder, these variations result in a swing of $\pm 50\%$ in benefits from base conditions.

The interrelationships between the more important system parameters and the benefits to be realized from introduction of the LMFBR are discussed in detail in the following paragraphs.

11.2.4.2.3 Breeder Introduction Date Effects

As evidenced in Figure 11.2-32, the LMFBR is capable of producing significant benefits of lower generation costs whenever it is introduced into the power system. However, the amount of benefits which can be realized depends on the date of LMFBR introduction. The U.S. power system must be constructed to meet the demand for electric power. If introduction of the breeder is delayed by a given period of time, its eventual penetration to a dominant position in the power economy will be correspondingly delayed. That portion of the power demand which is left unfilled by delay of the breeder must be fulfilled by the commitment of other types of generating plants--commitment to higher costs of power generation, including the important component of fuel resource purchases, over the life of those plants. As a result, the benefits realizable from breeder introduction are reduced by the amount of these added generation costs, and are not recoverable over any reasonable future period.

The change in the calculated benefits resulting from changes in introduction date, moreover, give a measure of the incentive for maintaining timely schedules for breeder development.

The effects on benefits of changes in the date of LMFBR introduction are shown in Figure 11.2-35. The Base case of 1987 LMFBR introduction produces benefits of \$19.4 billion discounted at 10% to mid-1974 (or \$53.9 billion, discounted at 7.5%). Acceleration of the program to provide breeder introduction by 1985 would increase the 10% discounted benefits to \$20.6 billion, an average of \$600 million in added benefits for each year the introduction date is advanced. Delay of introduction, on the other hand, would drop them to \$16.4 billion--a linear decrease of about \$750 million per year. The loss in benefits resulting from delay in breeder introduction from 1987 to 1991 is calculated at \$3 billion--60% of the entire discounted costs projected for the LMFBR program (\$4.9 billion program costs for 1987 introduction). Thus, there appears to be a strong incentive for maintaining schedules in the program.

EFFECTS OF LMFBR BENEFITS ON INTRODUCTION DATE
FOR DIFFERENT ASSUMPTIONS OF URANIUM RESOURCE AVAILABILITY

Figure 11.2-35

In commenting on the Draft Statement, the Environmental Protection Agency* has stated that:

The AEC analysis emphasizes...that a deferral of commercial introduction from 1987 to 1991 would reduce present discounted benefits by 8.3%...In our opinion [this] reduction...seems too low to support this position [that a strong incentive exists for early introduction]. The AEC analysis does not give any explanation of what would cause the decrease in benefits....application of the discount rate to a deferred stream of benefits could cause much of the small decline . . .

The Environmental Protection Agency* adds:

The four years deferral means that the growth pattern for LMFBR's is not altered at all from the date of introduction onward. So all the GWe of LMFBR capacity in Table 10.4...are moved back four years. No amount of "catch up" acceleration is allowed...the stream of benefits starting in 1987 has four more years than the stream of benefits starting in 1991...the two streams of benefits should be normalized. Since exactly the same post-introduction growth pattern has been assumed in the AEC analysis, normalization can be accomplished by shortening the 1987 stream by four years . . .

In an additional comment, the National Resources Defense Council** states:

It is little wonder that by using the same cutoff date for all dates of introduction of the breeder, the AEC finds that programs with later introduction dates do not fare as well as programs introduced earlier. Without a more careful treatment of the cutoff date, the AEC's conclusion that the breeder should be introduced as early as possible is invalid.

Deferral of the commercial introduction of the LMFBR decreases the 10% discounted benefits by 15.2% (\$3 billion). The AEC does not believe, as suggested by EPA and others,[†] that this increase is too low to support the position that these savings provide a strong incentive to introduce the breeder at the earliest possible date. It was noted above that the cost increase is nearly as great as the discounted cost for the entire LMFBR research and development program.

The accumulation of benefits for different years of breeder introduction is indicated in Table 11.2-20. In this table, accumulated benefits are compared for years ranging from 2000 to 2020, as well as for the year 2040, 20 years beyond the normal cutoff date for the cost-benefit calculations. As shown in the table, the differences in

*Comment Letter 53, pp. 41-43.

**Comment Letter 38, p. 9.

[†]Comment Letters: EPA, 53, pp. 41-43; NRDC, 38b, pp. 30-33; G. I. Rochlin and J. P. Holdren, 55, pp. 6-8.

Table 11.2-20

DEVELOPMENT OF BREEDER BENEFITS FOR DIFFERING
INTRODUCTION DATES

Year	LMFBR Benefits ^a for Introduction In:			Differential Benefits	
	1985	1987	1991	(1985-1987)	(1987-1991)
2000	5.6	4.5	2.1	1.1	2.4
2010	12.6	11.4	9.0	1.2	2.4
2012	14.6	13.5	10.5	1.1	3.0
2014	16.4	15.2	12.1	1.2	3.1
2016	18.0	16.9	13.8	1.1	3.1
2018	19.5	18.4	15.3	1.1	3.1
2020	20.9	19.7	16.6	1.2	3.1
2040	28.0	26.8	23.7	1.2	3.1

^a Benefits in billions of dollars were calculated based on 10% discounted costs of power generation from mid-1974 to the beginning of the indicated year, plus forward committed costs for all plants in operation in that year. Benefits as shown have not been corrected for safeguards costs (a correction of -\$0.3 billion to the year 2020).

benefits, for the variation assumed in years of breeder introduction, attain essentially their full maximum values in the period 2012 to 2016. This corresponds to the time range for the breeder cases in which the contributions of uranium-fueled plants to power generation, and therefore their forward costs, cease to be significant. Consumption of new uranium in the breeder cases also ceases during the 2012 to 2016 period. Once this period has passed, no significant changes appear in the differential benefits, even out to the year 2040.

The differences in benefits associated with deferral of the breeder are caused by commitments of other types of plants at the time of deferral. If introduction of the breeder is delayed, these alternate plant types must be committed to meet power demand which would otherwise have been met with breeder plants. For each year the breeder is delayed, additional plants of alternate types must be committed. Operation of these alternate plants involves additional costs to the system. As shown in Table 11.2-20, the effects of these commitments have run their course prior to the cutoff date of 2020 used in the calculations. The costs of operation of these substituted plants, including the costs of new uranium fuel and separative work requirements for these plants, are not recoverable at later times.

While the benefits associated with the earlier 1987 introduction are deferred and reduced by the 1991 introduction, the important consideration regarding the decrease in benefits is the increased requirements for uranium for the nonbreeders built to supply the capacity that would otherwise have been supplied by the LMFBRs. The commenters do not take into account the need to satisfy capacity requirements not supplied by the LMFBRs when noting that application of the discount rate to a deferred stream of benefits could cause much of the decline in the present value of benefits.

Cumulative uranium requirements to the year 2020 increase from about 2,550,000 tons of U_3O_8 for the 1987 introduction to about 3,400,000 tons for the 1991 introduction; the price of this extra 850,000 tons of uranium-oxide requirements ranges from \$25/lb of U_3O_8 to \$45/lb of U_3O_8 (refer to Section 11.2.4.2.6). The extra uranium requirements would cost about \$55 billion (undiscounted).

Since the stream of absolute benefits is continually expanding with time for any of the assumed breeder introduction dates, the use of a different cutoff date for each case, as suggested, would mask the attainment of an asymptotic constant difference in benefits and would impart a false bias to the calculations.

The effects of introduction date on breeder benefits were investigated for different assumed conditions of uranium availability and energy demand, and also for assumed nonavailability of a carbide-fueled breeder. Results of these investigations are summarized in Table 11.2-21. Although the changes in assumed conditions caused variations in the magnitude of the calculated benefits, the percentage changes in benefit appear for the most part to be about the same.

Table 11.2-21

SUMMARY OF EFFECTS OF LMFBR
INTRODUCTION DATE ON BENEFITS

Uranium Supply	Energy Demand	Introduction Constraints Imposed		Gross Benefits, Billions of Dollars (Discounted @ 10%) for LMFBR Introduction Date		
		HTGR	LMFBR	1985	1987	1991
Base	Base	Yes	Yes	20.6(+6.2%) ^a	19.4	16.4(-15.2%)
Optimistic	Base	Yes	Yes	12.6(+5.0%)	12.0	9.9(-17.5%)
Pessimistic	Base	Yes	Yes	32.6(+6.5%)	30.6	24.5(-19.9%)
Base	-20% ^b	Yes	Yes	15.3(+7.7%)	14.2	11.3(-20.0%)
Base	+20% ^c	Yes	Yes	27.1(+3.8%)	26.1	22.3(-14.6%)
Base	Base	Yes	Yes ^d	19.5(+11.4%)	17.5	15.1(-13.7%)

^aFigures in parentheses are percentage changes in benefits relative to a 1987 introduction date.

^bReduced energy demand: 20% below probable demand in 2020.

^cIncreased energy demand: 20% above probable demand in 2020.

^dCarbide-fueled breeder not available.

In further comments on the treatment of deferred introduction, EPA stated:*

The treatment of deferred introduction...is artificial for two additional reasons: (1) the introduction date...is not the date for which the LMFBR would be commercially competitive; (2) no possibility is allowed for alternative breeder programs which would be technically superior . . .

Constraints applied to LMFBR capacity in these deferral cases did not extend throughout the entire study period, as suggested by EPA. For the 1987 introduction date, capacity constraints were applied--to the breeder as to other reactor types--up to the year 2000. For the assumed 1985 introduction, the 1987 to 2000 breeder capacity

*Comment Letter 53, p. 42.

pattern was advanced two years--to span the period 1985 to 1998--and for 1991 introduction, the same pattern was retarded to the period 1991 to 2004. In each case, appropriate adjustments were made in the LWR-HTGR capacity to maintain the required total system capacity. Following the constraint period, selection of plant types was based on comparative economics, and it is noteworthy that only breeders were selected by the computer model until late in the study period, when plutonium-burning LWRs were introduced to use up the surplus plutonium. Indeed, the deferred breeder does not "catch up," because in each case, following the removal of constraints, the breeders are fully utilized in meeting increased power demand. No additional breeders (or plants of any type) could be added without exceeding the required generating capacity.

Calculations were made (case 47B) in which no constraints were placed on any reactor type, other than the availability of fissile fuels and the setting of practical rates of introduction during the early years of availability. In these calculations, LMFBRs were initially introduced at somewhat greater rates than were allowed by constraints. Because of limitations on total system growth, however, only a relatively small difference was observed in the total capacity of breeders operating after about 2010. Comparison of the system compositions with and without constraints was given earlier in Figure 11.2-27.

As a further check, a test calculation was made in which only the "early commercial" breeder--the model initially introduced--was assumed to be available. Even without subsequent availability of the advanced breeder types, this early breeder model was selected on a purely economic basis (no constraints were imposed) and produced a small benefit.

A parallel breeder program might result in having available another breeder at about the time of the availability of the carbide-fueled LMFBR. Even if this breeder had a fuel doubling time superior to the carbide-fueled LMFBR, it probably would have only a small impact on the LMFBR benefits. For base case conditions, the sequence of LMFBR installation results in a breeder fissile fuel surplus about five years after the introduction of the carbide-fueled LMFBR and by about year 2015, there is no requirement for mined uranium. It is anticipated that a parallel breeder could not greatly change the consumption of mined uranium nor would its fuel cycle and capital costs differ greatly from the carbide-fueled LMFBR.

Dr. Chauncey Kepford,* commenting on feasibility of timely introduction of the LMFBR, states:

[The LMFBR] also is dependent for initial charges of plutonium on LWRs. Few comments on the availability of plutonium from this source have been made.

The production rates of plutonium by LWRs are well known and are routinely calculated in fuel management calculations. These same calculations resulted in the fuel mass balances used in the cost-benefit calculational model. As explained elsewhere (Section 11.2.3), LWR capacity assumptions to 1982 are based on actual commitments of plants. Beyond 1982, capacities are based, in various cases, either on AEC projections or on economic comparisons within the model. In either case, running accounts are kept in the calculations of quantities of plutonium produced, consumed, and stockpiled. Constraints within the model would prohibit the introduction of breeder capacity if plutonium were not available for its fueling.

Barry Smernoff of the Hudson Institute makes the comment:**

While the USAEC continues to hold that "large scale commercial application can be achieved within 10 to 15 years," i.e., between 1985 and 1989, the history of commercial LWR's and the large delay in construction of the first LMFBR Demonstration Plant indicate that the earliest year of commercial introduction of the LMFBR is 1995. USAEC Commissioner William A. Anders, testifying before the Joint Committee on Atomic Energy on February 26, 1974, indicated that this LMFBR Demonstration Plant would require a longer period to complete than the 8-10 years needed for LWR's, implying that [completion by] 1980 is out of the question and 1985 is doubtful...assuming that this first Demonstration Plant is completed in 1985, and that 10-15 years are needed to commercialize the LMFBR...then 1995-2000 is the period of earliest introduction of commercial breeder reactors in the U.S.

Commissioner Anders' testimony has been seriously distorted, both in this comment and in the source material used by the commenter. Actual and potential delays, both in LWR deployment and in the breeder development program, have been taken into account in the estimate of the commercial availability of the LMFBR. The 10 to 15 years required for commercialization are not counted from completion of the LMFBR Demonstration Plant, but from the present day. Construction of the Demonstration Plant is but one phase of a comprehensive development program.

*Comment Letter 25, pp. 25-26.

**Comment Letter 26, pp. 11-12.

Recent evaluations of the LMFBR development program by the AEC taking into consideration cancellations and deferrals of generating capacity by electric utilities that had occurred by the end of September 1974 suggest that commercial LMFBR introduction would probably occur in the early 1990's. Calculations assuming alternate dates of introduction were performed to indicate the effect on the Nation's power costs if the development program were changed and to determine the incentives for maintaining or improving the program schedule.

Professor Robert C. Axtmann, of Princeton University, asks:*

What would be the monetary costs of postponing completion of the LMFBR's R&D effort 10, 15, or 20 years until harder answers concerning fusion are available?

In a related comment, Dr. Thomas B. Cochran of the Natural Resources Defense Council, states:**

This critique [referring to T. B. Cochran: The LMFBR: An Economic and Environmental Critique] makes it evident that there is no basis for concluding...a delay in the program, even for one or two decades, need necessarily result in an economic penalty.

The analysis reported in the text indicates that a four-year delay in breeder introduction would result in a 10% discounted penalty of \$3 billion (or \$5.6 billion at 7.5% discount), resulting from higher power generation costs during the period before the breeder achieves dominance in the power supply system. If these costs were extrapolated linearly, delays of 10, 15, or 20 years would indicate cost penalties of, respectively, \$7.5, \$11.3, and \$15 billion (again discounted at 10%), relative to introduction of the breeder in 1987. If such a delay were to occur, the steeply increasing costs of uranium associated with greater use of nonbreeder plants would increase the penalties to values even higher than these.

11.2.4.2.4 Effects of Constraint Assumptions

Constraints on HTGR and LMFBR plant capacity which were imposed under base conditions have been described in Sections 11.2.3 and 11.2.4.2.1. These constraints, based on capacity projections in WASH-1139(72),[†] are believed to represent the most likely trends in composition of the nuclear power system in the future.

*Comment Letter IP-12, p. 2.

**Comment Letter IP-2, p. 2.

[†]USAEC, "Nuclear Power 1973-2000," WASH-1139(72), February 1973.

Comments received on the Draft Statement* questioned the basis for imposition of capacity constraints on the HTGR, and requested several additional analyses involving unconstrained capacities under varying conditions. Several cases (described in Appendix IV.C) were added to the study involving unconstrained capacities in response to these comments. In addition, cases 29 through 31 tested effects of varying constraints on HTGR penetration under base uranium supply assumptions.

In the nonbreeder economy, the effect of varying HTGR constraints on the calculated total system energy costs are shown in Table 11.2-22.

Table 11.2-22

EFFECTS OF HTGR CONSTRAINTS ON SYSTEM
ENERGY COSTS IN A NONBREEDER ECONOMY

(base energy demand, base uranium resource availability)

HTGR Constraints Applied Until	Case No. Appendix IV.C	System Energy Costs in Billions of Dollars (10% Discounted)
No HTGR ^a	32	214.8
2020 ^b	1	210.8
2000	29	206.0
No constraints	30	202.3

^aNo HTGRs assumed to be introduced past 1982.

^bConstraints assumed for base calculations.

From this table, the worth of the HTGR under the conditions assumed in the calculations is, if no constraints are imposed, about \$12.5 billion (discounted at 10%) or about 6% of the total system power costs. Relative to base conditions, variation of the constraint parameter represents a cost variation of +2% to -4%.

This variation indicates the economic value of a reactor system whose utilization of uranium is substantially improved over that of the LWR designs used in the study. In the calculations, capital and operating costs were taken to be essentially identical for the HTGR and LWR. While cost assumptions differed for component parts of the fuel cycle, total fuel-cycle costs (excluding uranium purchase and enrichment) were very nearly the same for the two reactor types. The variation in power costs

*Comment Letters: L. K. Marbet, 28, pp. 73-75; EPA, 53, pp. 36-39.

shown is due almost entirely to the lower demand for newly mined uranium, and the correspondingly lower separative duty demands for enrichment, in the HTGR fuel cycle.

A similar economic value would be shown by any reactor system (including the LWR) operating on a fuel cycle with an equivalent degree of uranium utilization, assuming comparable capital and operating costs. On the other hand, the economic value of the HTGR as calculated is sensitive to the assumption of essential parity in capital and operating costs with the LWR. A substantial increase in one or more other cost components would tend to counter the savings from greater uranium utilization and reduce the effective worth of the plant type.

The effects on LMFBR benefits of various assumptions of HTGR capacity constraints are indicated in Table 11.2-23. Removal of the capacity constraints, for the cases studied, decreases benefits by about 40%. On the other hand, if the HTGR were assumed not to be a factor in future power systems, benefits would increase by about one-third over those for the constrained-introduction cases.

Since the HTGR consumes less uranium than an LWR in producing a given amount of electric energy, the market competitiveness of the former is enhanced by rising uranium prices. Thus, in no-breeder cases which show such price increases, HTGRs tend to dominate the market if plant selection is based only on comparative economics. This effect is reflected in the consistent decrease in LMFBR benefits shown in Table 11.2-22, as capacity constraints are progressively relaxed.

In cases assuming introduction of the breeder, however, the situation changes markedly. In all cases except those few with the least favorable combinations of parameters (e.g., low energy, high breeder capital costs, low cost uranium), essentially no new HTGRs are introduced after about the year 2000, when the breeder achieves dominance of the market. In later years, as the existing HTGRs are retired at the end of their service lives, the national power system gradually evolves toward an LMFBR-LWR plutonium economy, in which plutonium-fueled LWRs utilize surplus plutonium generated by the breeders. HTGRs fueled with plutonium were also available in the calculations, but were never selected, apparently because of higher fuel-cycle costs as compared with LWRs. It should be pointed out that, although not considered in this study, the LMFBR can function as a supplier of U-233 by loading a portion of the blanket with thorium. Thus, it could also support HTGRs as well as LWRs, in a mixed U-233-plutonium economy.

Table 11.2-23

EFFECTS OF HTGR CAPACITY CONSTRAINTS ON LMFBR BENEFITS

(1987 LMFBR introduction)

Energy Demand	Uranium Resource Assumption	LMFBR Capital Costs	LMFBR Constrained Before 2000	Benefits, Billions of Dollars (10% Discounted) with HTGR Capacity Constraints Until:			
				No. HTGR	2020 ^a	2000	No Constraints
Base	Base	Base	Yes	23.0	19.4	14.6	10.5
Base	Base	Base	No	25.1 ^b	21.2 ^b	17.5 ^b	12.2
Base	Optimistic	Base	Yes	15.7 ^b	12.0	9.5 ^b	7.8
Base	Optimistic	Base	No	16.3	12.4 ^b	10.0 ^b	8.2
Base	Pessimistic	Base	Yes	47.8 ^b	30.6	27.7 ^b	17.6
Base	Pessimistic	Base	No	50.2 ^b	34.5 ^b	30.2 ^b	19.5

^a HTGR capacity constraints to the year 2020, when applied, were imposed only in nonbreeder cases. With the breeder present, constraints were not imposed (or needed) beyond 2000.

^b These values were obtained by interpolation or extrapolation.

The comparative penetrations of HTGRs into the national power economy for various capacity constraint assumptions, with and without introduction of the LMFBR, are shown in Figure 11.2-36.

11.2.4.2.5 Effect of Variation in Electrical Energy Demand

Electrical energy demand in the United States is forecast, in the base projection used in this study, to increase from today's level of about 1.7 trillion kWhr annually to about 10.6 trillion kWhr in 2000, and to about 27.6 trillion kWhr by the year 2020. The portion of this demand allocated in the study to nuclear power stations was about 8 trillion kWhr in the year 2000 and 20 trillion kWhr by the year 2020.

Past forecasts of electric power demand have proven, at least in the near term, to be conservative. However, forecasts of demand for 50 years in the future clearly entail considerable uncertainty. The trend toward lower birth rates, if accelerated, could lessen future energy demand, through changes in population and age-group distributions, although the effect of these changes would not be apparent until the late 1990's.

Recent trends toward energy conservation, particularly in light of increasing costs of energy from fossil fuels, may have more important effects on reduction of overall demand. These cost trends, however, appear likely to increase the importance of nuclear generation relative to that from alternate fuels, and presage greater utilization of electrical energy in areas now primarily the domain of fossil fuels; that is, industrial process heat, heating of private residences and commercial buildings, and public transportation.

To assess the effect of differing energy demand on LMFBR benefits, cases were run in which the rate of increase in energy demand was increased or decreased to provide a demand in the year 2000 which varied by $\pm 20\%$ from the base projection. In these projections, the base energy demand projection was assumed to hold out to the year 1980. In subsequent years, demand progressively deviated from that of the base projection, the deviation increasing to $\pm 20\%$ in the year 2020. Results obtained using these modified energy projections were reflected in the Draft Statement.

A projection falling 50% below the base projection in 2020 was developed in order to analyze a wider range of energy projections. The additional, very low electrical demand projection, as well as the three projections considered in the Draft Statement, was shown in Figure 11.2-22. These projections are based on the assumption

EFFECTS OF VARYING HTGR CAPACITY RESTRAINTS
ON HTGR OPERATING CAPACITY

Figure 11.2-36

that the rate of increase in electrical energy demand will gradually decrease from today's value of 7.5 to 8% per year to the values shown below.

	Rate of Increase (%/year) for Projection			
	+20%	Base	-20%	-50%
Annual Rate of Increase, 1974	7.8	7.8	7.8	7.8
Annual Rate of Increase, 2000	<u>5.8</u>	<u>5.0</u>	<u>4.4</u>	<u>3.6</u>
Annual Rate of Increase, 2020	4.2	3.7	3.0	2.8
Average Rate of Increase, 1974-2020	6.7	6.2	5.7	4.6

For all cases except those in which economic competition between nuclear- and fossil-fueled plants was considered, the fraction of the electrical energy demand which was supplied by nuclear plants was assumed to be the same for each projection. The resultant projections of nuclear plant capacity were shown in Figure 11.2-23.

The effects of the +20% energy demand changes on benefits from LMFBR introduction, and on the incentives for early breeder introduction, are shown in Figure 11.2-37. For 1987 introduction, the calculated benefits with the 20% higher energy demand projection case are \$26.1 billion (discounted at 10%), which is 35% higher than the \$19.4 billion in benefits calculated for the reference-case energy demand. For the demand projection resulting in a 20% decrease from the base demand in 2020, benefits are reduced to \$14.2 billion--a 27% decrease from base conditions. Penalties associated with delay of breeder introduction--\$0.75 billion per year for the base demand--are increased to \$1.0 billion per year for the high demand projection, and reduced to \$0.72 billion per year for the lower energy projection. The increase in benefits associated with advancement of the breeder introduction date--\$0.6 billion per year under base conditions--does not change appreciably from that figure under the high and low demand assumptions.

EFFECTS ON ENERGY DEMAND VARIATIONS ON LMFBR
BENEFITS--VARYING INTRODUCTION DATES

Figure 11.2-37

For the 1987 breeder introduction date, Figure 11.2-38 shows the effects on benefits for energy demands varying from +20% to -50% of the base demand in year 2020, along with variations in other parameters. This figure provides a composite of curves showing the effects of change in energy demand for various assumptions related to uranium resources and costs, and the effects of constraining HTGR and LMFBR capacity versus allowing the different plant types to freely compete on the basis of economics. As would be expected, the effects of capacity constraint are more marked when pessimistic, high-cost uranium resources are assumed, than for optimistic resource assumptions.

11.2.4.2.6 Uranium Resources

The savings in uranium consumption which is effected by timely introduction of the LMFBR accounts for a large share of the benefits provided by the breeder. Accompanying the economic benefit is a substantial environmental benefit in the virtual cessation of requirements for mining and milling of uranium or thorium ores for nuclear fuels.

Not surprisingly, since such a large portion of the benefits are provided by reduction in uranium usage, these benefits are sensitive to the availability and recovery cost of ores which might exist beyond the presently known deposits. A large number of calculations in the study were, therefore, addressed to evaluation of the sensitivity of benefits to uranium availability and cost.

Consumption of Uranium

An LWR-based power economy is expected, under base conditions as expressed in case 1 (see Figure 11.2-39), to consume about 6.3 million tons of U_3O_8 by the year 2020. The supplying of uranium in this quantity would completely exhaust the present reserves and estimated potential reserves of Western U.S. ores available at recovery cost of \$30 per pound or less, and those expected to be recoverable as a by-product from phosphate deposits. Unless there is discovery of large amounts of new, low-cost domestic resources or increase of availability of foreign uranium, then exploitation of the high-cost, low-yield Chattanooga shale deposits, or other deposits of equivalent yield, would be needed to fill requirements. Under these conditions, cost of the refined U_3O_8 is conservatively expected to rise from an initial \$8.00 per pound to about \$100 per pound by the year 2020 (Figure 11.2-40).

Introduction of the LMFBR is projected to sharply curtail the requirement for natural uranium. Once the introductory period of the breeder has passed, the

SENSITIVITY OF BREEDER BENEFITS TO ENERGY DEMAND--1987 LMFBR INTRODUCTION

Figure 11.2-38

EFFECTS OF BREEDER INTRODUCTION ON URANIUM CONSUMPTION

Figure 11.2-39

EFFECTS OF BREEDER INTRODUCTION ON PRICE OF URANIUM

Figure 11.2-40

calculations indicate that no additional newly mined uranium will be required for the nuclear power plants that are being constructed. Both the breeders and the LWRs built in the latter years of the study will utilize plutonium from the breeders with depleted uranium previously stockpiled from uranium enrichment operations (or recycled from discharged breeder fuel). The only natural uranium required in this latter time period would be that needed to supply enriched uranium to previously introduced thermal reactors which are still in operation, and even these might be switched to plutonium fueling.

Strong introduction of the LMFBR, involving its rapid penetration of the market, will result in a peaking of uranium demand in about the year 2000 and a virtual cessation of consumption of new uranium after about 25 years following the date of introduction. Delay of introduction of the breeder thus correspondingly increases the time period over which uranium consumption is required, and increases the total consumption.

As is shown in Figure 11.2-39, introduction of the breeder in 1987 would reduce cumulative uranium requirements to the year 2020 by 3.7 million tons. The cost of the U_3O_8 (Figure 11.2-40) would rise only to \$25.00 per pound by 2020. This would provide net undiscounted savings of \$509 billion (or \$14.1 billion when discounted at 10% to mid-1974). When forward costs of operation to end-of-life of the plants involved are included, these savings increase to \$1.1 trillion (undiscounted) and \$16.6 billion (10% discounted). This savings in uranium ore consumption and cost is one of the largest components of the benefits obtained from LMFBR introduction.

Comparable uranium usage and cost projections are shown on Figure 11.2-39 and 11.2-40 assuming introduction of the LMFBR in 1985 and 1991. Delaying the introduction of the breeder four years to 1991 results in an increase in cumulative uranium requirements of about 850,000 tons of U_3O_8 by the year 2020 and a corresponding increase in uranium price of about \$20.00 to \$45.00 per pound.

More constrained rates of LMFBR introduction, such as were investigated in cases 37 through 44, affect uranium demand similarly to delays in breeder introduction. More uranium is consumed than under reference conditions, and the demand for new uranium extends over a longer time following introduction.

Ebasco Services, Inc., comments regarding introduction of the LMFBR;*

*Comment Letter 18, p. 5.

To the extent that plutonium available as initial fuel [for breeders] comes from water reactors that plutonium cannot be made available without a commitment for additional mining of U_3O_8 . In the absence of LMFBR's essentially all plutonium produced would be recycled promptly in LWR's thus every kilogram of plutonium diverted from recycle in LWR's would have to be replaced with enriched uranium to keep the LWR's in operation.

New generating plants are built either to replace retiring plants or to meet increases in power demand. Thus, the rate of addition of new capacity will be the same whether the breeder is introduced or not. As the breeder penetrates the market, new commitments of other plant types (LWRs and HTGRs) will decrease. Results of calculations indicate that, for the decade following LMFBR introduction, the total capacity of uranium-fueled LWRs is essentially the same with or without the presence of the breeder. However, the capacity of LWRs using recycled plutonium drops sharply during that period, with the plutonium being used to fuel the breeder. After the year 2000, no more uranium-fueled plants of any type are committed.

Consistently, in each year following introduction of the breeder, uranium usage is equal to or less than the nonbreeder case. The massive savings in uranium usage, however, occurs in later years, as shown in Figure 11.2-39--since, with the breeder, no new uranium is needed beyond (about) 2015. After that time, the entire nuclear electric economy is based on breeder-produced plutonium.

Effect of Uranium Availability and Cost

The effects of uranium availability and cost on the benefits from LMFBR introduction were investigated in calculations considering three alternate schedules of uranium ore availability and recovery cost. These schedules, discussed in Section 11.2.3, were:

- (1) A "base" availability-price schedule, considered by AEC to be the most likely projection of future uranium supplies and recovery costs;
- (2) A "pessimistic" (low-availability, high-cost) schedule, assuming lesser availability of low- and intermediate-cost ores, and higher eventual recovery costs from low-grade ores;
- (3) An "optimistic" (high-availability, low-cost) schedule, assuming greater quantities of higher-grade ores to be available, and recovery costs from low-yield ores to be lower, than in the base schedule.

The effects of the assumption of high and low availability of uranium on LMFBR benefits were shown in Figure 11.2-35. As seen in this figure, an optimistic assumption of uranium price-availability relationships decreases the benefits from 1987 breeder introduction from the reference case value of \$19.4 billion to \$12.0 billion. Assumption of a pessimistic uranium-price availability schedule, on the other hand, increases these benefits to \$30.6 billion.

The effects on benefits from advanced or delayed introduction of the breeder are also influenced by the availability and cost of uranium, as was discussed in Section 11.2.4.2.3. The rate of benefit increase in the reference case for advanced introduction of the breeder is \$0.6 billion per year of advancement. The rate of benefit increase changes to \$1 billion per year of advancement with the low-availability assumption and to \$0.3 billion per year of advancement with the high-availability assumption. The benefits are decreased when breeder introduction is delayed. The rate of decrease is calculated to be \$0.75 billion per year of delay for the reference case. For the low-availability and high-availability cases, the rate of decrease changes to \$0.5 billion per year of delay and \$1.5 billion per year of delay respectively.

The effects of uranium resource availability on LMFBR benefits under a wider range of assumed conditions are shown in Table 11.2-24. The high sensitivity of benefits to the price-availability schedule which was observed in perturbations of the base case is evidenced as well over large variations in energy demand projections. This sensitivity is even more pronounced when capital costs of the LMFBR are assumed to remain at higher levels than those of nonbreeder plants.

The variation of benefits under combined changes of assumed parameters is discussed later in Section 11.2.4.2.12 of this report. However, it is of interest that even for the optimistic (low-cost) uranium availability schedule, benefits from the LMFBR are significant for all cases except those with severe assumptions of combined parameter changes.

Prior to review of the Draft Statement, NRDC commented* that:

It is important to understand that the fraction of uranium not converted into either energy or plutonium in light water reactors is not "wasted" but is still readily available for conversion to plutonium at any later point an early LMFBR entry date cannot be viewed as a means of saving an exhaustible resource in the manner that fission, geothermal, and solar energy alternatives reduce the demand for coal or oil.

*Predraft Letter 1P2, p. 3.

Table 11.2-24

EFFECTS OF URANIUM RESOURCE AVAILABILITY ON LMFBR BENEFITS

(1987 LMFBR introduction)

Introduction Constraints Applied Until:		LMFBR Capital Costs	Energy Demand	Other Conditions	Benefits (10% Discounted) from Assumed Uranium Resource Availability:		
HTGR	LMFBR				Optimistic	Base	Pessimistic
2000	2000	Base	Base		12.0	19.4	30.6
2000	2000	Base	Base	a		29.3	
None	2000	Base	Base		7.8	10.5	17.6
None	2000	Base	Base	a		16.1	
None	None	Base	Base		8.2	12.2	19.5
2000	2000	Base	+20%	b	14.9 ^c	26.1	42.6 ^c
2000	2000	Base	-20%	d	9.8 ^c	14.2	23.0 ^c
2000	2000	Base	-50%	e	3.9	5.6 ^c	10.4
None	2000	Base	-50%	e	3.0	3.9 ^c	6.3
None	None	Base	-50%	e	3.2	4.2	6.9
2000	2000	+\$50 ^f	Base		7.9 ^c	15.2	26.7 ^c
2000	2000	+\$100 ^g	Base		4.8	12.6 ^c	23.8
None	2000	+\$100 ^g	Base		0.8	2.8 ^c	10.5
None	None	+\$100 ^g	Base		1.9	4.4	11.0
2000	2000	+\$100 ^g	-50%	e	0.4	0.9	6.7
None	2000	+\$100 ^g	-50%	e	0	0.2 ^c	2.9
None	None	+\$100 ^g	-50%	e	0.9	1.3	3.4

^aSeparative work charge of \$75/SWU^bIncreased energy demand: 20% above "probable" demand in 2020.^cExtrapolated/interpolated data.^dReduced energy demand: 20% below "probable" demand in 2020.^eGreatly reduced demand: 50% below "probable" demand in 2020.^fLMFBR capital costs remain \$50/kW above LWR costs after 2000.^gLMFBR capital costs remain constantly at \$100/kWe above LWR costs.

However, the issue at stake is not the conservation of uranium per se but of the isotope U-235, the only fissile material found in nature; and, more to the point, conservation of the higher-grade ores from which uranium can be recovered economically and without great environmental damage.

It is very true that U-238, the plentiful isotope of uranium, can be used at any future date as the fertile material for LMFBRs. By the year 2000, there will be enough U-238 on hand, as tails material from uranium enrichment facilities, that the breeder, once it is established, could supply the U.S. electrical energy demand for hundreds of years with no mining of new uranium.

If the breeder is delayed, however, the electrical demand must be fulfilled by an increased commitment of other types of plants, primarily of nonbreeding fission plants. These plants require U-235 fuel, which can be obtained only from newly mined uranium. As was explained in responses to comments in Section 11.2.4.2.3, this commitment to added mining and enrichment of uranium would entail large costs which must be counted as penalties associated with delayed introduction of the breeder. Additionally, the necessity to exploit increasingly lower-grade ores would result in increasing environmental impact from mining. Finally, the added consumption of U-235 would be, in a very real sense, added depletion of a scarce and exhaustible resource.

11.2.4.2.7 Separative Work Charges and Requirements

The enrichment of uranium in the U-235 isotope is an important element in the nonbreeder fuel cycle. The energy required for uranium enrichment is measured in terms of the separative work unit (SWU). This unit, discussed in Section 11.2.3, represents the energy required to produce 1 kg of enriched uranium with a U-235 content twice that of the feed material. The number of SWUs required will thus vary both with the amount of product and with its enrichment level.

Calculations for the reference cases, and for most other cases in the study, assumed enrichment of uranium with current gaseous diffusion technology, with a constant enrichment charge of \$36 per SWU.

The U-235 assay of the diffusion plant tails stream was adjusted in the calculations to provide an economic optimum based on these costs and the cost of uranium fuel. Thus, as uranium costs increase, the tails assay is decreased; less feed material and more separative work are required per unit of enriched uranium product.

The projection of a constant \$36/SWU enrichment charge was selected as a reasonable constant-dollar projection which would provide conservative estimates of LMFBF benefits. These charges must be set to cover capital and operating costs of the enrichment facilities, as well as costs of electrical energy required for plant operation. The enrichment charges will also differ depending on whether the plants are operated by the Federal Government or by private enterprise.

Recently, the AEC announced an increase in the basic separative work charge to \$44.25 per SWU, effective in December 1974.* Further increases in these charges may occur, even on a constant-dollar basis, depending on the circumstances under which additional enrichment capacity is introduced. To cover the potential range of such increases, four cases were run in which a separative work charge of \$75 per SWU was assumed, to test the effect of the higher enrichment costs under reference conditions and with removal of HTGR capacity constraints.

Use of the higher enrichment cost directly increases the separative work component of fuel-cycle costs. It also tends to increase the optimum assay in the tails stream, favoring use of more uranium and less separative work per unit of product.

In contrast to the possibilities of increases in separative work charges with facilities using current technology, research into new processes offers the prospect of substantial long-term decreases in the costs of uranium enrichment. In particular, the concept of laser enrichment has attracted notice recently as a potential high-efficiency, low-cost process. This concept is discussed in Section 6A.1.1.2 (Alternative Technology Options).

Separative work requirements for the Nation were based on reducing the U-235 assay of the depleted uranium tails stream to a value representing an economic optimum, minimizing the net costs of the power required and the costs of fresh uranium feedstock. The optimum assay value thus decreases with increasing uranium prices, and for all cases is lower than the 0.3% tails assay on which current diffusion plant operations are based. Use of 0.3% tails assay would reduce power requirements for the diffusion process, per unit of product, but would greatly increase uranium feed requirements relative to the tails assays used in this study.

With no breeder introduced into the national power economy, and with separative work charges of \$36/SWU, the annual demand for separative work will increase from an initial 7 million separative work units (SWU) per year in 1974 to a

*Nuclear Industry, 21(6): 10-14, June 1974.

EFFECTS OF BREEDER INTRODUCTION ON SEPARATIVE WORK DEMAND
Figure 11.2-41

rate of 450 million SWU/year in 2020, as shown in Figure 11.2-41. By comparison, the existing separative work capacity in the United States is 17.5 million SWU/year. Improvement and upgrading of the existing diffusion cascades is expected to increase this capacity to 27.7 million SWU/year by about the year 1984; separative work demands above that capacity must be met by construction of new plants. A large size plant (9,000,000 SWU/year capacity) is estimated to cost about \$170,000 (in 1974 dollars) per 1000 SWU annual separative work capacity. To increase annual separative work capacity from the 27.7 million SWU capacity in 1984 to the 450 million SWU capacity needed for the nonbreeder situation would require a capital investment of about \$70 billion in 1974 dollars.

Introduction of the breeder in 1987 sharply reduces the separative work requirements. In this case, the rate of increase in separative work demand is considerably lower between 1987 and 2000. The demand for separative work reaches a maximum of 95 million SWU/year in about the year 2000; it subsequently declines steadily as uranium-fueled reactors introduced in earlier years are removed from service. It should be noted, however, that even under these conditions, the demand reaches a level about three times the maximum projected capacity of existing plants, following the power uprating and cascade improvement programs. The capital expenditures for the required separative capacity in this instance would be about \$9 billion, instead of about \$70 billion for the no-breeder situation.*

Based on the value of \$36.00 per separative work unit used in the calculations, a total undiscounted separative work cost savings of \$174 billion (or \$6.4 billion discounted at 10%) results from introduction of the breeder in 1987. Accompanying the economic benefits is an added availability of electric energy from reduction in separative work requirements using current technology, which results from breeder introduction. The electrical energy required for uranium enrichment represents only some 4% of the energy produced by a typical LMFBR. Even so, the savings in separative work using current technology over the period 1974 to 2020 represents a total savings of about 13 trillion kWhr of electricity, equivalent to about 120% of the total annual demand in the year 2000. This added energy availability is estimated at 10.8 trillion kWhr for the optimistic uranium availability schedule; or 15 trillion kWhr assuming low availability. The difference in the estimated added availability of energy stems from the

*Capital costs of enrichment facilities are amortized against the cost of separative work, and are included as such in the cost-benefit calculations. The quoted savings in capital costs should not be added to the calculated benefits. However, this saving is an important component of those benefits, acting to compensate for the higher capital requirements for LMFBRs.

fact that optimum operation of uranium enrichment plants requires that, as cost of natural uranium increases, the U-235 concentration in the tails stream decreases and energy expended in separative work increases for each unit of product.

The patterns of separative work requirements as functions of time are shown in Figure 11.2-41 for LMFBR introduction in 1985 and 1991, as well as for the 1987 reference date. Delaying the introduction of the breeder four years to 1991 increases the maximum demand from about 95 million SWUs to about 140 million SWUs and also delays the year of the maximum demand by two years. This could require about an additional \$7.5 billion (1974 dollars) for the added separative work capacity.

When the \$75/SWU enrichment charge was applied under reference conditions, benefits from LMFBR introduction increased from the reference value of \$19.4 billion (10% discounted) to \$29.3 billion (cases 73 and 74). In the reference nonbreeder case, 6.3 million tons of U_3O_8 were consumed by 2020, and the separative work demand in 2020 was 447 million SWU. With the higher separative work charge applied, 7.1 million tons of U_3O_8 were consumed and the 2020 separative work demand was 367 million SWU. For the cases with LMFBR availability, uranium consumption increased from 2.6 to 3.0 million tons, and the maximum annual separative duty demand (in the year 2000) declined from 94 million to 78 million SWU.

In the cases assuming no constraints on HTGR penetration, the higher separative work charge had similar effects. LMFBR benefits were increased from \$10.5 billion (cases 30 and 31) to \$16.1 billion (cases 75 and 76). Again, the consumption of uranium up to 2020 increased (5.2 to 6.2 million tons without the breeder, 2.5 to 3.0 million tons with the LMFBR available). The maximum separative work demand without the breeder declined from 264 million SWU (in 2020) to 237 million; and with the breeder, it decreased from 95 million SWU (in 2000) to 79 million.

Estimates assuming the availability of a hypothetical high-efficiency, low-cost laser enrichment process indicated benefits of about \$9.9 billion, or about half the reference benefits of \$19.4 billion.

11.2.4.2.8 Effects of LMFBR Capital Cost Variations

In the reference case, LMFBRs were assumed to be introduced with capital costs greater than those of LWRs by \$100/kW of capacity. This differential was assumed to decrease linearly with time, until LMFBR capital costs attained parity with LWR costs in year 2000. Costs for the two power plant types were assumed to be

identical beyond 2000. The rationale for these projections was given in Section 11.2.3.

To test the sensitivity of benefits to capital costs, one case (case 21) was calculated in which LMFBR capital costs were assumed to decline to a level of \$50/kW more than LWR costs by 2000 with this differential remaining constant thereafter. The benefits calculated for this case were \$15.2 billion, a decline of \$4.2 billion from the reference case benefits. This corresponds to a decline in discounted benefits of \$84 million for each increment of \$1/kW in LMFBR capital cost above parity with the LWR.

The assumption of parity of LMFBR total plant costs with those of LWR plants does not infer parity in costs of the two nuclear steam supply systems. The higher efficiency of the LMFBR results in savings of \$26/kW in costs associated with turbine-generator equipment and cooling towers (or other heat rejection equipment). Physically smaller and simpler equipment, comparable to that in fossil plants, may be used. Thus the assumption of parity infers that the cost of the LMFBR nuclear steam supply system (NSSS) plus the indirect construction costs associated with this system, is greater than the corresponding LWR costs by \$21/kW, or 20%. Similarly, the cost differential of \$50/kW used in the sensitivity calculation of case 21 is equivalent to assuming a capital cost increment of \$71/kW, or a 70% increase, for the NSSS costs.

Several calculations employing a more pessimistic view of LMFBR capital costs were made in which LMFBR capital costs, initially \$100/kW greater than LWR costs, were maintained at that level throughout the study. Although this treatment of costs is highly pessimistic for a newly developing technology, the calculations offer added insight into the sensitivity of breeder benefits, and the range of parameters over which the LMFBR will yield positive benefits.

Results obtained from these calculations, for differing assumptions of uranium availability and HTGR-LMFBR capacity constraints, are given in Table 11.2-25. Detailed calculations were not made for all combinations of parameters but many of the additional combinations (whose values are shown in parentheses) were

obtained by interpolation or extrapolation from other conditions, supported by hand calculations of discounted costs for comparable numbers of breeder plants introduced.

Correlation of these results is shown in Figure 11.2-42. Capital costs of the breeder are seen to have a significant effect on benefits. This effect, however, is strongly influenced by assumptions as to availability of uranium resources and constraints imposed by capacity of HTGRs. Except in those cases with combinations of assumptions adverse to the LMFBR, benefits from LMFBR introduction remained greater than LMFBR program research and development costs. The lowest curve (optimistic uranium resource assumptions, unconstrained HTGR) indicates that the breakeven point for the breeder (benefits equal research and development costs) under these conditions occurs with a cost differential of about \$50/kWe. For the other cases considered, benefits continue to be obtained at progressively higher capital cost differentials, although the breakeven points on the upper curves cannot be reliably obtained.

Table 11.2-25

EFFECTS OF LMFBR CAPITAL COSTS ON BENEFITS

Uranium Resources Assumed	Energy Demand	HTGR Capacity Constraints Imposed	Benefits, Billions of Dollars for LMFBR Capital Cost Differential Above LWR's at End of Learning		
			\$0	\$50/kW	\$100/kW
Optimistic	Base	Yes	12.0	7.9 ^a	4.8
Base	Base	Yes	19.4	15.2	12.6 ^a
Pessimistic	Base	Yes	30.6	26.7 ^a	23.8
Optimistic	Base	No	8.2	4.0 ^a	1.9
Base	Base	No	12.2	8.0 ^a	4.4
Pessimistic	Base	No	19.5	13.4 ^a	11.0

^aThese figures were obtained by interpolation, extrapolation, or by hand calculations.

11.2.4.2.9 Fuel Development Considerations

The first commercial LMFBR models introduced are expected to be supplanted within a few years by improved models. These improvements constitute a normal evolutionary process for this or any similar development effort. For the LMFBR, the improvements will be implemented through: (1) fruition of LMFBR Program research and development;

EFFECTS OF LMFBR CAPITAL COSTS DIFFERENTIAL ON BENEFITS

Figure 11.2-42

(2) adaptation of advanced LWR and HTGR technology; and (3) learning from construction and operation of the LMFBR demonstration plant and the first commercial breeders.

An important aspect of projected improvements in the breeder is that of LMFBR fuels development. The timely development of advanced, high-performance fuels, which will permit the achievement of low doubling times for plutonium production together with reliability of operation, is expected to play an important part in attaining the benefits calculated from introduction of the LMFBR.

Planned LMFBR Fuels Development

As a part of the LMFBR Program research and development effort, work is now under way on the development of advanced LMFBR fuels. This effort is expected to result in fuels with superior performance characteristics during the decade of the 1990's.

The events projected for base conditions in the cost-benefit calculations include the introduction in 1987 of an LMFBR model whose fuel is only slightly improved over that of the demonstration plant. Advanced oxide fuels are projected to become available in 1991, and carbide-fueled breeders (representing use of either carbide or nitride fuels) are introduced in 1995. These developments result in progressive improvements in LMFBR performance, providing generation of electric energy at lower costs.

Benefits from Advanced Fuels Development

The LMFBR models considered in the study included two carbide-fueled breeder models of 2000-MWe capacity, assumed to become available about eight years after introduction of the first commercial breeder. These reactors exhibit higher plutonium breeding ratios than those of the oxide-fueled breeders considered. It was expected that the carbide-fueled breeders would be important in assuring sufficient plutonium during the period when the breeder capacity of the Nation is rapidly increasing. To examine the benefits associated with the use of carbide fuels, three cases were run in which carbide fuels were not assumed to be available, assuming different dates of introduction of the LMFBR. A fourth case, involving extended postirradiation cooling times for LMFBR fuels, will be discussed later in the section on the effects of cooling time (Section 11.2.4.2.10).

Additionally, check cases were run assuming unconstrained entry of HTGR and LMFBR plant types into the national power system, in which carbide and advanced oxide

fuels were, in progression, assumed not to be available. (These cases are not included in the list of cases in Appendix IV.C). Results of these calculations provide a measure of the benefits associated with development of either of the advanced fuel types.

The changes in benefits which are occasioned by the assumed nonavailability of the advanced fuels are summarized in Figure 11.2-43, in terms of the doubling times attainable with the various fuel types.

Nonavailability of the carbide fuels reduces base benefits by \$1.9 billion, from \$19.4 to \$17.5 billion. In the cases assuming removal of capacity constraints from HTGRs and LMFBRs, the decrease in benefits is \$1.7 billion (a decrease from \$12.2 to \$10.5 billion).

In the absence of carbide fuels, the rate of breeder penetration into the market is about the same as that for the reference case until about 2010. In the reference case, the breeder economy reaches maturity shortly after 2010, and equilibrium breeder-burner economy is established. Without carbide fuels, however, the breeder continues as a larger fraction of the economy after 2010, since the lower rate of plutonium production results in the introduction of fewer LWR plutonium burners in proportion to the capacity of breeders. To the extent that excess plutonium is available, the plutonium burners will be chosen selectively, based on relative power costs, to use the excess plutonium as fuel materials.

When neither the carbide nor the advanced oxide fuels are available, reference benefits are estimated to drop to about \$7 billion from the reference value of \$19.4 billion. When no capacity constraints are imposed on LMFBRs or HTGRs, lack of the advanced fuels drops benefits to \$4.0 billion. Penetration of the LMFBR into the power system in the unconstrained calculations, with no advanced fuels available, proceeded nearly as rapidly as when advanced fuels were used, and at a greater rate than when LMFBR capacity constraints were applied. This rate of LMFBR capacity growth, however, required the use of considerable additional plutonium. In the calculations, this was supplied through the utilization of LWRs with fuel cycles optimized for plutonium production.

Uranium consumption as affected by the availability of advanced LMFBR fuels is shown in Figure 11.2-44.

EFFECTS OF DOUBLING TIME ON LMFBR BENEFITS

Figure 11.2-43

EFFECTS OF DOUBLING TIME ON LMFBR URANIUM CONSUMPTION

Figure 11.2-44

The results of these calculations indicate that breeder introduction rates assumed in the reference cases can be sustained by use of oxide fuels alone, but that considerable economic incentive (about \$2 billion) exists for timely development of carbide and/or nitride fuels. Furthermore, the carbide fuels would be required if the breeder were to be introduced at rates appreciably greater than those assumed.

If neither carbide nor advanced oxide fuels were developed, benefits from LMFBR introduction would be reduced significantly. Further, introduction of the breeder in this case at more than nominal rates would require more plutonium than is normally available from the LWR fuel cycle. Thus, the development of advanced fuels appears to be a requirement for successful development of the LMFBR after introduction. Current research and development efforts are aimed toward timely development of those fuels.

In the calculations, the doubling times attainable with the advanced fuels were taken at 12.5 years for the oxide fuel and about 7.5 years for carbide (or nitride) fuels. While these goals appear reasonably attainable, it is possible that doubling times actually achieved could be somewhat longer due to: (1) inability to obtain fuel performance quite as high as the goal values; or (2) extraneous fuel-cycle factors which lengthen the time required for return of bred plutonium to the reactor as fresh fuel.

The calculations indicate, however, that benefits provided by the LMFBR are relatively insensitive to small changes in doubling time. In the case of the carbide fuels, for example, extending the doubling time by one year will result in the consumption of an additional 45,000 tons (approximately) by the year 2000. A lengthening of the doubling time from 7.5 to 9 years, therefore, would result in about 70,000 additional tons being consumed, and would decrease 10% discounted benefits by about \$0.5 billion.

If carbide fuels are available, LMFBR benefits would be unaffected by lengthening of the doubling time obtainable with oxide fuels. Without the carbides, however, an increase in doubling time of oxide-fueled plants from the reference 12.5 years to 15 years would result in the consumption of 180,000 additional tons of uranium (70,000 tons for each one-year increment of doubling time), and would decrease benefits by about \$1.2 billion (10% discounted).

Thus, modest increases in LMFBR fuel doubling times from those used in the calculations, should such increases occur, would have only minor effects on benefits.

11.2.4.2.10 Effects of Varying LMFBR Spent Fuel Cooling Time

In the reference case, the postirradiation cooling period for LMFBR spent fuel, prior to shipment to the chemical processing plant, was taken to be 120 days. Economically, there appears to be considerable incentive for maintaining a short cooling period for this fuel. The out-of-reactor fuel cycle for plutonium is lengthened as this cooling time is increased. Under some conditions, increases in cooling time may affect the availability of plutonium needed for fueling new breeders coming on line. Also, since plutonium generated in the LMFBR fuel has a capital value, utility accounting practices normally apply inventory charges to the spent fuel in storage.

On the other hand, lengthening of the cooling time reduces the radionuclide inventory and heat generation in the cooled fuel and tends to ameliorate handling problems involved in the transportation and subsequent chemical processing of the spent fuel. There is, therefore, some incentive to increase the postirradiation cooling time. To test the sensitivity of LMFBR benefits to increased cooling time, three cases were calculated, with postirradiation cooling time of 365 days, assuming 1987 introduction of the LMFBR.

When base values of energy demand and uranium available were assumed, use of a cooling period of one year instead of 120 days produced benefits of \$18.4 billion, a decrease of \$1 billion from those of the reference case. Some 10% more uranium resources were consumed than in the reference case, and more plutonium was produced, being required because of the additional fuel-cycle inventory caused by the lengthened cooling time. However, the increase in the inventory-in-storage resulting in less plutonium available for other than LMFBR use, as is evidenced by Figure 11.2-45. Actually, slightly greater utilization of LMFBRs was indicated in the case with one-year cooling because of the lower availability of plutonium for use in LWRs in the mature LMFBR economy.

To examine the effects of the one-year cooling period when other variables were considered, two other cases were calculated incorporating the 365-day cooling assumption. In one of these cases, the high energy demand schedule was assumed. In the other, the base energy demand schedule was used, but a carbide-fueled

EFFECTS ON LMFBR COOLING TIME ON PLUTONIUM AVAILABILITY

Figure 11.2-45

breeder was not assumed to be available, thus increasing the effective doubling time for plutonium production in the LMFBR system.

Assumption of the higher energy demand resulted in benefits of \$24.8 billion, or \$1.3 billion less than the corresponding benefits calculated with the shorter cooling period. With normal energy demand but without the carbide-fueled breeder, benefits were \$16.1 billion, a decrease of \$3.3 billion from the reference case, or \$1.4 billion from a case assuming nonavailability of the carbide-fueled breeder, but with 120-day cooling.

Plutonium availabilities in the two cases with extended cooling time were noticeably lower than in the reference case. In the case where carbide fuels are assumed not to be available, plutonium availability is indicated as being marginal from 1998 through 2016; all plutonium produced in this period is used for fueling of breeders.

It should be noted that the National Power Economy model, used for computer calculations in this study, uses a cash flow method of analysis in which plutonium is generated and used totally within the modeled system, and thus has no external market price. The computer model calculates a "shadow price" for plutonium as a function of time; this represents the intrinsic value of plutonium as a fuel within the power system. Plutonium used for fueling a nuclear plant is "purchased" from a stockpile at a given shadow price, and is returned at a later date, after reprocessing of the spent fuel, and "sold" at the shadow price prevailing at that time. Through discounting procedures, an effective interest is charged based on the purchase price.

It was incorrectly stated in the Draft Statement that no plutonium inventory charge is considered by the computer model. As noted by EPA and others,* this would result in erroneous power costs, if the Statement correctly described the model procedure. However, as described above, the inventory charges are, in fact, treated by the model and included in the power costs.

The additional inventory charges resulting from a longer cooling period can be important to an individual utility. These charges appear as a component of the annual fuel-cycle cost, and are paid on essentially a current basis. Therefore, the undiscounted costs attributable to assumption of a one-year cooling period are of interest. For the case assuming base energy demand and availability of

*Comment Letters 53, pp. 30-42; General Electric Co., 64, p. 4.

the carbide reactor, the decrease in 10% discounted benefits of \$1 billion is equivalent to a decrease of \$25 billion on an undiscounted basis--an average of \$700,000 per year for each 2000-MWe breeder in operation over the study period.

A 2000-MWe breeder will, on the average, discharge 2400 kg of fissile plutonium per fuel batch, or an average of 1750 kg per year at an average capacity factor of 72%, the lifetime average nuclear plant capacity factor used in this study. At an after-tax interest rate of 7.5% applied over two-thirds of a year (the increase in cooling time from four months to one year), an average inventory charge of \$700,000 per year as calculated above would correspond to a plutonium worth of about \$7.90 per gram. At a 10% interest rate, the corresponding worth would be about \$6.00 per gram. For the case assuming one-year cooling time, the reactor-average price of plutonium for all breeders introduced until 2020, including end-of-life operation to 2050, is estimated at \$5.00 per gram--in fair agreement with the estimates above. This low average value for plutonium results from the fact that most reactor years of breeder operation considered occur after the year 2010, in a period when a surplus of plutonium exists.

In earlier years, however, plutonium values are much higher, ranging from \$15 per gram in 1987 to a maximum of \$32 per gram in 2006. At this maximum value, the added inventory charges for a breeder at 72% plant factor because of the longer cooling time would be about \$2.8 million per year (7.5% interest) to \$3.7 million per year (10% interest). At a plant factor of 80%--the maximum assumed for breeders--these charges would be, respectively, \$3.1 and \$4.1 million per year.

Effects such as these on individual utilities, which tend to be deemphasized in comparison with discounted costs, must be carefully weighed in assessing the effects of longer cooling times.

11.2.4.2.11 Plutonium Production and Consumption

Introduction of the LMFBR greatly increases the utilization of plutonium in the power system. The comparative rates of utilization of plutonium with and without the breeder are shown in Figure 11.2-46. The curves of this figure represent the total annual throughput of plutonium in the fuel cycle; they include both newly produced plutonium and "old" plutonium recycled after prior use in a reactor.

Without introduction of the breeder, the rate of use of plutonium fuel increases to a rate of 500 metric tons per year in 2020, reflecting the increasing number of operating LWRs. The assumption of a storage charge of \$500/year per kilogram

EFFECTS OF LMFBF ANNUAL FUEL CYCLE UTILIZATION OF FISSILE PLUTONIUM

Figure 11.2-46

of plutonium strongly favors the use of plutonium in a recycling economy. In the latter years of the study period, increasing uranium prices also reinforce the favorable economics of recycling. In the nonbreeder case, therefore, all available plutonium is recycled, with essentially no accrual in stockpiles. With introduction of the breeder, the rate of use of plutonium is, of course, markedly increased. While plutonium recycle fueling of thermal reactors is utilized before the date of the breeder introduction, this use decreases rapidly as the breeder is incorporated into the power economy. In the introductory years, most of the available plutonium is used to provide fuel to new LMFBRs. Later, when the breeder market has attained maturity, excess plutonium starts to become available. At that time, it becomes economical to use the excess plutonium as fuel in LWRs which act as plutonium burners.* As before, the economic optimum mix of reactors results in essentially full utilization of the available plutonium; stockpiles of stored plutonium are essentially nonexistent.

Actual rates of production and consumption of fissile plutonium (as opposed to total fuel-cycle throughput) by the various reactor types introduced into the power economy, with and without the breeder, are given in Figures 11.2-47 and 11.2-48. The first figure, with no breeder available, shows the balance of plutonium supply and consumption achieved by attainment of an equilibrium mixture of uranium-fueled and plutonium-fueled LWRs.

Introduction of the LMFBR (Figure 11.2-48) occurs at a sufficiently rapid rate that it is a net consumer of plutonium for about 20 years following introduction. During this period, fewer LWRs are introduced than in the nonbreeder case. The LWRs which are introduced, however, are mostly uranium-fueled producers of plutonium. As the breeders approach self-sufficiency and become net producers of plutonium (about 2005 to 2010), the capacity of uranium-fueled LWRs drops rapidly. However, relatively large numbers of plutonium-fueled LWRs are introduced, using the surplus plutonium produced by the breeders. During the entire time period, the production and consumption of plutonium are essentially balanced, with virtually no accumulations of plutonium in stockpiles.

When carbide fuels for the LMFBR are assumed not to be available, the lower breeding ratio of the oxide fuels results in the patterns shown in Figure 11.2-49.

*Thermal reactors were used as plutonium burners, because that was the only route available to the model for economic gain from the excess plutonium. Actually, when this situation is reached, it is probable that the LMFBR would be reoptimized for lower cost at the sacrifice of some breeding gain (for example, by reducing the loading of the blanket). This would provide an alternative route to obtain economic gain from the excess plutonium which is being produced.

FISSILE PLUTONIUM PRODUCTION--CONSUMPTION BALANCE WITHOUT LMFBR

Figure 11.2-47

FISSILE PLUTONIUM PRODUCTION--CONSUMPTION BALANCE WITH LMFBF

Figure 11.2-48

FISSILE PLUTONIUM PRODUCTION CONSUMPTION BALANCE WITHOUT
CARBIDE FUEL AVAILABILITY--120 DAY COOLING

Figure 11.2-49

In order to provide sufficient plutonium for introduction of breeders from about 1987 to 2010, the LWR fuel cycle is shifted to emphasize production of plutonium and reduce its consumption. More uranium is thus consumed than under base conditions, and the use of plutonium as an LWR fuel drops nearly to zero around the year 2000. In a similar case involving 365-day cooling of LMFBR fuels with no carbides available, a total cessation of plutonium use by LWR's was indicated in this period; this was shown in Figure 11.2-45.

Extension of the postirradiation cooling period to one year for LMFBR fuels results in the production-consumption balances shown in Figure 11.2-50. The added delay in the fuel-cycle results in an effective loss of availability of plutonium; hence, before about the year 2010, production-consumption patterns are similar to those of Figure 11.2-49 which reflected a loss in plutonium availability due to lower production rates from oxide fuels. However, once the carbide-fueled breeder achieves dominance in the market, the effects of the longer cooling period become less important and considerable plutonium becomes available for use in LWRs.

Patterns of plutonium production and consumption such as the above show considerable difference in detail with the changing conditions assumed for different cases in the study. In virtually all cases studied, they were in balance. Plutonium was seldom stockpiled in more than nominal amounts in any case, and enough was always available, through choice of fuel-cycle variations, to provide fuel for LMFBRs being introduced. Only in one case--in which neither the LMFBR advanced oxide nor carbide fuels were assumed to be available--was the need for additional plutonium indicated. In this case, the computer model selected specially optimized fuel cycles for LWRs to fill the additional need.

11.2.4.2.12 Effects of Combined Parameter Changes

One of the major comments made by EPA* in their review of the Draft Statement was that additional calculations should be made to investigate the so-called "synergistic" effects of combined changes in two or more parameters. Calculations shown in cases 45 through 72 were added in response to the comment.

Results of the calculations involving multiple parameter changes have been discussed repeatedly in earlier parts of this section. From the foregoing discussions, it is obvious that combinations of parameters can be selected which will drive benefits from LMFBR introduction to a level below that of the program

*Comment Letter 53, pp. 28, 49-51.

FISSILE PLUTONIUM PRODUCTION--CONSUMPTION BALANCE WITH
 365-DAY COOLING REVIEW--CARBIDE FUELS AVAILABLE

Figure 11.2-50

research and development costs. However, it requires a combination of unlikely parameter values to drive benefits that low.

For example, some of the worst-case assumptions used included: (1) removal of all capacity constraints for various nuclear plant types, resulting (in the non-breeder case) in an HTGR capacity commitment nearly four times the sole HTGR vendor's own estimates; (2) a greatly decreased projection of electric energy demand, falling 50% below the base demand projection in 2020; and (3) an assumption that the LMFBR receives no learning curve benefit in reduction of capital costs as it penetrates the market.

It is of interest to examine the change in benefits from the reference case when each of these worst-case assumptions is applied progressively. The trends of benefits, for each of the three cases of assumed uranium resource availability, are shown in Table 11.2-26.

Thus, the benefits from LMFBR introduction remain greater than program costs for all but severe combinations of assumptions, which are considered highly unlikely by AEC. For all cases in which less adverse assumption of parameters are made, benefit/cost ratios were favorable.

11.2.4.2.13 Effects of Nuclear--Fossil Competition

In the reference calculations, as in most of the sensitivity calculations, it was assumed that the nuclear capacity of the Nation's power economy increased with time in a set pattern, regardless of the nuclear plant mix involved or of variations in power generation costs. The remainder of the central station capacity was assumed to consist of fossil-fired steam plants and of installation using other energy sources (e.g., geothermal energy, etc.).

In reality, of course, nuclear and fossil plants compete economically in the market; previous cost/benefit studies assumed such competition. In order to correlate these studies to prior studies and to examine the potential effects of nuclear-fossil competition on LMFBR benefits, a set of calculations was made in which fossil and nuclear plants were assumed to compete for inclusion in the power economy.

Cases 34, 35, and 36 tested the changes from the reference case when competition among fossil and nuclear plants was assumed, under differing HTGR constraints.

Table 11.2-26

BENEFITS (BILLIONS OF DOLLARS, 10% DISCOUNTED) FOR URANIUM RESOURCES

Reference Conditions	Optimistic	Base	Pessimistic
	12.0	19.4	30.6
First:			
(1) Remove HTGR Constraints	8.2	12.2	19.5
Then Assume:			
(2) Low Energy Demand (-50%)	3.2	4.2	7.0
Then Assume:			
(3) No Learning Curve for LMFBR (Constant \$100/kW above LWR)	0.9	1.2	3.4

When program costs and benefits are discounted at 7.5%, the benefit trends are shifted as shown in Table 11.2-27.

Table 11.2-27

BENEFITS (BILLIONS OF DOLLARS, 7.5% DISCOUNTED) FOR URANIUM RESOURCES

Reference Conditions	Optimistic	Base	Pessimistic
	34.2	53.9	78.1
First:			
(1) Remove HTGR Constraints	22.0	32.0	49.4
Then Assume:			
(2) Low Energy Demand (-50%)	8.7	12.3	18.6
Then Assume:			
(3) No Learning Curve for LMFBR (Constant \$100/kW above LWR)	1.9	4.3	8.5

The base projections of generating capacity for the Nation (Section 11.2.3) indicate 700,000 megawatts of nonnuclear central station capacity by the year 2000 and 2,130,000 megawatts by the year 2020. In the near future this nonnuclear capacity will be essentially all fossil; in more distant years an increasing portion may be represented by other types of generation.

In order to evaluate the effects of nuclear-fossil competition, a varying portion of the nonnuclear capacity was assumed to represent fossil plants. From the current 1974 capacity of about 315,000 megawatts, fossil capacity was assumed to increase to 600,000 megawatts (85% of nonnuclear central station capacity) by the year 2000, and to 1.4 million megawatts (65%) by 2020.

This projection of capacity, added to the nuclear projection, represented the total capacity which, after the year 1982, was assumed to be subject to nuclear--fossil competition. (The entire nuclear capacity prior to 1982 is now committed to construction).

It is recognized that generation methods other than fossil may penetrate the power economy to a greater or lesser extent than that assumed. Nevertheless, the projection used for expansion of fossil capacity appears reasonable, and serves to test the conversion of the constraints applied to total nuclear capacity in most of the cases.

As was described in Section 11.2.3, through analysis of historical costs of coal, ten cost ranges were evolved for fossil fuel costs and a fraction of total generation was assigned to each cost range. These fractions of generation were assumed to apply throughout the period of study, although the average fuel cost within each range increased in varying amount with time.

Plant types were assumed to compete separately within each fossil fuel cost range; base-loaded and "load-following" plants also competed separately (a total capacity composition of 60% base-loaded plants and 40% load follower plants was assumed). Thus, for instance, under given conditions, fossil plants might be selected in low fuel cost ranges, while the higher ranges are occupied by nuclear plants; or a given cost-range capacity mix might contain nuclear base-loaded plants and fossil load-following plants. If the proper conditions occurred for any given year, a single plant type could be installed exclusively in that year.

Two nonbreeder cases were considered; in one (case 34), HTGR capacity was constrained to a maximum of one-third the LWR capacity throughout the study period; in the second (case 35) no constraints were applied.

In both cases, nuclear capacity increased significantly above that assumed for base-case conditions. As shown in Figure 11.2-30, the nuclear capacity in the constrained case increased to 4720 megawatts by the year 2020, an increase of 1420 megawatts over capacities under base conditions. The increase in capacity for the unconstrained case by the year 2020 was 1420 megawatts.

Case 36, assuming availability of the LMFBR, imposed no capacity constraints on any plant type. In this case, nuclear capacity by the year 2020 was calculated to be 4720 megawatts, an increase of 1420 megawatts over base conditions (Figure 11.2-31). No fossil plants were introduced after the year 1980.

11.2.4.3 Relationship of LMFBR Benefits to Program Costs

A measure of the economic value of the U.S. LMFBR Program may be obtained by comparing, under appropriate conditions, the economic benefits provided by the LMFBR to the program costs devoted to developing the breeder to the point of commercial feasibility. Program costs were shown and discussed in Section 11.2.2. A summation of the costs is given for convenience in Table 11.2-28.

Table 11.2-28

SUMMARY OF PROJECTED U.S. LMFBR PROGRAM COSTS

<u>Discount Rate (%)</u>	<u>LMFBR Program Costs, Billions of Dollars, Discounted to Mid-1974, For Commercial Introduction of LMFBR in:</u>		
	<u>1985</u>	<u>1987</u>	<u>1991</u>
0	8.6	8.4	8.7
5	6.3	6.1	6.2
7.5	5.5	5.3	5.4
10	4.8	4.7	4.7

A historical criterion for evaluating the economic value (or desirability) of a program is the benefit/cost ratio -- the simple ratio of benefits derived from a program to costs of the program, both values discounted at the same appropriate

rate. According to this criterion, a benefit/cost ratio of 1.0 or greater, at the appropriate discount rate, indicates economic viability of the program. Benefit/cost ratios were calculated for all cases considered in the study and are shown in Appendix IV.C.

An alternate criterion of program value is the effective rate of return realized, on the "investment" of program costs, through benefits from the program. This criterion, though closely related to the concept of the discounted benefit/cost ratio, is felt by some to provide a more realistic measure of the worth of a program. The Environmental Protection Agency* specifically requested that rate-of-return analyses be provided for cases exploring key parameters of the study.

Rates of return were calculated for 15 cases in the study, and are discussed in Section 11.2.4.3.2.

11.2.4.3.1 Benefit/Cost Ratios

Introduction of the LMFBR in 1987, under base conditions as used in the study, is calculated to provide a benefit/cost ratio of 4.1, with costs and benefits discounted to mid-1974 at 10%. Variation of the benefit/cost ratio with changes in key parameters is indicated in Figure 11.2-51. Changes in the conditions assumed for the calculations can provide large savings in the resulting benefit/cost ratio. As was discussed earlier, the cost and availability of uranium ore has a particularly significant effect on the benefit/cost ratio.

As the figure indicates, benefit/cost ratios are greater than 1 resulted in most cases considered in the calculations; for base conditions, and for most changes in parameters away from base conditions, these ratios were well above 1. Only for a few cases representing combinations of adverse assumptions which are not considered likely by AEC, were ratios of less than 1 calculated.

The program costs for development of the LMFBR are expected to be largely spent prior to introduction of the commercial breeder. Benefits from the breeder, although they will begin to accrue with its introduction, would result mainly from cost savings in later years, after the breeder has become dominant in the power economy. Discounting procedures thus affect LMFBR benefits more strongly than program costs, and the benefit/cost ratio is therefore highly sensitive to the discount rate used. Figure 11.2-52 compares benefit/cost ratios, under base

*Comment Letter 53, pp. 45-47.

- a) INCREASED ENERGY DEMAND: 20% ABOVE "PROBABLE" DEMAND IN 2020
 b) REDUCED ENERGY DEMAND: 20% BELOW "PROBABLE" DEMAND IN 2020
 c) GREATLY REDUCED DEMAND: 50% BELOW "PROBABLE" DEMAND IN 2020
 d) LMFBR CAPITAL COSTS REMAIN \$50/KW ABOVE LWR COSTS AFTER 2000
 e) LMFBR CAPITAL COSTS REMAIN CONSTANTLY AT \$100/KW_e ABOVE LWR COSTS

LMFBR COST/BENEFIT RATIOS (10% DISCOUNT)

Figure 11.2-51

- a) INCREASED ENERGY DEMAND: 20% ABOVE "PROBABLE" DEMAND IN 2020
 b) REDUCED ENERGY DEMAND: 20% BELOW "PROBABLE" DEMAND IN 2020
 c) GREATLY REDUCED DEMAND: 50% BELOW "PROBABLE" DEMAND IN 2020
 d) LMFBR CAPITAL COSTS REMAIN \$50/KW ABOVE LWR COSTS AFTER 2000
 e) LMFBR CAPITAL COSTS REMAIN CONSTANTLY AT \$100/KW_e ABOVE LWR COSTS

COMPARISON OF BENEFIT/COST FOR DIFFERENT DISCOUNT RATES

Figure 11.2-52

conditions and for several assumed variations in key parameters, when discount rates of 10% and 7.5% are used. When the lower discount rate is applied, benefit/cost ratios are obtained which are from two to three times the value of those obtained with the 10% discount rate used as a base rate in this study. As was discussed in Section 11.2.3.2, the 7.5% discount rate agrees more closely with utility financing practices, and with the 10% before-tax discount rate preferred by OMB. Thus, use of the 7.5%-discounted benefit/cost ratios may be preferred by some as a measure of value of the LMFB program.

11.2.4.3.2 Rates of Return

Benefits obtained from introduction and use of the LMFB in the national power system represent a return on the investment made in developing the LMFB. The effective rate of return represented by the accrual of benefits may be calculated by the analysis of annual cash flows in the national power economy. As was previously mentioned, this rate of return is preferred by some as a measure of the value of a project.

Through progressive summation of annual cash flows, and evaluation of comparable systems with and without the breeder, the accrual or present-worth benefits from LMFB introduction were calculated, year-by-year, as:

$$(\text{Benefits})_{n,D} = [(\text{cost with breeder}) - (\text{cost without breeder})]_{n,D}$$

representing the summation of annual costs (and benefits) from 1974 to the year n , discounted to mid-1974 at discount rate D .

This annual progression of benefits was then compared to the annual progression of LMFB program expenditures, as:

$$[\text{Benefits}]_{n,D} - [\text{Program Costs}]_{n,D} = Q_{n,D}$$

A discount rate may be found at which the value of Q is zero. That discount rate is equivalent to the effective rate of return on the investment.

Rates of return were calculated for 15 cases, representing base conditions and assumed variations in key parameters, are listed in Table 11.2-29 compared with benefit/cost ratios.

Under base conditions, the calculated effective rate of return is 14.6%. For 11 of the 15 cases considered, the rate of return varies between 10 and 16.5%. For one of the most adverse cases considered in the study, combining high LMFBR capital costs with a greatly reduced energy demand projection, the rate of return dropped to about 2%.

Table 11.2-29

EFFECTIVE RATES OF RETURN FROM LMFBR PROGRAM IMPLEMENTATION
AND COMPARISONS WITH BENEFIT/COST RATIOS
(1987 LMFBR introduction)

Case	Capacity Constraints Imposed		LMFBR Capital Costs	Energy Demand	Uranium Cost	Other Conditions	10% Discounted Benefit/Cost Ratio	Effective Rate of Return (%)
	HTGR	LMFBR						
3	Yes	Yes	Base	Base	Base	(a)	4.1	14.6
7	Yes	Yes	Base	Base	Low Cost		2.6	12.9
11	Yes	Yes	Base	Base	High Cost		6.5	16.5
31	No	Yes	Base	Base	Base		2.2	12.2
47	No	No	Base	Base	Low Cost		1.7	11.1
19	Yes	Yes	Base	+20%	Base	(b)	5.6	15.5
15	Yes	Yes	Base	-20%	Base	(c)	3.0	13.5
51	No	No	Base	-50%	Low Cost	(d)	0.7	8.1
65	No	No	Base	-50%	High Cost	(d)	1.5	11.3
21	Yes	Yes	+\$50	Base	Base	(e)	3.2	13.6
54	No	No	+\$100	Base	Low Cost	(f)	0.4	4.5
68	No	No	+\$100	Base	High Cost	(f)	2.3	12.3
57	No	No	+\$100	-50%	Low Cost	(d) (f)	0.2	2.2
71	No	No	+\$100	-50%	High Cost	(d) (f)	0.7	8.0
74	Yes	Yes	Base	Base	Base	(g)	6.2	16.3

^aBase conditions for study.

^bIncreased energy demand: 20% above base demand in 2020.

^cReduced energy demand: 20% below base demand in 2020.

^dGreatly reduced demand: 50% below base demand in 2020.

^eLMFBR Capital costs remain \$50/kW above LWR costs after 2000.

^fLMFBR Capital costs remain constantly at \$100/KWe above LWR costs.

^gSeparative work charge \$75/SWU.

11.2.5 The Logic of Cost-Benefit Models as Related to Utility Planning Methods

Both Natural Resources Defense Council* (NRDC) and the Environmental Protection Agency** (EPA) presented an analysis endeavoring to show initially the fuel-cycle cost differential favorable to the LMFBR that would be necessary to offset the capital cost differential (unfavorable to LMFBR) in order for the breeder system to be competitive. EPA concludes--"In order for the LMFBR to be competitive with the LWR, its fuel cycle costs must be lower than the LWR's by at least the same differential disadvantage it has in relation to the LWR in capital costs and operation and maintenance costs. For the AEC assumptions, that differential is 2.15 mills/Kwh."

These analyses were extended then to determine the price level for U_3O_8 necessary to realize this fuel cycle cost differential, and finally the year that U_3O_8 of this price would be brought to market. With this rationale and using information developed by Bupp and Derian[†] one conclusion reached by NRDC is--"uranium prices would not reach these levels for almost a decade beyond the turn of the century --."

Another commentator^{††} states that, "...no advanced reactor is likely to be deployed in large numbers until it can compete economically with light water reactor plants."

The cost-benefit model used in the AEC studies does not generate explicit year-by-year fuel cycle cost estimates for individual plants, nor does it directly compare individual plants such that one can point to a precise date^{††} when the LMFBR becomes "economic" on an individual plant basis. However, the model does consider all fuel-cycle cash flows occurring throughout the system of plants, and works to minimize the discounted value of the total cash flows.

The model will not build plants that do not help minimize system costs, and it includes full consideration of both cost advantages and disadvantages of plant candidates. The model allows consideration of many of the following factors which are important to a utility endeavoring to determine economical desirability of alternative power plant types. Factors which are not treated directly may be treated in the input assumptions.

*Comment Letter 38g, pp. 31-38, 76.

**Comment Letter 53, pp. 60-67.

†Draft Document, I.C. Bupp and D. Derian, "Another Look at the Economics of Breeder Reactors" (November 9, 1973).

††Ebasco Services, Comment Letter 18, p. 11.

- (1) Current dollars may be used either solely or in combination with constant dollars in the analysis. With persistent inflation, it is important to know how the inflation impacts the cost of each type of plant. For this study, constant dollars are utilized in the model. Should current dollars be used, the breeders' benefits would be increased.
- (2) A discount factor based on the cost of financing new plants. For this study a deflated discount rate of 10% is used. As noted in Section 11.2.4.1, a deflated discount factor of about 5% is appropriate to the utility industry, and, if used will increase the breeders' benefit by a factor of about 6.5.
- (3) The effect of building a large number of these plants in order to determine the resulting rate of depletion of low-cost fuels and impact on the fuel costs for this and other plant types that the utility is operating or will buy.
- (4) The buildup of the industry associated with the particular plant type since this should improve the economic competitiveness of the plant. Utilities will require additional plants for new capacity and replacements and, therefore, it is important to appreciate its ultimate potential.

Accordingly, the AEC system analysis model is thought to provide a superior representation of utility methods for making the most economic choice for new plants, and is preferable to the suggested constant dollar comparative analysis of individual plants. The individual plant approach is unable to include synergistic benefits which the breeder provides through its fuel-cycle interaction with the thermal reactors. These effects are included by the AEC cost-benefit model. These effects are well recognized by the utility industry, as discussed in the next section, which reflects a view of the utility interests.

11.2.5.1 A Utility View of the LMFBR*

The electric utility industry views the breeder as an insurance policy that will guarantee that even if other sources of energy prove inadequate, the Nation will have available a many-centuries' supply of electric power. They believe that the breeder is the concept that currently has the best promise of providing the Nation with an alternative energy option.

The utility industry has concluded that nuclear power is essential to the future well-being of the nation. The utilities also believe current knowledge of domestic

*This section generally reflects views of some utility executives whose companies have a large commitment to nuclear power.

uranium resources indicates that the breeder will be needed to ensure the viability of the nuclear option. It is the hope of the electric power industry that large new bodies of low-cost uranium ore will be found in the U.S. But they feel their plans must be based on knowledge, not on hope. It must be realized that if the Nation commits itself to using large amounts of uranium in light-water reactors, it will reach a level of utilization at the turn of the century where even a doubling of low-cost resources through successful exploration will provide uranium for only ten more years.

The electric utility industry has selected nuclear plants to meet a growing portion of its new capacity requirements. This choice has been made on the basis of favorable overall costs, low sensitivity to future escalation of fuel costs, and the inherent cleanliness of nuclear power. Even though the initial capital investment for nuclear plants is higher than for fossil plants, the compensating long-term fuel cost advantage gives nuclear an overall cost advantage.

It is because of the long-term outlook by utilities that nuclear power, even with its initial higher capital costs, has been selected. Moreover, as the Nation's resources of low-cost fuels become depleted, it can be expected that utility decisions regarding new capacity will include even longer-term considerations related to fuel availability. From the point of view of the utilities, the breeder promises to stabilize and magnify the economic benefits that nuclear power has already brought to the nation. Its yet lower fuel cycle costs will hold down long-term power costs and will be even more effective in guarding power costs against the effects of inflation. Also, the breeder will work to reduce the costs of power from light water reactor plants by increasing the resale value of plutonium. Even more important, the breeder will provide the kind of economic stability in meeting the nation's energy needs that can be provided only when there exists assurance of adequate long-term fuel supplies.

Beyond these better-recognized advantages, the utilities have called attention to certain, more subtle advantages of the breeder which may prove to be of even greater economic importance. A breeder plant will require only 1/30th to 1/60th of the U_3O_8 that a water reactor would require.

A mature breeder industry will conserve the Nation's limited resources of low-cost U_3O_8 and in this way reduce the cost of power from every water reactor in service. Utility studies indicate that whenever a breeder is selected over a thermal reactor, the savings that accrue in the costs of fueling thermal reactors (because the

breeder is conserving U_3O_8) may equal the direct economic benefit that the breeder will yield through its lower costs. It is inevitable that utilities will give this aspect emphasis because of the need to preserve, on an individual and collective basis, resources of reasonably priced uranium for existing thermal reactors.

The economic advantage for nuclear plants is increased when evaluated in a period of escalating fuel costs. The capital investment is made over a few years leading up to initial operation, and is subject to escalation only during that period, whereas the fuel cost continues to escalate during the 30 to 40 years of plant operation. Fuel costs for LWR and HTGR plants operating in the early 1980's are projected to be about 2-2.5 mills/kWh(e), in 1974 dollar values, while coal-fired plants are projected to have fuel costs of 5 to 8 mills/kWh(e) (12 to 20 dollars per ton). The effects of fuel price escalation make this cost differential progressively larger during the 30 to 40 year operating life of the plants, increasing the unescalated cost advantage of the nuclear plant.

Some commenters* have discussed the conditions under which the LMFBR would be economically competitive, placing emphasis on cost comparisons between individual plants rather than the AEC technique of using long-range cost-benefit studies. These commenters have suggested that utility planners would evaluate the LMFBR on the individual plant basis rather than using system optimization techniques.

However, the literature** on utility planning techniques shows that this is not the case. The utilities have placed great emphasis on evaluation techniques which allow system analysis studies of expansion strategies, rather than simple present-worth economic analysis of single projects.

The procedure of comparing the lifetime present-worth costs of plant A with those of plant B, and choosing the lowest in cost, is appropriate when the plant candidates have no synergistic effects on the rest of the system. This is essentially the case with fossil plants, although there may be some small effects through plant reliability, system reserve margin, etc. For example, a very large unit may have attractive capital cost, but may impose a need for additional capacity reserve margin to maintain system reliability.

However, nuclear units generally do have significant feedback effects on the rest of the system, which utilities consider in their economic evaluation. The most

*Comment Letters: NRDC, 38g pp. 31-40; EPA, 53, pp. 60-67.

**"A collection of papers presented at the Nuclear Utilities Planning Methods Symposium," ORNL-TM-4443, January 1974.

obvious difference between nuclear and fossil plants is that nuclear plants are shut down about once a year and refueled with a full year's supply of energy, whereas fossil plants are fueled continuously. Currently, this refueling of nuclear plants removes the plant from service for several weeks of each year. During this outage, some other generating unit must be substituted for the nuclear plant capacity, and the economics of this replacement energy must be evaluated. (It should be noted that nuclear plants are economically attractive, even with this refueling outage cost included.)

The breeder reactor will have important synergistic benefits to the utility system, since it will be producing fissile plutonium for use in starting up new plant additions or for refueling existing LWR or HTGR plants. In whatever way the breeder-produced plutonium is used, it results in the utility requiring less U_3O_8 and separative work than if the breeder were not built, thereby reducing the cash outlays for these two quantities. The resulting cost savings will be credited to the breeder when making economic comparisons with other expansion candidates. This procedure is analogous to that utilized in the power economy optimization model used to make the LMFBR cost-benefit calculations, in which the breeder produces national power-cost savings by generating electricity at low cost while simultaneously producing fissile plutonium for use in nonbreeders. Before a self-sustaining plutonium fuel cycle is established for the entire system, the nonbreeders derive benefit from the reduced consumption of U_3O_8 , which stabilizes uranium prices at a lower level.

In the same way that current nuclear plants are less sensitive to escalation than fossil plants, the LMFBR will be less sensitive than the LWR or HTGR. This arises because the LMFBR has a lower total fuel-cycle cost and because it produces its own fissile material. Escalation of fissile material values will work to the advantage of the LMFBR since it is selling fissile material, but will work to the disadvantage of nonbreeders which must annually purchase additional fissile material. Thus, the initial fuel cost advantage of the LMFBR will be increased by escalation during plant operation.

The utility planner is fully aware of the cost increases which can occur due to escalation, and has always considered the effects of escalation when evaluating alternative expansion strategies. The LMFBR reduces the utilities' risk of escalating fuel costs and also enables the utility to produce its own supply of fissile material, becoming independent of U_3O_8 and enrichment industries. Therefore, the utility acquires control over a greater fraction of its future operating costs at the same time it is reducing those costs.

Just as the AEC uses a national power-economy optimization model to choose expansion strategies, utilities use sophisticated systems analysis methods in making expansion planning decisions. It is especially significant to observe that utilities place very great importance on the ability to consider cost escalation, present-worth discounting, and total system costs when evaluating expansion plans.

In this respect, the utilities are making expansion decisions based on long-term projections of fossil fuel and U_3O_8 prices, other fuel-cycle prices, operating and maintenance costs, and plant capital costs. These projections include consideration of the effect of the total national demand for U_3O_8 on the future price of uranium, and will reflect the effect of a viable breeder industry on slowing the rise in uranium price.

Thus, the utility viewpoint of breeder economic evaluation closely parallels the viewpoint taken in the AEC cost-benefit studies. That viewpoint is based on a long-range system cost optimization, and is not limited to isolated cost comparisons between individual LMFBRs and alternative plants.

11.2.5.2 Economics of the LMFBR in 1990

While the AEC cost-benefit analysis procedure is believed to be the most appropriate method of evaluating the LMFBR in the long term, the following section is presented in response to some of the requests* for a simplified analysis.

This analysis uses information from the cost-benefit studies, but includes escalation of costs to 1990.

Typically, utilities may use values in the range of 3 to 4% per year for escalation and 7 to 10% per year for discount rates. These are equivalent to using 3 to 7% per year discount rates in constant-dollar calculations.

In the following calculations for plants beginning operating in 1990, the 1974-dollar costs used in the cost-benefit studies were escalated to 1990 at 3% per year, except that U_3O_8 prices were escalated at 4% per year and capital costs were escalated at 7.5% per year. Costs incurred after 1990 were discounted to 1990 at 5% per year, a rate which is consistent with the use of constant-dollar costs after 1990.

*Comment Letters: Ebasco Services, 18, p. 11; NRDC, 38g, p. 31; EPA, 53, p. 63.

The escalated values for U_3O_8 price versus quantity were derived from the base cost used in the cost-benefit studies giving the values shown in Table 11.2-30. These values are considered to be conservative projections of 1990 prices in view of present prices (in the range of \$20/lb U_3O_8) being quoted for uranium to be delivered during the next decade. Also, the rate of U_3O_8 price escalation is likely to be higher than the assumed 4% per year. An additional factor which may lead to higher prices is the present stiff competition by utilities for available uranium supplies. This competition tends to cause prices for depletable raw materials to escalate at a higher rate than other prices.

Table 11.2-30
BASE COST PROJECTION OF U_3O_8 PRICE VERSUS
CUMULATIVE AVAILABILITY (ESCALATED TO 1990 AT 4%/YEAR)

Cumulative Availability, Millions of Tons of U_3O_8	Projected Price (\$/lb U_3O_8)
0-1	15
1-2	25
2-3	40
3-4	60
4-5	115
5-6	155
6-7	195
7-8	215
8-9	235
9-10	245

With the U_3O_8 consumption rates calculated in cost-benefit cases 1 and 3, the U_3O_8 price versus time is as shown in Table 11.2-31. These uranium prices are applicable both to new plants built in 1990 and to plants already built which will continue to operate after 1990. These values illustrate the effect of the LMFBR in reducing U_3O_8 consumption and slowing the rise in uranium prices, and are the reason why the utilities are interested in the benefits the breeder can bring to their LWR fuel-cycle costs by holding down the U_3O_8 cost. It should be pointed out that utility studies are based on resources of uranium that are reasonably assured, rather than the more optimistic AEC view of probable reserves which is used here.

Table 11.2-31
PRICE OF U_3O_8 VERSUS TIME

Year	U_3O_8 Prices, ^a (\$/lb)	
	Case 1 (no Breeder)	Case 3 (1987 LMFBF)
1990	25	25
1998	25	
1999	40	25
2000		40
2004	40	
2005	60	
2008	60	
2009	115	
2010	115	40

^aConstant 1990 dollar values.

11.2.5.2.1 New Plants Built in 1990

In this section the average power cost is analyzed for the mix of new power plants added in 1990 to 1991* by the system analysis model for case 1 (no breeder) and case 3 (1987 LMFBF introduction). The purpose of this analysis is to show that the 30-year levelized system power cost is reduced by the presence of the breeder.

- (1) Fuel Costs. The type and number of new plants built in 1990 to 1991 are shown in Table 11.2-32, along with the 30-year levelized costs of each. It is again emphasized that the cost benefit model does not calculate 30-year fuel costs for individual plants nor make decisions based on the numbers shown in Table 11.2-33. These fuel costs were calculated by approximate methods, using available data from the cost-benefit model. The results are only a simplified approximation of the costs used by the model.

As shown, the case with the breeder results in an average fuel-cycle cost reduction of 0.7 mill/kWhr(e), and a total discounted fuel cost savings of about 7.4 billion dollars for the plants built in 1990 to

*It is expected that the breeders introduced prior to 1990 (the reference oxide designs) will probably have the advanced oxide core installed when they are available in 1990 or shortly thereafter.

Table 11.2-32

THIRTY-YEAR LEVELIZED FUEL-CYCLE COSTS FOR PLANTS BUILT IN 1990-1991
(in 1990 dollar values)

Plant Type	Case 1 (no Breeder)		Case 3 (1987 LMFBR)	
	Plants Added GW(e)	Fuel Cost [mills/kWhr(e)]	Plants Added GW(e)	Fuel Cost [mills/kWhr(e)]
Uranium-Fueled LWR	61	3.93		
Uranium-Plutonium-Fueled LWR	6	3.97	65	3.55
Plutonium-Fueled LWR	17	3.49		
HTGR	19	3.65	11	3.19
Advanced Oxide LMFBR			26	1.96
Average Fuel Cost, mills/kWhr(e)	3.8		3.1	
Total Fuel Cost Savings (Discounted to 1990 at 5% per year)	Base		\$7.4 billion	

11.2-192

1991. This savings results from the lower fuel-cycle costs of the LMFBFR, plus the reduction [about 0.3 mill/kWhr(e)] in the fuel cost of the thermal reactors. About one-third of the 0.7 mill/kWhr(e) reduction in average fuel cost results from reduced U_3O_8 prices to the thermal reactors. The other two-thirds is due to the lower fuel cost of the LMFBFR.

- (2) Capital Costs. The capital cost of LMFBFRs in 1990 was estimated to be \$70/kW(e) higher than LWRs, in 1974 dollars. If capital costs continue to escalate at about 7.5% per year, this differential increases to about \$220/kW(e) in 1990. This differential produces a total 1990 capital cost penalty of about 5.7×10^9 for case 3, as shown in Table 11.2-33.
- (3) O&M Costs. The O&M cost for the LMFBFR was estimated to be about 0.1 mill/kWhr(e) higher than for an LWR, in 1974 dollars. Escalating at 3% per year, the penalty becomes 0.16 mill/kWhr(e) in 1990 dollars. There were 26 LMFBFRs built in case 3, each generating 188×10^9 kWhr(e) during its operating lifetime. This produces a total levelized O&M cost penalty of 0.4×10^9 , discounted to 1990, as shown in Table 11.2-33.
- (4) Total Cost Savings in 1990. The net lifetime power cost comparison for the plants built in 1990 to 1991 is shown in Table 11.2-33. This shows that the power costs for this mix of plants is reduced by \$1.3 billion in the case with breeders being deployed (case 3).

Table 11.2-33

SUMMARY OF THE DIFFERENCES IN DISCOUNTED 30-YEAR POWER COSTS FOR PLANTS INSTALLED IN 1990, CASE 3 (WITH BREEDER) RELATIVE TO CASE 1 (NO BREEDER)

Cost Category	Discounted Cost of Case 3 Relative to Case 1 (1990 dollars)
Capital	+\$5.7 billion
O&M	0.4 billion
Fuel Cycle ^a	- 7.4 billion
Net Total	-\$1.3 billion

^aFrom Table 11.2-32.

11.2.5.3 Cost Reductions for Plants Built Before 1990

As shown in Table 11.2-31, deployment of the LMFBFR sharply limits the rise in price of U_3O_8 . In turn, the fuel costs of all operating thermal reactors are lowered due to this reduction in U_3O_8 prices. This results in significant cost savings in

addition to the direct cost savings that accrue from the lower fuel cost of the breeder.

This effect can be displayed by examining the lifetime fuel-cycle costs of light-water reactor plants in a breeder economy compared with their costs if the breeder is not deployed.

A simplified analysis was made for the approximately 400 GW(e) of nonbreeders in service at the beginning of 1990. These plants were presumed to have an average of about 20 years of service life remaining.

With a discount rate of 5% per year, the reduction in U_3O_8 price shown for case 3 in Table 11.2-33 would reduce the levelized fuel cost for a uranium-fueled LWR by about 0.3 mill/kWhr(e). Cost reduction for an HTGR would be somewhat less since it is less sensitive to uranium price. This leads to an approximate average cost reduction in case 3 of 0.25 mill/kWhr(e) in the 1990 to 2010 time period for all nonbreeder reactors built prior to 1990.

The savings of 0.25 mill/kWhr(e) credited to these reactors amounts to a total cost savings of about \$8 billion, present valued to 1990.

Some Expectations for a Mature LMFBR Industry

The commercial introduction of the LMFBR in about the year 1987 can result in a large nuclear power industry (consisting mostly of breeders, in about the year 2010) that is capable of generating all the fissile material required for all the industry's operating and new nuclear power plants. The only requirement for uranium or thorium at that time will be as source (fertile) material. This source material will be used (1) to replace source material that has been converted to fissile material in the nuclear power plants and to (2) replace source material that has been lost in the fuel process streams. A 1000-MWe nuclear breeder power plant would require about 1.5 tons of source material per year of operation. This is in contrast to a present-day 1000-MWe LWR that requires about 150 tons of uranium per year of operation. Moreover, there would be about 2 to 3 million tons of tails uranium from the U-235 separation facilities available in the year 2010 which could supply all the source material requirements for the nuclear power industry for hundreds of years. The availability of this uranium supply would be the beginning of an era where costs for source material would have a small impact on fuel-cycle costs due to the small consumption of this material per unit of electric energy.

generation and fissile material, which would be in plentiful supply, as a by-product of reactor operation.

For the utilities, the era of a nuclear power industry that is self-sufficient in fissile material and has available to it a stockpile of fuel source material that will sustain it for hundreds of years means guaranteed low fuel-cycle costs. It also means that nuclear power plant designers need not give much consideration to fuel utilization when optimizing capital costs and, thereby, be able to lower them.

Fuel-cycle costs for breeders during this period due to their being low (in terms of 1974 dollars) and relatively insensitive to fuel source material price will not experience large increases as a result of inflation. Fuel-cycle costs will also be low for nonbreeders as the price for fissile and source (tails stockpile) material will be low. The increases due to inflation will also probably be compensated to some extent by lower costs for the components of the fuel cycle as fuel throughput and productivity (due to learning) increase with a growing nuclear power industry.

It is not unreasonable to expect that in the future there will be increases in the thermal efficiency of power plants and that devices similar to heat pumps that offer superior conversion factors for converting electric energy to other forms of energy will be in wide use. These expected improvements when coupled with the low cost, cleanliness, and essentially unlimited abundance of cheap fuel associated with a breeder-oriented nuclear power industry can result in electric energy usage much greater than predicted in present-day projections and attendant greater benefits for the breeder.

11.3 CONCLUSION

The potential benefits of the LMFBR are identified as direct dollar savings in the cost of electricity and the reduction in environmental impacts from strategies which employ the LMFBR as compared to those without the LMFBR.

The major quantifiable conclusions of the direct economic analysis presented in Section 11.2 are:

- (1) The introduction of a fast breeder into the U.S. electric power utility system will produce significant financial benefits. This results largely from a reduction in uranium ore and U-235 enrichment requirements.
- (2) Capital requirements accumulated to the year 2020 for a nuclear industry based on fast breeders are projected to be about 10% less (about \$150 billion from a total of about \$1500 billion) for the base case than those for a nuclear industry without the breeder. The lesser capital requirements primarily are due to the reduced need for fuel mining and milling, and for U-235 enrichment facilities. The estimated additional capital requirements attributed to LMFBR plants is about \$11 billion, based on an initial capital differential of LMFBRs over LWRs and HTGRs of \$100/kWe that decreases linearly to a zero differential by the year 2000.
- (3) The benefit-cost ratio is estimated to be substantially greater than one for most of the cases examined, assuming a very conservative discount rate of 10%. At a lower discount rate of 7.5% the benefit-cost ratio increases to about 10 for base conditions. The ratio falls below one only when two or more large adverse circumstances--each considered unlikely--are assumed to occur in concert. The progressively large increase in fast breeder benefits (for a given discount rate) throughout the study period of the AEC's cost-benefit analysis is due primarily to the fast breeder fuel-cycle costs being relatively insensitive to the price of fuel as compared with the actual and projected escalation of nuclear and fossil fuel prices which have markedly increased the operating costs of LWRs, HTGRs, and coal-fueled plants.

The uranium prices used in this analysis are estimates of recovery costs plus a reasonable allowance for profits and are not necessarily an indication of what the market price might be. As with the price of oil and coal, the price of uranium can go far above the cost to recover the fuel if the demand/supply situation becomes tight.

- (4) The fast breeder results in a nuclear power industry that will have total power costs, in constant dollars, that decrease with time. It is projected to decrease from about 13 mills/kWhr for today's LWRs, to about 10 mills/kWhr (1974 dollars) by year 2020. The fast breeder may well be the doorway to unlimited low-cost power which can enhance the Nation's prosperity.
- (5) Postponement of the time of introduction of the LMFBR reduces the projected financial benefits. For the base conditions, at a discount rate of 10%, the benefits are reduced by about \$0.75 billion for each year of deferral. Under pessimistic uranium availability conditions, the annual reduction in benefits is estimated to be about \$1.5 billion at a 10% discount rate, and \$3.3 billion per year when discounted at 7.5%. The earliest possible introduction of the breeder offers the greatest potential benefits.
- (6) The advanced oxide fueled breeder, with its estimated 10-year compound doubling time, can meet the fissile fuel demand of a growing nuclear power industry with self-generated plutonium shortly after the turn of the century. Use of the breeder offers the opportunity to the nuclear industry to eventually free itself of the need to mine uranium.
- (7) Sizeable supplemental benefits are projected to result from development of new LMFBR fuels such as the carbides; such fuels also provide an attractive backup to the oxide fuels.

With regards to the potential reduction in adverse environmental impacts from strategies which employ the LMFBR as compared to those without the LMFBR, three situations were examined. One situation assumed that the LMFBR is not developed, but that the nuclear fission technology continues to be deployed in the form of LWRs and HTGRs. Another assumes that no additional nuclear plants are constructed beyond those now committed (1974) and that all other new central station capacity is provided by conventional coal-fired units. The third situation assumes the LMFBR is developed and widely deployed by the year 2000 and beyond.

A comparison of the two situations which assume large scale nuclear capacity, with and without the LMFBR, indicates that the use of the LMFBR would have (1) a negligibly smaller cumulative health and safety impact and (2) a significantly smaller physical resource requirement, primarily in fuels and related land commitment. Use of the LMFBR reduces the amount of U_3O_8 committed by reactors built by the year 2000 by one million tons, and by the year 2020 the reduction is over 8 million tons of U_3O_8 .

The strategy of no nuclear plants beyond those presently committed, and with coal the primary fuel, would require an estimated cumulative use of about 340 billion tons of coal by the year 2020. This quantity of coal approaches the estimate of economically recoverable coal in the U.S. There would also be an increase in occupational fatalities of about 100,000, public fatalities in fuel transportation of about 55,000 and total man-days lost of about one billion, as compared with either of the large-scale nuclear options.

There would be a small difference in the environmental impact of the nuclear industry attributable to the LMFBR. This difference is primarily associated with the quantity of uranium mined and associated commitment of land. Indirectly, however, the LMFBR can have a large environmental impact in that it can help to ensure a viable nuclear industry which, in turn, defers the use of large quantities of coal for the generation of electricity.

Other important benefits which could accrue from early introduction of the breeder are not as susceptible to quantitative analysis and can be better explained qualitatively. They are summarized in Appendix IV.C with the advantageous safety and environmental features of the breeder.

Appendix IV.A
RECENT AEC SAFEGUARDS REVIEWS

Introduction

Section 7.4.7.6 identified three reviews of the AEC safeguards that have been done in recent years. The major conclusions and recommendations of these reports are summarized and discussed below:

General Accounting Office, "Improvements Needed in the Program for the Protection of Special Nuclear Material," November 7, 1973.

Recommendation

Expedite the formal issuance of the proposed changes to 10 CFR 73 and AECM 2401.

Status

Amended requirements to 10 CFR 73, "Physical Protection of Special Nuclear Material," covering physical protection of plants and material in transit and at fixed sites were published in effective form on November 6, 1973. The amendments require licensees who possess quantities equal to or more than 2 kg of plutonium or U-233, or 5 kg of U-235 contained in uranium and enriched to 20% or more in the isotope U-235, or appropriately weighted combinations of these materials, to meet certain physical protection requirements for their plants and materials. The regulation requirements are stated in general terms and specific protection plans must be developed by licensees and approved by the AEC. These plans must be incorporated in licenses as technical specifications or as license conditions. No changes which would decrease the effectiveness of the protection plans can be made without the prior approval of the AEC. The regulations require that existing plants be back-fitted to meet the new requirements.

AECM 2401, "Physical Protection of Classified Matter and Information," has been revised to substantially strengthen the protective requirements for Secret and Confidential material, including special nuclear material.

A revision to AECM 2405, "Physical Protection of Unclassified Special Nuclear Material," which strengthens the protective requirements for unclassified special nuclear material (SNM), was sent to the field for comment on October 29, 1973.

Both manual chapters were further revised and again transmitted to AEC field offices for comment. Responses from the field offices were extensive and in order to

resolve the field problems and finalize the requirements, a meeting with field office representatives was held in August 1974.

Recommendation

Define in greater detail the expected capability of a system designed to prevent, detect, and effectively respond to a possible SNM diversion or diversion attempt and strengthen the protection requirements to the extent necessary.

Status

(a) Licensee Facilities

The purpose of the new 10 CFR 73 amendments is to impose requirements for the protection of licensees' plants and nuclear material shipments against acts of sabotage and for the protection of special nuclear material against theft and diversion by establishing and maintaining a physical protection system of: (i) protective barriers and intrusion detection devices to provide early detection of an attack; (ii) deterrence to attack by means of armed guards; and (iii) liaison and communication with law enforcement authorities capable of rendering assistance to counter such attacks.

The 10 CFR 73 requirements designed for fixed-site protection against theft and industrial sabotage include the use of armed guard forces which are provided with redundant communications to call for assistance from plant personnel and local law enforcement authorities; and controlled access to special nuclear material and vital plant areas by means of multiple physical barriers which are alarmed and monitored for advanced warning, a picture badge identification system, and physical or electronic searches of personnel and packages on entering and leaving such restricted areas for weapons, explosives, and stolen nuclear material. Other requirements have been imposed to provide detection mechanisms for protection against covert theft of smaller quantities of SNM. These mechanisms include tamper-safe seals, locks, and intrusion alarm systems for vaults and unoccupied areas containing SNM, surveillance of individuals in areas containing SNM, and searches of personnel and packages entering or leaving such areas.

The regulations for the protection of special nuclear material in transit by truck or rail require the use of armed guards, radio-telephone communications, planned emergency aid by local police, and the use of locks and seals on shipping containers and vehicles. Provision is also made for the use of special design vehicles when trucks are used.

Shipments of special nuclear material in quantities exceeding 20 g or 20 Ci, whichever is less, of plutonium or U-233 and in excess of 350 g of U-235 are prohibited on passenger aircraft. Shipments on cargo aircraft are required to be arranged so as to minimize the number of scheduled transfers and these must be monitored by armed guards.

Shipments by sea must be made on vessels making the minimum ports of call. Transfer at domestic ports from other modes of transportation must be monitored by a guard. While at sea, periodic communications must be maintained with shore installations.

The material control and accounting requirements of 10 CFR 70 also provide for deterrence and detection of the theft or diversion of special nuclear material from licensed plants and shipments. The amended regulations published in effective form November 6, 1973, covering revised material control and accounting requirements, specified time requirements for the taking of more frequent physical inventories and the closing of material balances. Limitations on the measurement uncertainty of material balances are specified and new physical inventory procedures are delineated. The amended regulations provide new requirements for item control, tamper-safing of material containers, and recordkeeping. A comprehensive quality assurance program for material balance measurements was specified through license conditions in May 1974 as part of the material control and accounting backfitting reviews.

The new protection regulations published in November required existing licensees to submit to the AEC for approval detailed plans describing how the new requirements would be implemented. By March 11, 1974, the review of 21 fixed site and 13 transportation protection plans was completed. By May 10, 1974, the review of 26 material control and accounting plans was accomplished. Two other transportation and one material control and accounting plans were submitted and approved at later dates. In order to assure that an adequate level of protection would be provided to meet the intent of the regulations, a number of specific license conditions were incorporated in each license.

The requirements of the regulations are general performance requirements to allow the licensee flexibility to develop systems that can meet required performance levels. The AEC regulation staff has developed and issued 36 guides which provide the licensee with descriptions of acceptable systems and programs for complying with the amended regulations. Other studies and guides

are planned including the issuance of standard format and content guides for new applications. Some of the published guides are as follows:

- 5.7 Control of Personnel Access to Protected Areas, Vital Areas, and Material Access Areas
- 5.12 General Use of Locks in the Protection and Control of Facilities and Special Nuclear Material
- 5.14 Visual Surveillance of Individuals in Material Access Areas
- 5.15 Security Seals for the Protection and Control of Special Nuclear Material
- 5.20 Training, Equipping, and Qualifying of Guards and Watchmen
- 5.27 Special Nuclear Material Doorway Monitors
- 5.31 Specially Designed Vehicle with Armed Guards for Road Shipment of Special Nuclear Material
- 5.32 Communication with Transport Vehicles

(b) AEC Facilities

The Division of Safeguards and Security has formulated a theoretical standard involving an attack by terrorists armed with light weapons upon vital AEC facilities. Fourteen major facilities were surveyed against this standard and the results reviewed with principal staff members in Headquarters and in the field. An upgrading program designed to bring the level of protection to a level which would provide reasonable assurance that such an attack could be successfully resisted has been initiated. A supplemental budget request has been made to the Office of Management and Budget to cover these upgrading actions.

Steps have been taken to improve the firearms proficiency of the guard forces and to impose more stringent physical fitness standards. Supplemental armament is being updated. Field offices have strengthened existing liaison arrangements with local law enforcement organizations to assure a prompt response to emergencies by such forces. A number of other measures, such as increases in guard forces, additional fencing, and the installation of perimeter alarm systems, which require substantial funding, have been included.

(c) Other

The Division of Safeguards and Security is sponsoring safeguards research and development efforts to develop doorway monitors which provide capabilities

for detecting unauthorized removal of gram quantities of plutonium or U-235. Surveys were conducted of all locations requiring doorway monitors. Funds are being requested in the FY-76 budget to cover the cost and installation of the equipment.

Recommendation

Impose the same protection requirements on both licensees and contractors holding unclassified SNM, or justify the difference.

Status

Revised 10 CFR 73 and the revision to Manual Chapter 2405 were reviewed for consistency by the staffs of the General Manager and the Director of Regulation prior to issuance.

The protection requirements on both licensees and contractors are essentially comparable, differing only in details; for example, in a licensed facility, all personnel entering a protected area must be searched, except those employees who possess AEC security clearance; however, personnel with such clearance are subject to search on a random basis. In a license-exempt facility, all employees requiring access to SNM must possess an AEC security clearance, and all hand-carried packages are subject to search entering and leaving the protected area.

The new regulations will, in the interest of the common defense and security, strengthen requirements for the protection of significant quantities of SNM at fixed-sites against theft or diversion for unauthorized purposes. They will also remove the existing exemption of classified SNM from the provisions of 10 CFR 73. The requirements of 10 CFR 73 are in addition to, rather than a substitution for, any security procedures for the protection of classified material specified by the AEC or other Government agency.

Recommendation

Improve its inspection practices, as planned, by (1) conducting an overall evaluation of the physical protection measures employed at licensee/contractor plants covering both classified and unclassified SNM and (2) developing new inspection procedures which will place increased emphasis on evaluating the effectiveness of the physical protection afforded SNM at licensee facilities.

Status

Responsibility for inspection of plants operating under both a license and a contract has been delegated, by agreement between the General Manager and the Director of Regulation, to the Director of Regulation. In cases where classified material is involved, a representative of the General Manager's staff accompanies the representative of the Director of Regulation with final responsibility for issuance of the report resting with the Director of Regulation.

Amendments to 10 CFR 73 published November 6, 1973, revised AEC policy regarding inspection procedures for classified SNM. Part 73.1(b)(4) stipulates that SNM may also be protected pursuant to security procedures prescribed by the Commission or another Government agency for the protection of classified materials. The provisions of the new amendment are in addition to and not in substitution for such security procedures. Therefore, compliance with the new requirements will not relieve any licensee from any requirement or obligation to protect SNM pursuant to security procedures prescribed by the Commission or other Government agency for the protection of classified materials. Therefore, AEC Regulatory inspectors during inspections conduct overall evaluations of the physical protection measures employed at the licensee site regardless of the classification of the SNM.

Regulatory has developed and implemented an upgraded inspection program based on the strengthened requirements contained in amendments to 10 CFR 50, 70, and 73 relating to (1) material control and accountability, (2) physical protection of plants and special nuclear material located at fixed sites, and (3) physical protection of special nuclear material in the transportation cycle. The primary objective of the regulatory inspection program is to assure that licensees are complying with all applicable AEC regulatory requirements and to provide independent assurance of the effectiveness of the licensees' overall safeguards program. The basic strategy of the inspection program is to perform periodic unannounced inspections of each licensees' operation and transportation program which have been approved and licensed by the Directorate of Licensing and to take enforcement action including imposition of civil penalties as appropriate to assure timely compliance by licensees.

GAO Report dated April 12, 1974: Protecting Special Nuclear Material in Transit: Improvements Made and Existing Problems

The report notes that concurrent with the GAO review, "The AEC made some and proposed other significant changes in its requirements for protecting SNM in transit; there-

fore, we [GAO] decided to curtail our review." The observations made in the report are summarized and discussed below.

Observation

A shipment was made on a flatbed truck with an open cargo compartment.

Status

Paragraph 73.30(c) of 10 CFR 73 prohibits shipment of containers weighing 500 lb or less in open trucks, railroad flatcars or boxcars, and ships. Heavier containers may be shipped on flatbed trucks. All containers, regardless of weight, must be sealed and either the outer container or the vehicle must be locked. Other applicable regulations include requirements covering armed guards, special protection vehicles, and communication equipment. On the General Manager's side, it is required that packages be either in the continuous custody of AEC or DOD cleared personnel, or, if shipped via for-hire carrier, the material must be in a sealed van and the truck escorted by AEC couriers.

Observation

The truck was not equipped with an alarm or communications equipment.

Status

Paragraph 73.31(b) of 10 CFR 73 requires that each motor vehicle used to transport SNM be equipped with a radiotelephone for making required periodic calls and emergency calls. The licensee or agent with whom communications shall be maintained for different segments of the shipment shall be predesignated before a shipment is made. The General Manager uses a high-frequency ten-channel radio system, thereby having a continuous communications capability between en route shipments and the communications center at the Albuquerque Operations Office.

Observation

The truck driver was alone and unarmed.

Status

Paragraph 73.31(c) of 10 CFR 73 governs motor vehicle shipments and requires one of the following:

- (a) an armed escort, consisting of at least two armed guards, shall accompany the shipment in a separate escort vehicle. Also, the shipment vehicle must have two occupants for trips equal to or greater than one hour and one person for shipments less than one hour; or
- (b) use of a special truck with penetration resistance features (armored truck) and armed guards inside; or
- (c) use of a special truck with penetration resistance features and immobilization features.

In regard to shipments subject to AEC's regulatory requirements, the AEC and GAO advise that the Supreme Court's decision in 1968, in the *Schneider vs Smith* case, indicates that it would be advantageous to clarify a section of the Atomic Energy Act to specify that the AEC's authority to prescribe regulations to guard against the loss or diversion of special nuclear material includes the authority to pre-determine the trustworthiness of drivers and guards involved in shipments. The Joint Committee has no question about the intent underlying Sect. 161(i) of the Atomic Energy Act [42 U.S.C. 2201(i)] and believes such authority is implicit in that section. If necessary or advisable, the Joint Committee will recommend that this intention be restated by the Congress.

The General Manager requires that shipments be accompanied by two people having AEC or DOD security clearances. All escorts of shipments are armed.

Observation

There was no preplanned routing; the driver chose his route.

Status

Paragraph 73.30(b) of 10 CFR 73 requires that shipments be preplanned to assure that deliveries occur at a time when the receiver will be present at the final destination. Both paragraph 73.30(b) and the General Manager require that routes be selected to avoid areas of natural disaster or civil disorders. Also, paragraph 73 requires each licensee to submit a plan outlining the procedures that he will use to meet the new transportation security requirements of paragraph 73.30 through 73.36 and 73.70(g). Each approved plan contains a license condition which requires that telephone calls be preplanned.

Observation

There were no periodic call-in points to let the shipper or receiver know the truck's whereabouts and to confirm that no problems had been encountered en route.

Status

Paragraph 73.31(b) and the General Manager require that periodic calls be made to specified reporting points every two hours, with allowances up to five hours for licensees under certain specified circumstances.

Observation

The seals on the shipping containers could be easily duplicated, thus defeating the purpose of seals which was to detect unauthorized tampering.

Status

Paragraph 73.30(c) of 10 CFR 73 requires that SNM be shipped in containers which are sealed by tamper-indicating type seals, and also that either the container or the vehicle be locked. In most cases, the freight container (into which packages are loaded) or vehicle must also be sealed with a tamper-indicating seal. Regulatory Guide 5.15, "Security Seals for the Protection and Control of Special Nuclear Material," provides guidance on seals and identifies three types of seals which are generally acceptable to Regulatory. The General Manager also requires that for-hire trucks must be locked or sealed and escorted by armed couriers.

Observation

The material was shipped in portable containers that could be carried by one individual without the aid of mechanical handling equipment.

Status

Use of portable containers is still permitted. However, containers of 500 lb or less must be locked and shipped in locked trucks. The General Manager has essentially prohibited less than full-load shipments so that packages would never be exposed to across-the-dock handling by uncleared personnel; access to the cargo, except by cleared and authorized personnel, is also prohibited. All truck shipments of trigger quantities* of SNM involving for-hire couriers are under an exclusive-use arrangement with no interim cargo transfers.

Observation

At the airport, the material was stacked on a dolly in an open bay area.

*A trigger quantity is an amount in excess of 5 kg of U-235 (contained in uranium enriched to 20% or more), 2 kg of U-233, 2 kg of plutonium, or a weighted combination of these.

Status

Paragraph 73.35(b) of 10 CFR 73 requires that an armed guard maintain continuous visual surveillance of a shipment at all times while located in a terminal or in storage. The General Manager's requirements also prohibit such operations, unless conducted in the continuous personal custody (direct observation) of AEC- or DOD-cleared people.

Report on Special Safeguards Study, Rosenbaum et al., April 1974, Recommendations for Improved Physical Protection

Summary

The Special Safeguards Study proffers four specific recommendations for improving the physical protection of special nuclear material. The study recommends that the Commission attack the problem of physical protection in a manner analogous to its approach to reactor safety by postulating design basis incidents upon which physical protection systems are designed. To assure effective physical protection systems, the study recommends a program of "blackhat" exercises to identify potential system weaknesses. To assure uniform and effective security personnel, the study recommends the establishment of a Federal Guard Force to provide protection of special nuclear material both at fixed sites and in transit. Finally, the study recommends closer continuing liaison with other Federal agencies which have responsibility for national security.

Study Recommendation--Design Basis Incidents

We recommend that the threat represented by unauthorized acquisition of special nuclear materials and the adequacy of systems to meet that threat should be viewed in terms of design basis incidents. Safeguard systems should be designed to assure that no single failure of an active or passive feature of a system will lead to the inability of that system to perform its function. The regulations and the level of review should be sufficient to reduce the hazard to the public from unauthorized acquisition of special nuclear materials to the same level as that from nuclear power plants.

In order to carry out this recommendation the budget allowed for safeguards reviews and the number and qualifications of the people concerned with safeguards will have to be substantially increased.

STAFF COMMENT:

We believe that the approach to protection against the occurrence of safeguards-related incidents should be somewhat analogous to the design basis incident approach used in reactor safety. As stated in section 7.4.8, the methodology for development of future safeguards includes systematic identification of the events to be protected against (which can be analogous to design basis incident analysis), classification of these events according to the magnitude of their potential consequences, and identification of protective measures to prevent occurrence of the events or minimize their consequences. The adversary action sequences used as the basis for identifying the protective actions describe types of actions which would necessarily precede the events being protected against, rather than specific threat scenarios (see section 7.4.8).

Fault tree analysis, basically a threat-independent analytic technique, is also being used to identify protective actions. At present, applying a risk probability value with the same meaning and significance to materials and plant protection as to a reactor accident appears extremely difficult. In the case of a nuclear power plant, considerable study has been done to identify the various normal, abnormal, and accident conditions that a plant might experience in its lifetime. These studies, together with the accumulation of data for component reliability, not only from nuclear power plants, but also from similar components in other engineering applications (e.g., fossil-fueled power plants), have aided in establishing design basis events and estimates of their probability.

Regarding the hazard to the public from unauthorized acquisition of special nuclear materials, section 7.4.2 states:

The safeguards program has as its objective achieving a level of protection against such acts to insure against significant increase in the overall risk of death, injury, or property damage to the public from other causes beyond the control of the individual.

Proposed Action

As indicated above, proposed actions pertinent to this matter include development of a family of safeguards-related events to be protected against, with consideration for each type of facility and mode of transport to be protected, and selection of appropriate and if necessary, redundant countermeasures to provide a "protection in depth" principle to safeguards. We agree that additional qualified personnel will be required to implement these actions on a timely basis.

Study Recommendation--"Blackhat" Exercises

In addition to conventional compliance inspections to determine adherence to regulations, a dynamic testing system should be devised to provide a realistic examination of the overall safeguards afforded SNM by each licensee. We suggest the use of gaming analysis, including "blackhat teams" such as those used by Sandia Labs., to study sabotage and diversions involving weapons. Licensing should use the existing capability of AEC contractors to perform theoretical "blackhat" studies of fixed facilities and transportation. These studies should develop threat scenarios and detect systems weaknesses so that safeguards can be evaluated on a more realistic basis than that which can be accomplished by inspecting only for compliance with regulations. The resulting threat scenarios could form the basis for a simulated but dynamic testing of a licensee's SNM safeguards, and the modification of regulations to close loopholes.

STAFF COMMENT

We fully support the recommendation that "blackhat" safeguards studies should be carried out. However, threat scenarios should be developed and systems weaknesses analyzed without using "blackhat" teams to actually attempt to steal SNM. Such tests should not be conducted for they not only could desensitize the guard force to the point where a real threat would not be recognized, but also could result in the loss of life.

Proposed Action

We appreciate the utility and value of "blackhat" studies and encourage their use on a continuing basis. Accordingly, vulnerability studies presently under way should be expanded to include "blackhat" gaming in the areas of transportation and fuel processing plant security. In addition, in-house technical staff should be expanded to perform "blackhat" analyses of licensee security programs as part of the licensing review process, and to use "blackhat" studies as input to the development of new regulations with the ultimate objective of establishing a high degree of assurance that, in the event of an attack, an appropriate level of response would be provided to neutralize the threat. Moreover, the results of these "black-hat" exercises should be used in the development of Regulatory inspection strategies. Studies currently under way and planned to begin in FY-75 will incorporate "blackhat" gaming and other techniques to assess the vulnerability of mixed-oxide fuel-fabrication facilities and transportation systems respectively.

Study Recommendation--Federal Guard Force

In order to limit the responsibility of licensees for the national defense and in order to insure a properly graded capability against the diversion of special nuclear material, we recommend the establishment of a federal nuclear protection and transportation service. We further recommend that all protection functions which could require the use of force be direct federal responsibilities. There are many possible ways to do this and the alternatives ought to be studied in a systematic and careful way, but an upgraded system ought to be adopted immediately as a temporary measure. If a small federal force is formed now it will help to meet the present pressing need and can be enlarged and improved as the need grows.

STAFF COMMENT

This recommendation is made principally on the basis of the argument that protection of the common defense and security against significant armed attack is not a proper responsibility of private industry. Under the Atomic Energy Act, industry and Government share the responsibility for protection in the public interest. As the actual custodian of nuclear materials, the licensee bears the primary operating responsibility for the administration and implementation of materials and plant protection programs meeting requirements set by the Government through regulations and license provisions.

However, aside from the policy question of whether licensees should be expected to protect special nuclear materials from armed attack, there is the question of whether a Federal guard force can more effectively protect nuclear facilities and SNM in transport than private guard forces augmented by assistance from local law enforcement authorities. While it must be noted that private security guards are under greater restrictions concerning the use of force to repel an attack than the restrictions which would be imposed upon a Federal guard, local law enforcement authorities do constitute an already deployed armed force which can be utilized for response to attack and recovery of stolen SNM.

A study is now under way at Brookhaven National Laboratory, which we expect to be complete in the near future, to analyze the legal, social, and technical limitations of protection of SNM: (1) by private guard forces assisted by local law enforcement authorities and (2) by Federal guard forces.

Proposed Action

Based upon increasing terrorist activities in the United States and elsewhere, we are reassessing whether the level of protection needed is not greater than that which can reasonably be expected from a private organization which must rely upon local law enforcement authorities to provide assistance in the event of a squad-sized attack.

Based upon that reassessment, the following options will be considered for action as appropriate:

- (1) Maintain the system of licensees providing armed security with extensive reliance upon local law enforcement authorities as at present.
- (2) Initiate legislation to provide licensee guards with broader prerogatives and protection.
- (3) Initiate development/deployment of a Federal guard force.
- (4) Evaluate the policy of military forces providing protection of licensee plants and shipments.

It should be recognized that the bulk of highly enriched uranium and plutonium presently being shipped by licensees is government-owned material for military or AEC developmental programs. This government-owned strategic material is planned to be provided protection in transit comparable to that afforded shipments of material in the AEC weapons programs by the General Manager (i.e., escorted specially designed vehicles and the existing SECOM communication system). This action will provide suitable protection against potential in-transit diversion for essentially all strategic materials now being handled by AEC licensees. This step will also provide the necessary time to fully explore and resolve the broad issues discussed above before recycled plutonium or highly enriched uranium come into general use in the civilian power industry.

Study Recommendation--Other Agency Liaison

The AEC should establish a continual and strong liaison with the CIA, FBI, and other appropriate agencies, and should exert every effort to see that these agencies expend a level of resources on safeguards problems commensurate with the importance of the issue.

STAFF COMMENT

We fully support this recommendation. A number of contacts have been made with these agencies over the last several years, and we agree with the desirability of strengthening and formalizing these contacts as well as contacts with the DOD, to

assure that all responsible Federal agencies involved in the protection of special nuclear material are aware of the needs and take appropriate action to commit resources to meet their responsibilities in this area.

Proposed Action

An interagency agreement should be negotiated with all responsible Federal agencies clearly defining responsibilities and interests and committing resources in the protection of SNM. Attendant to such an agreement, definite interagency contingency plans should be instituted and operational manuals prepared and disseminated to effectively cope with the threat of theft of SNM, and sabotage. In addition, a program of communication and contact on a regular basis for review and update of intelligence data should be established.

Recommendations for Improved Material Control

Summary

This Special Safeguards Study recommends a change in the methods and procedures being used in nuclear material accountability. Instead of continuing to rely on the material unaccounted for (MUF) and the accuracy with which one can determine the MUF, that is, the limit of error (LE) for the MUF calculations, LEMUF, the study recommends phasing out the use of MUF-LEMUF concepts and instead developing a system that will provide more positive and more sensitive control over the material and permit immediate detection of any material missing. For the sake of continuity and more complete interrelation of the study recommendations, all of the material control recommendations are listed below and are followed by staff comments and proposed actions.

Study Recommendations

1. Develop Alternate Material Control Concepts

We recommend that the concept of a periodic measure of material balance around large flows and inventories as expressed in the current concepts of MUF and LEMUF be abandoned as a basis of safeguards.

2. Establish Measurement Redundancy Controls, Piece Count and Item Identity Procedures, and Process Modeling Capabilities

We recommend the adoption of a philosophy of double contingency in measurement through the scheduling of measurements out of

and into process or storage steps, the observation of measurements by two independent individuals with redundant responsibilities, and, where possible, the precise measurement of two or more parameters of a given batch for tamper checking purposes.

We recommend that any object generated in operations involving SHM be counted as soon as an identifiable shape is established and that a number count of movements of these items be maintained as they progress through the process until identity is lost.

We recommend that emphasis be given to the frequent collection and analysis of easily obtained numerical information about SHM processing plants. This information should be compared against a working model of the system on a daily basis and where possible should be made to employ measurement techniques that yield material balance consistency checks within a period of one day.

3. Establish a Material Control "Blackhat" System

We recommend the establishment of a continuing effort on diversion path analysis by the AEC with the objective of insuring an increasingly effective application of advanced measurement techniques to the solution of safeguards problems. We further recommend that the licensees be required to perform such analyses in their facilities, and to formulate measurement schemes to protect against every potential diversion path discovered.

4. Strengthen Licensee Material Control Organization

We recommend that an organization be established by each licensee with the duty of examining all of the data which relates to safeguards, including material flow information and information about personnel. We further recommend that as part of its responsibility this organization should make a daily determination of the most likely deviation from measurement expectations which could have safeguards significance and investigate it. The committee should have the duty to suggest changes which might be made in the materials flow measurement, the physical protection technique or the assignment of personnel that could promote safeguards efficiency.

STAFF COMMENT

Staff agrees that changes must be made in the accountability program in order to provide greater assurance that, as increasing quantities of special nuclear material are handled in the private sector, thefts or diversion would be detected on a real-time basis. Materials accounting provides the quantitative basis for obtaining safeguards assurances. It provides quantitative but after-the-fact evidence that the material is indeed present and accounted for. In the event of a diversion, materials accounting is capable of assessing the extent of loss and of identifying the form and composition of the material which is missing. It also has a deterrent value in discouraging diversion by virtue of its power to detect loss and the possible identification of the diverter(s).

The need for improving material balance accounting in terms of timeliness and in both an absolute and a relative percent basis is recognized, and staff is aware of the limitations of requiring periodic inventories expressed in terms of MUF and LEMUF concepts. In fact, this was the basis for the new regulations printed in effective form in the Federal Register on November 6, 1973. Additional staff papers proposing new regulations for fundamental material controls, measurement quality control, and design criteria are being developed and will provide for much of the upgrading of material control recommended by the Special Safeguards Study.

The AEC has always recognized that the material control and accounting function encompasses more than material balance accounting. This is the reason for the long standing concept of "fundamental materials controls" reflected in license conditions as far back as January 1969. Proposed regulations for strengthened fundamental material controls were published for public comment on September 25, 1973. These include requirements for checks and balances to be built into the materials management organization; a management system to develop, revise, implement, and enforce material control and accounting procedures; multiple material balance and item control areas established within nuclear plants; a system of nuclear measurements to substantiate the quantities of SNM received, produced, transferred between material balance areas, on inventory, or shipped, discarded, or otherwise removed from inventory; a measurement quality control program; procedures for evaluating of shipper-receiver differences; a system of storage and internal handling controls; procedures for SNM scrap and waste control; physical inventory procedures; and a system of accountability records and reports.

Staff agrees with the recommendation for application of "diversion path analysis" techniques to determine and alleviate the weaknesses in the measurement program

in particular and the overall material control program in general. A study of diversion path analysis techniques has been under way for some time and additional effort is needed in this area.

Staff concurs in the usefulness of the concept of daily review of process and material transfer records for the purpose of highlighting significant deviations from expected process data as a means to identify potential diversions. Since April 1974 (the date of the Special Safeguards Study) no fewer than eleven Regulatory Guides have been issued for the specific purpose of improving special nuclear material measurement, control, and accounting techniques and practices.

Proposed Action

- (1) AEC staff will continue the ongoing programs to develop improved measurement methods, inventory procedures, and accounting measures to improve the accuracy and the timeliness of the present SNM accounting system. As a first step, the Commission has for its consideration the proposed new regulation, "Measurement Control Program for Special Nuclear Materials Control and Accounting," to strengthen measurement controls to improve the quality of material balance accounting.

The AEC staff had proposed to initiate a program in FY-1976 to develop a computer-based real-time accounting system for SNM (REal-TIME Materials Control). Many of the features of this system are new and require development and testing to justify their acceptance and implementation. Development of the RETIMAC system should be initiated immediately as part of a program to explore and develop alternative accounting methods for special nuclear material.

- (2) The Commission is considering for final approval, effective regulations for Fundamental Nuclear Material Controls to immediately strengthen internal material control measures.
- (3) A study should be initiated to re-examine and specify requirements for an integrated system of internal controls including the use of tamper-safing techniques, redundancy measures, counting techniques, and modern methods of data interrogation and analysis.
- (4) Efforts have been increased in process modeling with the objective of employing actual process data in a mathematical simulation of the process to derive diversion indicators.

- (5) Increased resources need to be expanded to accelerate progress in the area of diversion path analysis. Additional staff is needed to consider diversion path analysis for each of the types of plants in the fuel cycle, to recommend measurement schemes to improve material control, and to determine the most efficient manner in which the licensee might carry out such analysis.
- (6) Studies should be initiated to determine the organization, procedures, and criteria that would be necessary and beneficial in carrying out such data analysis function in the licensees' organization. Regulations would then be amended to require establishment of groups within the licensee organizations with the sole responsibility of assuring the adequacy of the internal safeguards program.

LMFBR ADVANCED DESIGN CONCEPTSIV.B.1 Advanced Core Design

The characteristics of the LMFBR core designs which were used in the present cost/benefit study are given in Table IV.B-1. In the study, progress is assumed to proceed from early commercial plants with simple doubling times of about 28 years introduced in 1987 to 1990, through advanced commercial oxide-fueled plants with doubling times of about 12 to 15 years introduced in 1991, to carbide core designs with doubling times of about 7 to 9 years introduced in 1995. This sequence is expected to be realized through the planned supporting technology programs as described below.

Each stage in the progression assumes an advance in LMFBR core design and fuels and materials technology. The design of the early commercial oxide reactor will be based primarily on FFTF and CRBRP experience. The key differences between this reactor and FFTF or CRBRP is expected to be that the core average specific power will be increased **due** to an increase in the fuel element linear heat rating to an average of 9 kW/ft from 7 kW/ft in FFTF and CRBRP, while the fuel smear density will be increased from 85 to 90%. In addition, the potential exists (if required) for: (1) an even higher average specific power, without an attendant increase in maximum fuel pin heat rating, via axial zoning of the fuel enrichment, and (2) an increase breeding gain by an increase in pin diameter, and a reduction in cladding thickness made possible through utilization of a bottom fission gas plenum and/or reduction in the currently conservative cladding design allowances, and/or through utilization of advanced cladding alloys presently under development. It is also expected that the fuel assembly pitch-to-diameter (P/D) ratio may be able to be reduced from 1.24 to 1.20 if sufficient advances in both primary pump design and core mechanical design are achieved.

The advanced oxide commercial design, which is expected to be available for utilization in LMFBRs scheduled for operation in 1991, assumes further improvements in reactor design and operation, such as operation at higher average specific power, that is, 12 kW/ft average and 18 kW/ft maximum, and a further increase in breeding gain and fuel burnup through utilization of advanced cladding and core structural alloys now under development (discussed later). Through the use of alloys with reduced swelling and improved creep behavior characteristics, the core can be made more compact, since space to accommodate steel swelling and

Table IV.B-1
TYPICAL LMFBR REACTOR CHARACTERISTICS

Reactor Design	Plant Net Thermal Efficiency(%)	Fuel	Years of Availability	Equilibrium Fuel	Core Power Density (kW/kg metal)	Linear Heat Rate (kW/ft)	kg/MWe-Year		Plutonium Simple ^a Doubling Time (Years)	Breeding Ratio
				Exposures (MWD/Tonne Heavy Metal)			Net Yield Fissile Plutonium	Net Consumption U-235		
LMFBR Early Oxide	40	Plutonium-fueled oxide	1987-1990	110,000-Core 6,000-Blanket	182	9(avg) 16(max)	0.141	0.011	28	1.15 ^{ng}
LMFBR Advanced Oxide	40	Plutonium-fueled oxide	1991-	110,000-Core 6,000-Blanket	221	12(avg) 18(max)	0.247	0.010	12.5	1.25
LMFBR Advanced Carbide (small-diameter pin)	40	Plutonium-fueled carbide	1995-	110,000-Core 6,000-Blanket	243	19(avg) 30(max)	0.303	0.013	7.6	1.34
LMFBR Advanced Carbide (large-diameter pin)	40	Plutonium-fueled carbide	1995-	110,000-Core 6,000-Blanket	120	19(avg) 31(max)	0.381	0.012	7.4	1.46

^aBased on one year out-of-reactor fuel cycle with 1% loss during reprocessing and refabrication.

flow duct deformation and/or the excess core sodium fraction used for heat removal can be eliminated. Higher cladding creep strengths will allow increased fuel burnup, while in the case of the duct, it is anticipated that the wall thickness will be reduced from 120 to 60 mils and the duct-duct clearance from 90 to 40 mils. In addition, the ex-reactor cycle plutonium losses and the ex-reactor reprocessing times will be reduced, which will lead to further reductions in the fuel system doubling time. Improvements in other core design factors are also anticipated, such as optimized above-core parking of the control assemblies, and improved axial and blanket assemblies, which may utilize cast uranium carbide of 100% theoretical density in place of uranium oxide of 95% density.

The combination of doubling time and fuel burnup capabilities which are projected for these advanced oxide reactors appears to represent an optimistic maximum on the capabilities of reactors utilizing this fuel system. As such, the possibility exists that reactors utilizing oxide fuel will not be able to perform as projected in 1991. In this case, it is expected that a backup position will exist whereby carbide/nitride fuel systems will be sufficiently developed to provide these doubling times (12.5 years) and burnup capabilities in 1991.

The carbide/nitride fuel reactor designs presented in Table IV.B-1 represent the more advanced LMFBR core designs which are expected to be available as an option for utilization in LMFBRs scheduled for operation during the period beginning in 1995.

Because of their high heavy-atom density and high thermal conductivity, uranium--plutonium carbide and nitride fuels currently offer a better potential for achieving the long-term objectives of high breeding ratios and low doubling times for the LMFBR Program than do the oxides. The very good thermal conductivity of these fuels coupled with a relatively high melting point enables the use of larger diameter fuel pins at reduced specific power relative to the oxide, or smaller pins (but still larger than the oxide) at relatively high specific power.

Both of the potential advanced carbide/nitride fuel reactor designs, described in Table IV.B-1, are characterized by very short doubling times and are also dependent on the success of the fuels and materials development programs. The design, based on a small-diameter fuel pin, has a high specific power, a low fuel volume fraction, and a relatively small breeding ratio and relies on a low in-reactor fissile inventory and frequent reprocessing to achieve short doubling times. The large-diameter fuel pin design has a low specific power, a high fuel volume fraction and

a high breeding ratio, and assumes relatively infrequent fuel reprocessing. This latter design is presently the favored approach.

LMFBRs of the late 1990's which utilize this latter advanced fuel design can be expected to operate with fuel pins at 30 kW/ft peak and 19 kW/ft average and have doubling times of less than 10 years. The relatively large pins will significantly reduce reprocessing and refabrication costs and associated material fissile losses, and can be expected to result in greatly reduced fuel-cycle costs.

Several comments from the reviewers of the Draft Statement have been received questioning the basis for the use of several of these aforementioned design parameters. In general, these comments pointed out that the parameters are more optimistic than those used in the "1970 Cost Benefit Analysis" (WASH-1184) or those used by the Bethe Panel in its review of LMFBR characteristics. It is further implied that since the design used in the 1970 Analysis was "not safe" there is no way to use the more optimistic design parameters from the 1973 Analysis and still have a safe design. For example, EPA has commented: "In particular, the AEC assumptions for burnup and specific inventory for advanced oxide and carbide LMFBRs appear to be extremely optimistic. The AEC should provide further justification for these assumptions."

In addition, NRDC has submitted the following comments in this area: "There are several observations that can be made with respect to these data. First, all LMFBRs in the 1973 Analysis achieve core burnups of 110,000 MWd/tonne, whereas in the 1970 Analysis the early oxide had a core burnup of only 68,000 MWd/tonne. The initial specific inventory of the early oxide LMFBR in the 1973 Analysis, 1.88 kg fissile/MWe, represents a considerable improvement over the initial specific inventory of the advanced oxide LMFBR in the 1970 Analysis."*

NRDC continues by presenting a table which compares the 1973 Analysis estimates against those presented in the Bethe Report. According to this table, the principal differences are: "(1) that AEC's assumptions that high 10% burnup will be achieved, and (2) the AEC's assumption with respect to the specific power (MWe/kg-fissile) of the LMFBR cores are higher than the Bethe estimates by 90 percent and 2.70** percent for the oxide fuel, and 50 percent for the carbide

*Since specific power (MWt/kg-fissile) is equal to one over the specific inventory times the thermal efficiency, the early oxide LMFBR in the 1973 Analysis also represents the same improvement over the advanced oxide LMFBR in the 1970 Analysis with respect to specific power.

**While the text of the NRDC comments reads 2.70 percent, a value of 270 percent is consistent with the data described in their letter.

fuel." NRDC concludes their comments in this area with: "In other words, the characteristics of advanced oxide LMFBF in the 1970 Analysis was based on a design that optimized performance at the expense of safety considerations, could not be licensed today, and has been shown since to be infeasible due to the stainless steel swelling phenomena. Nevertheless, in the 1973 Analysis the oxide-fueled LMFBFs have even superior performance characteristics, but there are no detailed LMFBF designs (at least none available to the public or the AEC) from which these characteristics are derived. It would be interesting to know the safety characteristics of LMFBFs having these performances. None are given. We seriously question whether these specific inventories are representative of anything close to realistic designs."

In general, the primary reason that the parameters in Table IV.B-1 differ from those used in the 1970 Analysis is that they reflect the increased knowledge of materials and core behavior which: (1) has been developed since the time of the pre-1970 1000-MWe LMFBF follow-on design studies, and (2) will be realized through the existing research and development programs on advanced fuels systems development. Also, many developmental options and choices with regard to design and materials have been identified, and while a final detailed design for high performance cannot be specified now, this divergence is a basis for confidence that sufficiently high performance without any diminution in assurance of safety can be achieved. Specific discussions of the basis for the selection of several of these key parameters are as follows:

IV.B.1.1 Fuel Burnup Capabilities

Regarding the basis for projecting burnup capabilities, Dr. P. Murray, recognized internationally as one of the leading researchers in the field, has summarized in a recent article:*

...that over the past 10 years many thousands of mixed oxide fuel rods clad in stainless steel have already been irradiated in fast test reactors such as EBR-II in Idaho, the Dounreay reactor in Scotland, the Rapsodie reactor in France, and the BR-5 and BOR-60 reactors in the Soviet Union.

If one excludes anomalies which occurred early in these programs, the occurrence of defects has been very small. the number of defects has steadily decreased to almost zero despite the large increase in the number of fuel rods tested.

*P. Murray, "Will We Need New Alloy System for the Fast Reactor?" Iron Age, August 23, 1973.

By now, several hundred rods, both individual rods and assemblies of rods, have achieved 100,000 megawatt days per ton (MWd/t) of fuel and beyond satisfactorily.

Whereas, 75,000 MWd/t was once considered a peak, it now appears that 100,000 MWd/t can be achieved. This is an average figure which corresponds to about 140,000 MWd/t peak, and represents a firm objective to be achieved in the LMFBR demonstration plant."

In addition, in the Cornell Workshops report, Dr. Bethe also recognizes the level of testing of the oxide system to a burnup of 10% (100,000 MWd/tonne) and more. Thus, as far as the oxide fuel system is concerned, the projected fuel burnups of 110,000 MWd/tonne appear to be realizable.

In the case of the carbide fuels which are expected to be introduced in 1995, exposures as high as 80,000 MWd/tonne have been achieved to date, noting that the data are not very extensive because of the limited number of tests conducted to date. The capability to reliably achieve goal burnups to 110,000 MWd/tonne, and more, will be demonstrated as part of the advanced fuels systems development programs.

IV.B.1.2. Core Specific Power

Regarding the comments which were made on core specific power, the value of 0.7 MWt/kg used by the Bethe Panel in their analysis of oxide cores is similar to those used in the FFTF and CRBRP designs. This core specific power corresponds to an average linear heat rate of 7 kW/ft and a maximum linear heat rate of 12 kW/ft; however, these linear heat rates are purposefully conservative for first-of-a-kind designs, as has been demonstrated experimentally in EBR-II. The increased core specific powers assumed for the early and advanced oxide designs correspond to maximum linear heat rates of 16 and 18 kW/ft, respectively, well below the more than 20 kW/ft required to produce incipient centerline melting. The average specific power can be increased without increasing the maximum rod linear power by axial and radial zoning of the fuel.

The maximum linear heat rate assumed in the GE follow-on design used in the 1970 Analysis was 16 kW/ft. With the high breeding ratios and consequent short doubling times being calculated at that time for that design, there was little incentive to increase the core specific density by increasing the linear heat rate with an increase in pumping power.

The core specific powers used for this analysis are reasonable extensions of present design knowledge and experience. There is no reason to believe that the parameters used in this analysis in anyway compromise the integrity of the core design.

IV.B.3 Doubling Time

It should be noted that the demonstration of low doubling time for an LMFBR system has not been a primary objective of any LMFBRs (domestically and abroad) under construction to date, including the FFTF, and will not be a primary goal of the CRBRP. Rather, the prime objective has been the design and operation of a safe and reliable reactor, noting that a high plant availability factor is one of the key requirements for low doubling times and for commercial acceptance of LMFBRs.

Consistent with this approach, the simple doubling time for the CRBRP will be modestly high at a value of approximately 36 years.* This value when related to a specific power value of 0.95 Mwt/kg, an average fuel burnup value of 100,000 MWd/tonne (assumes use of today's reference oxide fuel and cold-worked 316 stainless steel cladding and duct material), a breeding ratio of 1.2, a one year reprocessing time, and a 1% process loss, is consistent with the value reported by Bethe in the Cornell Workshops report. Similarly, a simple doubling time value of 28 years (20 years compound doubling time) for the early commercial reactor is in keeping with a core specific power value of 1.33 Mwt/kg, and all other conditions essentially the same as for the CRBRP.

Table IV.B-2 presents the pertinent parameters on which the remaining doubling time values for the advanced LMFBR systems are based.

These doubling times are consistent with results expected from the design, materials, and fuel programs now underway as part of the overall LMFBR research and development program. Table IV.B-3 shows the progress expected from some of these advances in technology. From a schedular standpoint, they are also consistent with the planned dates for introduction and growth of the commercial LMFBRs.

A final comment** on doubling times is made by EPA:

...the tradeoff between LMFBRs with low breeding ratios but lower \$ cost/Kwh versus LMFBRs with higher ratios and higher \$ cost/Kwh (ignoring the

*Expressed as compound doubling time, this value is 25 years.

**Comment Letter 53, p. 77.

Table IV.B-2
ADVANCED LMFBR SYSTEMS

	Oxide	Carbide Small Dia. Pin	Carbide Large Dia. Pin
Simple Doubling Time (years)	12.6	7.6	7.4
Specific Power (MWt/kg)	1.88	2.21	1.38
Breeding Ratio	1.25 / 1.30	1.34	1.46
Fuel	Advanced Oxide	Carbide	Carbide
Cladding and Core Structural Materials	Advanced Alloy	Advanced Alloy	Advanced Alloy
Reprocessing Time (years)	1	1	1
Process losses (%)	1	1	1

Table IV.B-3

POTENTIAL IMPROVEMENTS FOR OXIDE FUEL LMFBR

Case	Smear Density (Percent)	Peak Linear Power (kW/ft)	Peak Discharge Burnup (MWd/kg)	Pin Diameter (Inches)	Pin Pitch Diameter Ratio	Clad Thick- ness (Inches)	Breed- ing Ratio	Fissile Specific Power (MWt/kg)	Change in Fuel Cycle Doubling Time (Years)
A ^a	90	16	80	0.23	1.243	0.015	1.178	1.13	0
B	95	16	80	0.23	1.243	0.015	1.207	1.16	-8
C	90	18	80	0.23	1.243	0.010	1.178	1.24	-1
D	90	16	150	0.23	1.243	0.015	1.178	1.03	-9
E	90	16	80	0.27	1.243	0.010	1.211	0.88	-5
F	90	16	80	0.23	1.200	0.010	1.22	1.23	-11
G	90	16	80	0.23	1.243	0.010	1.250	1.18	-15
H ^b	95	18	150	0.27	1.20	0.010	1.361	1.13	-30 (est)

^aReference (case A) fuel-cycle system simple doubling time of 37 years based on a one-year out-of reactor inventory and a 1% assumed fuel-cycle loss, for a 1000-MWe oxide LMFBR.

^bCombined (case H) improvements indicate a possible 9 to 10 year doubling time with oxide fuel. However, the goal for oxide fuel is about 15 years, which is a more conservative target.

value of the fuel bred). In our opinion, this tradeoff is very important for cost-benefit consideration, and may also have significant environmental implications. The EIS does not address these issues of current controversy.

First, it is not necessarily true that the goals of low doubling time and optimized costs are mutually exclusive. Recent system studies indicate that for many of the important design parameters there is not a substantial difference between designs meeting the goals of low fuel cost and short doubling time. Furthermore, the largest segment of the total dollar cost/kWhr for an LMFBR is that associated with the plant capital cost--this comprises approximately 70 to 80% of the total. Changes in breeding ratio are more related to changes in fuel costs, and since fuel costs for LMFBR are relatively small and represent a small segment of the total power cost, modest changes in this segment would not have significant impact on the overall cost. Further, it is estimated that only very small changes in capital costs of a commercial LMFBR that has already been optimized for capital costs will result from modifications associated with breeding ratio. Such modifications might entail increasing the fuel pin spacing and reducing axial blanket length to reduce coolant pressure drop, or removal of a row of radial blanket to reduce reactor containment volume. However, the reduction in plant costs associated with these modifications may not even compensate for the loss of plutonium revenue due to the decreased breeding ratio.

IV.B.2 Advanced Fuels and Materials Development

An important adjunct of the expected core design development is the development of advanced fuels and materials. This program which is part of the AEC LMFBR research and development program, has as its objective the development of fuel and core materials permitting the option of introducing fuel systems having doubling times of not more than 10 years beginning in about 1986. The program will also develop and demonstrate the use of advanced oxide fuel systems expected to have doubling times of about 13 to 15 years beginning in about 1982.

There are two major tasks to be accomplished in the advanced fuels and materials program. These are:

- (1) The development of advanced cladding and core structural materials via large scale testing in EBR-II and FFTF followed by utilization of advanced cladding, assembly ducts and improved fuel pin spacers in the **CRBRP** demonstration plant;
- (2) The development of the advanced oxide and carbide/nitride fuel systems which will utilize the advanced cladding and core structural materials.

This will be accomplished via large scale irradiation testing in FFTF in order to obtain statistically meaningful data under prototypic operating conditions and to confirm reliable performance of these advanced fuel systems as a prelude to their use in the demonstration plant. In addition, efforts will be directed toward the expansion of the LMFBR reprocessing and refabrication programs with a view to shortening out-of-reactor fuel handling intervals and maximize process yield.

In all of these efforts guidance will be provided by studies and analysis, including this cost/benefit study, which will determine optimum core parameters. Specifics of each of these major development areas are described on the following pages:

IV.B.2.1 Core Structural Materials Development

The basic structural material to be employed in the fuel, fuel pin cladding, and fuel assembly ducts of FFTF and CRBRP, and scheduled for utilization in the early commercial LMFBRs, is 20% cold-worked 316 stainless steel. It is recognized that this material is subject to both irradiation-induced swelling and creep--two basic materials problems. As has been mentioned previously, since the irradiation-induced growth which results from these effects has been accommodated by allowing additional space in the core, thereby reducing the fuel volume fraction and causing a decrease in breeding ratio of about 0.1, there is a strong incentive to develop improved materials for these applications.

Efforts in this area have been initiated and are progressing well. Through the use of inexpensive short-time techniques such as accelerator ion bombardment, several alloy classes have been identified which are likely to exhibit superior resistance to neutron irradiation-induced swelling and creep. Specific commercially available alloys which have already been identified as showing much promise are Fe-Cr-Ni alloys with compositions such as that of the British Nimonic PE-16 and ferritic alloys such as HT-9. Neutron irradiation experiments are currently being designed and fabricated for the purpose of confirming that these alloy classes do exhibit improved behavior under prototypic LMFBR irradiation conditions. These experiments, which will be performed in parallel with ex-reactor investigations of the sodium compatibility and fabricability of these candidate alloys, will also provide fundamental information on neutron irradiation effects which will be used to develop the optimum LMFBR alloys by tailoring commercially available materials or by developing new alloys. Communications will be continually maintained with parallel efforts on fuel systems development during this program to assure that alloys developed meet designers' needs.

Key near-term schedular aspects of this effort include:

Fiscal Year

1975	Initiate structural material irradiation experiments in EBR-II
1977	Select three to four candidate advanced duct alloys
1978	Select three to four candidate cladding alloys
1979	Install 12 fuel assemblies with advanced duct and cladding materials into FFTF
1980	Select primary advanced duct alloy
1982	Select primary advanced cladding alloys for oxide and carbide/nitride fuels

IV.B.2.2 Advanced Fuel Materials Development

Even though much has been learned of the performance of the oxide fuel system, its further development, together with the development of promising alternate materials, such as carbide and nitride fuels, is another of the major LMFBR research and development programs. The advanced oxide fuel development will be directed toward providing a fuel with improved characteristics relative to the reference oxide fuel such as higher density, higher average specific power, improved fission gas retention (e.g., bottom gas plena as is in use in Europe) and fuel swelling accommodations, and optimized fuel bundles and ducts. These improvements will also contribute to significant reductions in the fuel systems doubling time. Such improvements can reduce advanced oxide systems below a 15-year doubling time.

The development of the more advanced mixed carbides and mixed nitrides fuels is another major objective. These fuels, by virtue of their higher fissile atom densities and better thermal conductivity, presently offer a greater potential for developing fuel systems with doubling times of ten years or less. Despite the attractive basic attributes of the mixed carbide and mixed nitride fuels, a satisfactory fuel element design has not been demonstrated. This is primarily because of the relatively small number of mixed carbide fuel pins which have been irradiated and the paucity of performance data to base improvements in the fuel pin designs. Therefore, the investigation of the technical and economic standing of these advanced fuels will depend on a large-scale irradiation test program in the EBR-II, which will result in refined designs for extensive testing in FFTF and culminate in irradiation in CRBRP.

The irradiation test effort in EBR-II will yield important parametric data on the relative behavior of the most promising mixed carbide fuel system designs and permit

an assessment of the effect of all significant variables that influence fuel performance on a statistical basis. Concurrently, irradiations in the TREAT reactor will be performed to define performance limitations and potential safety problems associated with the transient behavior of irradiated carbide and nitride fuels. These data will provide key information to guide the FFTF irradiation test programs wherein the potential viability of the advanced fuels will be assessed. The large-scale test programs in FFTF will yield statistically meaningful data under prototypic LMFBR conditions to confirm reliable performance of the carbide and nitride fuel systems as a prelude to possible use in the CRBRP.

A systematic fuel system development approach is expected to result in carbide and nitride fuels with proven reliability and safety, which are economically attractive, and are considered as a viable alternative to the oxide fuel system in the design of commercial LMFBRs scheduled for start of operation in the mid-1990's.

Appendix IV.C
SUMMARY OF LMFBR ADVANTAGES*

Environmental Considerations

(1) LMFBR provides a clean source of power

No chemical or particulate emissions from burning of the fuel, as in case of fossil fuels. Radiological emissions from normal operation essentially zero.

Iodine, tritium, and other fission and corrosion products are more easily removed and controlled in the sodium coolant and cold trapping system of the LMFBR than in the water coolant of the LWR.

(2) Reduces thermal discharge

Thermal efficiencies of 40% for LMFBR compared to 33% for LWR provides the LMFBR with a 30% lower thermal discharge for same energy. The HTGR has thermal efficiencies comparable to LMFBR.

(3) Containment and Safety

Many levels of barriers and containment to prevent release of radioactive materials (e.g., clad, ducts, blankets, reflectors, core restraint internals, vessel, guard vessel, compartments, containment).

Three levels of safety

- (1) The first level concerns the intrinsic features of the design of the nuclear plant and the quality, redundancy, testability, inspectability, and fail-safe features of the components of the reactor and plant. The design must be such that the plant is unquestionably safe in normal operation and has a maximum tolerance for errors, abnormal operation, and component malfunction. Analyses are made and test programs conducted to detect those types of malfunctions or faults that could affect safety so that they can be guarded against by design, quality assurance, or fail-safe features as appropriate. A reactor plant built in this way and routinely tested and monitored not only provides protection for the heavy investment made by the utility owner, which would be seriously jeopardized by a severe accident, but also provides a maximum of protection for the operating staff and the public.

*Some of the LMFBR advantages given in this appendix are qualitative assessments of the quantitative benefits provided in other sections.

- (2) The second level concerns such incidents as partial loss of flow, reactivity insertions, failure of parts of the safety system, or fuel handling errors, which are assumed to occur in spite of the care taken in design, construction, and operation. This second level provides fault detection equipment and design features which enable such occurrences to be arrested or accommodated safely. Conservative design practices, adequate safety margins, and parallel, independent, redundant arrangements of detecting and actuating equipment (so that if one fails, others will be available to provide protective action) are used in the design and operation of such reactor protection systems. In addition, these systems are designed to be readily inspected and tested so that there is a high degree of assurance that they will operate reliably in the infrequent event they are required.
- (3) The third level concerns the postulated failure of protective safety systems simultaneously with the accident they are intended to control. The consequences of such hypothetical accidents must be evaluated and understood. Furthermore, if a practical means can be found to provide an additional measure of safety to mitigate the accident or accommodate the consequences, that also may be considered.

Stored energy is low due to low pressure of sodium and cover gas, together with operation well below boiling point.

The high thermal conductivity of sodium (compared with water in the LWR and helium in the HTGR) provides an ideal heat sink, thus ensuring excellent cooling under all conditions.

Inherent in the LMFBR is a strong negative temperature coefficient of reactivity due to the Doppler effect which provides an automatic reliable feedback resulting in stable reactor operation. The negative doppler coefficient rapidly reacts to an unplanned change in operating temperature by producing a reactivity change that results in helping to return to the planned operating temperature.

Other safety-related reactor design features include:

- (1) A core restraint system to position the core and assure that a negative power coefficient exists for all conditions.

- (2) Devices in each control rod mechanism to prevent any rapid outward motion of rods.
- (3) Fuel assembly inlet design features that prevent coolant blockage.
- (4) Mechanical interlocks which prevent the mislocation of control and fuel assemblies.

Safety-related plant design features are:

- (1) Independent primary sodium loops to provide reliable cooling during normal operation, shutdown, and emergency conditions.
- (2) Elevated piping, along with guard vessels, around primary system components to assure that cooling capability can be maintained in the remaining loops if any malfunction occurs in one loop.
- (3) A large sodium inventory in the reactor vessel to assure that the vessel nozzles remain covered at all times.
- (4) Natural circulation capability to assure adequate decay heat removal during emergency conditions.

Energy Utilization

Maximizes utilization of uranium resource

As much as 70% of the energy in natural uranium can be made available by the use of the LMFBR compared with about 1% from thermal reactors whether of the light-water reactor type or the HTGR, assuring most beneficial utilization of the stockpile of depleted uranium from the diffusion plants.

Improved efficiency and economy will be stimulated in other energy-producing industries, including those associated with the production, transportation, and utilization of fossil fuels.

The energy released from 1 lb of uranium used in the breeder cycle is comparable to that released from 1000 tons of coal or 4000 barrels of oil.

A premium market will be provided for plutonium produced by LWRs.

Access of the public to a virtually limitless supply of low-cost electricity and the potential use of this low-cost electricity in energy-intensive applications will be provided.

An ample supply of low-cost electricity will be available to areas which have been denied low-cost energy.

Liquid Sodium as a Coolant

Technology and application experience have been developed over more than 20 years.

The current reference materials that will be in contact with sodium are fully compatible with high temperature, liquid sodium.

Sodium permits high operating temperatures at low pressure in the reactor, and hence good thermal efficiency is assured.

Strong U.S. Utility and Industrial and Worldwide Support Evidenced for LMFBRs

U.S. utilities participate in reviews of AEC plans, in preparation of assessments of fast breeder programs; and in the construction and operation of fast breeder programs; and in the construction and operation of fast breeder demonstration plants. The participation of 285 U.S. utilities in the LMFBR demonstration plant and over 100 utilities in GCFBR development program are indicative of utility interest in promoting fast breeder reactors in the U.S.

U.S. industry's prime role in the fast breeder program is to help develop fast breeder reactor demonstration plants and commercial plants. Industry's acceptance of this responsibility is indicated by its strong participation in the program, particularly the LMFBR demonstration plant and the Fast Flux Test Facility and the large contribution of its own funds and manpower to the total effort.

The development of the LMFBR is a priority objective of most of the major industrial nations, Great Britain, France, U.S.S.R., Republic of West Germany, Japan, and others. Technical exchanges with these countries should enhance the development of the breeder.

Development of Advanced Technologies is Appropriate for Advanced Industrial Nations

Maintaining nuclear power technological leadership permits the continued preeminence of the U.S. in its leadership role in nuclear power. It also permits the U.S. to be a major exporter of nuclear power.

A developed LMFBR technology helps permit the use of technical and economic ties as a principal vehicle for international cooperation and a means for promoting peace and for assisting industrial developments in other countries.

The LMFBR with its associated high-temperature sodium technology can be a stepping stone to further technological developments.

The LMFBR can help defer the burning of fossil fuels, which could otherwise be used as chemical feedstocks.

Appendix IV.D

DETAILED RESULTS OF LMFBR
COST-BENEFIT CALCULATIONS

Table IV. D-1

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 10% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
1	2020				Base	Base			210.8			
2	1998	1998	1985	Base	Base	Base		1	190.2	20.6	4.8	4.3
3	2000	2000	1987	Base	Base	Base		1	191.4	19.4	4.7	4.1
4	2004	2004	1991	Base	Base	Base		1	194.4	16.4	4.7	3.5
5	2020				Base	Optim.			201.4			
6	1998	1998	1985	Base	Base	Optim.		5	188.8	12.6	4.8	2.6
7	2000	2000	1987	Base	Base	Optim.		5	189.4	12.0	4.7	2.6
8	2004	2004	1991	Base	Base	Optim.		5	191.5	9.9	4.7	2.1
9	2020				Base	Pessim.			225.3			
10	1998	1998	1985	Base	Base	Pessim.		9	192.7	32.6	4.8	6.8
11	2000	2000	1987	Base	Base	Pessim.		9	194.7	30.6	4.7	6.5
12	2004	2004	1991	Base	Base	Pessim.		9	200.8	24.5	4.7	5.2
13	2020				-20%(a)	Base			188.4			
14	1998	1998	1985	Base	-20%(a)	Base		13	173.1	15.3	4.8	3.2
15	2000	2000	1987	Base	-20%(a)	Base		13	174.2	14.2	4.7	3.0
16	2004	2004	1991	Base	-20%(a)	Base		13	177.1	11.3	4.7	2.4
17	2020				+20%(b)	Base			235.0			
18	1998	1998	1985	Base	+20%(b)	Base		17	207.9	27.1	4.8	5.6
19	2000	2000	1987	Base	+20%(b)	Base		17	208.9	26.1	4.7	5.6
20	2004	2004	1991	Base	+20%(b)	Base		17	212.7	22.3	4.7	4.7

Footnotes listed at end of tables.

Table IV. D-1 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 10% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
21	2000	2000	1987	+\$50(f)	Base	Base		1	195.6	15.2	4.7	3.2
22	2000	2000	1987	Base	Base	Base	(d)	1	192.4	18.4	4.7	3.9
23	2000	2000	1987	Base	Base	Base	(d)(e)	1	194.7	16.1	4.7	3.4
24	2000	2000	1987	Base	+20%(b)	Base	(d)	17	210.2	24.8	4.7	5.3
25	1998	1998	1985	Base	Base	Base	(e)	1	191.3	19.5	4.8	4.1
26	2000	2000	1987	Base	Base	Base	(e)	1	193.3	17.5	4.7	3.7
27	2004	2004	1991	Base	Base	Base	(e)	1	195.7	15.1	4.7	3.2
28	2000	2000	1987	Base	+20%(b)	Base	(e)	17	210.3	24.7	4.7	5.3
29	2000				Base	Base			206.0			
(3)	2000	2000	1987	Base	Base	Base		29	191.4	14.6	4.7	3.1
30	(none)				Base	Base			202.3			
31	(none)	2000	1987	Base	Base	Base		30	191.8	10.5	4.7	2.2
32	(h)				Base	Base	(h)		214.8			
33	(h)	2000	1987	Base	Base	Base	(h)	32	191.8	23.0	4.7	4.9
34	2020				Base	Base	(i)		391.3			
35	(none)				Base	Base	(h)(i)		378.2			
36	(none)	(none)	1987	Base	Base	Base	(i)	34	358.4	32.9	4.7	7.0
								35		19.8	4.7	4.2

Footnotes listed at end of tables.

Table IV. D-1 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 10% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
37	2020								142.1			
38	2000	2000	1988	Base	A	Base	A	37	137.0	5.1	4.7	1.1
39	2020								211.4			
40	2000	2000	1988	Base	B	Base	B	39	192.2	19.2	4.7	4.1
41	2020								245.7			
42	2000	2000	1988	Base	C	Base	C	41	221.6	24.1	4.7	5.1
43	2020								184.4			
44	2000	2000	1988	Base	D	Base	D	43	172.8	11.6	4.7	2.5
45	(none)				Base	Optim.			197.1			
46	(none)	2000	1987	Base	Base	Optim.		45	189.3	7.8	4.7	1.7
47	(none)	(none)	1987	Base	Base	Optim.		45	188.9	8.2	4.7	1.7
47B	(none)	(none)	1987	Base	Base	Base		30	190.1	12.2	4.7	2.6
48	2020				-50%(c)	Optim.	(c)		148.1			
49	(none)				-50%(c)	Optim.	(c)		146.8			
50	(none)	2000	1987	Base	-50%(c)	Optim.	(c)	49	143.8	3.0	4.7	0.6
51	(none)	(none)	1987	Base	-50%(c)	Optim.	(c)	49	143.6	3.2	4.7	0.7
52	2000	2000	1987	Base	-50%(c)	Optim.	(c)	48	144.2	3.9	4.7	0.8

Footnotes listed at end of tables.

Table IV. D-1 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 10% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
53	(none)	2000	1987	+\$100(g)	Base	Optim.	(g)	45	196.3	0.8	4.7	0.2
54	(none)	(none)	1987	+\$100(g)	Base	Optim.	(g)	45	195.2	1.9	4.7	0.4
55	2000	2000	1987	+\$100(g)	Base	Optim.	(g)	5	196.6	4.8	4.7	1.0
56	(none)	2000	1987	+\$100(g)	-50%(c)	Optim.	(c)(g)	49	147.3	0.0	4.7	0.0
57	(none)	(none)	1987	+\$100(g)	-50%(c)	Optim.	(c)(g)	49	145.9	0.9	4.7	0.2
58	2000	2000	1987	+\$100(g)	-50%(c)	Optim.	(c)(g)	48	147.7	0.4	4.7	0.1
59	(none)				Base	Pessim.			211.6			
60	(none)	2000	1987	Base	Base	Pessim.		59	194.0	17.6	4.7	3.7
61	(none)	(none)	1987	Base	Base	Pessim.		59	192.1	19.5	4.7	4.1
62	2020				-50%(c)	Pessim.	(c)		157.3			
63	(none)				-50%(c)	Pessim.	(c)		152.8			
64	(none)	2000	1987	Base	-50%(c)	Pessim.	(c)	63	146.5	6.3	4.7	1.3
65	(none)	(none)	1987	Base	-50%(c)	Pessim.	(c)	63	145.9	6.9	4.7	1.5
66	2000	2000	1987	Base	-50%(c)	Pessim.	(c)	62	146.9	10.4	4.7	1.0
67	(none)	2000	1987	+\$100(g)	Base	Pessim.	(g)	59	201.1	10.5	4.7	2.2
68	(none)	(none)	1987	+\$100(g)	Base	Pessim.	(g)	59	200.6	11.0	4.7	2.3
69	2000	2000	1987	+\$100(g)	Base	Pessim.	(g)	9	201.5	23.8	4.7	5.1
70	(none)	2000	1987	+\$100(g)	-50%(c)	Pessim.	(c)(g)	63	149.9	2.9	4.7	0.6
71	(none)	(none)	1987	+\$100(g)	-50%(c)	Pessim.	(c)(g)	63	149.4	3.4	4.7	0.7
72	2000	2000	1987	+\$100(g)	-50%(c)	Pessim.	(c)(g)	62	150.6	6.7	4.7	1.4

Footnotes listed at end of tables.

Table IV. D-1 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 10% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
73	2020				Base	Base	(J)		230.7			
74	2000	2000	1987	Base	Base	Base	(J)	73	201.4	29.3	4.7	6.2
75	(none)				Base	Base	(J)		217.9			
76	(none)	2000	1987	Base	Base	Base	(J)	75	201.8	16.1	4.7	3.4

Footnotes listed at end of tables.

Table IV. D-2

SUMMARY OF COST-BENEFIT STUDY RESULTS UNDISCOUNTED

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Comparison With		Billions of Dollars			Benefit/Cost Ratio
	(HTGR)	(LMFBR)					Notes	Case No.	Energy ^(k) Cost	Gross Benefit	R&D Cost	
1	2020				Base	Base			6560.4			
2	1998	1998	1985	Base	Base	Base		1	4890.6	1669.8	8.6	
3	2000	2000	1987	Base	Base	Base		1	4905.6	1654.8	8.4	197.0
4	2004	2004	1991	Base	Base	Base		1	5033.4	1527.0	8.7	
5	2020				Base	Optim.			5918.3			
6	1998	1998	1985	Base	Base	Optim.		5	4836.2	1082.1	8.6	
7	2000	2000	1987	Base	Base	Optim.		5	4866.0	1052.3	8.4	125.3
8	2004	2004	1991	Base	Base	Optim.		5	4946.4	971.9	8.7	
9	2020				Base	Pessim.			7200.9			
10	1998	1998	1985	Base	Base	Pessim.		9	4920.9	2280.0	8.6	
11	2000	2000	1987	Base	Base	Pessim.		9	5034.3	2166.6	8.4	257.9
12	2004	2004	1991	Base	Base	Pessim.		9	5267.4	1933.5	8.7	
13	2020				-20%(a)	Base			5288.2			
14	1998	1998	1985	Base	-20%(a)	Base		13	4024.1	1264.1	8.6	
15	2000	2000	1987	Base	-20%(a)	Base		13	4054.0	1234.2	8.4	146.9
16	2004	2004	1991	Base	-20%(a)	Base		13	4060.2	1228.0	8.7	
17	2020				+20%(b)	Base			7905.4			
18	1998	1998	1985	Base	+20%(b)	Base		17	5710.7	2194.7	8.6	
19	2000	2000	1987	Base	+20%(b)	Base		17	5761.1	2144.3	8.4	255.3
20	2004	2004	1991	Base	+20%(b)	Base		17	5939.6	1965.8	8.7	

Footnotes listed at end of tables.

Table IV. D-2 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS UNDISCOUNTED

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
21	2000	2000	1987	+\$50(f)	Base	Base		1	5762.3	798.1	8.4	95.0
22	2000	2000	1987	Base	Base	Base	(d)	1	4938.3	1622.1	8.4	193.1
23	2000	2000	1987	Base	Base	Base	(d)(e)	1	5269.6	1290.8	8.4	153.7
24	2000	2000	1987	Base	+20%(b)	Base	(d)	17	5823.4	2082.0	8.4	247.9
25	1998	1998	1985	Base	Base	Base	(e)	1	5007.6	1552.8		
26	2000	2000	1987	Base	Base	Base	(e)	1	5027.1	1533.3	8.4	182.5
27	2004	2004	1991	Base	Base	Base	(e)	1	5223.5	1336.9		
28	2000	2000	1987	Base	+20%(b)	Base	(e)	17	5979.0	1926.4	8.4	229.3
29	2000				Base	Base			6041.2			
(3)	2000	2000	1987	Base	Base	Base		29	4905.6	1135.6	8.4	135.2
30	(none)				Base	Base			5915.1			
31	(none)	2000	1987	Base	Base	Base		30	4836.3	1078.8	8.4	128.4
32	(h)				Base	Base	(h)		6800.2			
33	(h)	2000	1987	Base	Base	Base	(h)	32	4902.9	1897.3	8.4	225.9
34	2020				Base	Base	(i)		9536.2			
35	(h)				Base	Base	(h)(i)		8711.0			
36	2000	2000	1987	Base	Base	Base	(i)	34	6989.5	2546.7	8.4	303.2
								35		1721.5	8.4	204.9

Footnotes listed at end of tables.

IV.D-7

Table IV. D-2 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS UNDISCOUNTED

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
37	2020				A	Base	A		3289.0			
38	2000	2000	1988	Base	A	Base	A	37	2755.7	533.3	8.5	62.7
39	2020				B	Base	B		6656.3			
40	2000	2000	1988	Base	B	Base	B	39	5065.6	1590.7	8.5	187.1
41	2020				C	Base	C		7978.6			
42	2000	2000	1988	Base	C	Base	C	41	5998.5	1980.1	8.5	233.0
43	2020				D	Base	D		5177.2			
44	2000	2000	1988	Base	D	Base	D	43	4056.7	1120.5	8.5	131.8
45	(none)				Base	Optim.			5516.9			
46	(none)	2000	1987	Base	Base	Optim.		45	4840.8	676.1	8.4	80.5
47	(none)	(none)	1987	Base	Base	Optim.		45	4832.6	684.3	8.4	81.5
47B	(none)	(none)	1987	Base	Base	Base		30	4894.4	1020.7	8.4	121.5
48	2020				-50%(c)	Optim.	(c)		3116.7			
49	(none)				-50%(c)	Optim.	(c)		2988.3			
50	(none)	2000	1987	Base	-50%(c)	Optim.	(c)	49	2734.8	253.5	8.4	30.2
51	(none)	(none)	1987	Base	-50%(c)	Optim.	(c)	49	2725.4	262.9	8.4	31.3
52	2000	2000	1987	Base	-50%(c)	Optim.	(c)	48	2738.0	378.7	8.4	45.1

Footnotes listed at end of tables.

Table IV. D-2 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS UNDISCOUNTED

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
53	(none)	2000	1987	+\$100(g)	Base	Optim.	(g)	45	5363.7	153.2	8.4	18.2
54	(none)	(none)	1987	+\$100(g)	Base	Optim.	(g)	45	5381.1	135.8	8.4	16.2
55	2000	2000	1987	+\$100(g)	Base	Optim.	(g)	5	5369.9	548.4	8.4	65.3
56	(none)	2000	1987	+\$100(g)	-50%(c)	Optim.	(c)(g)	49	2973.9	14.4	8.4	1.7
57	(none)	(none)	1987	+\$100(g)	-50%(c)	Optim.	(c)(g)	49	2955.0	33.3	8.4	4.0
58	2000	2000	1987	+\$100(g)	-50%(c)	Optim.	(c)(g)	48	2977.2	139.5	8.4	16.6
59	(none)				Base	Pessim.			6339.0			
60	(none)	2000	1987	Base	Base	Pessim.		59	4961.6	1377.4	8.4	164.0
61	(none)	(none)	1987	Base	Base	Pessim.		59	4937.2	1401.8	8.4	166.9
62	2020				-50%(c)	Pessim.	(c)		3619.6			
63	(none)				-50%(c)	Pessim.	(c)		3330.9			
64	(none)	2000	1987	Base	-50%(c)	Pessim.	(c)	63	2774.4	556.5	8.4	66.3
65	(none)	(none)	1987	Base	-50%(c)	Pessim.	(c)	63	2754.7	576.2	8.4	68.6
66	2000	2000	1987	Base	-50%(c)	Pessim.	(c)	62	2784.0	835.6	8.4	99.5

Footnotes listed at end of tables.

Table IV. D-2 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS UNDISCOUNTED

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			Benefit/Cost Ratio
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	
67	(none)	2000	1987	+\$100(g)	Base	Pessim.	(g)	59	5527.4	811.6	8.4	96.6
68	(none)	(none)	1987	+\$100(g)	Base	Pessim.	(g)	59	5529.5	809.5	8.4	96.4
69	2000	2000	1987	+\$100(g)	Base	Pessim.	(g)	9	5528.7	1672.2	8.4	199.1
70	(none)	2000	1987	+\$100(g)	-50%(c)	Pessim.	(c)(g)	63	3056.2	274.7	8.4	32.7
71	(none)	(none)	1987	+\$100(g)	-50%(c)	Pessim.	(c)(g)	63	3066.3	264.6	8.4	31.5
72	2000	2000	1987	+\$100(g)	-50%(c)	Pessim.	(c)(g)	62	3076.6	543.0	8.4	64.6
73	2020				Base	Base	(j)		7155.2			
74	2000	2000	1987	Base	Base	Base	(j)	73	5006.6	2148.6	8.4	255.8
75	(none)				Base	Base	(j)		6131.1			
76	(none)	2000	1987	Base	Base	Base	(j)	75	4939.2	1191.9	8.4	141.9

Footnotes listed at end of tables.

Table IV.D-3

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 5% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			Benefit/Cost Ratio
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	
1	2020				Base	Base			897.0			
2	1998	1998	1985	Base	Base	Base		1	736.6	160.4	6.3	25.6
3	2000	2000	1987	Base	Base	Base		1	740.6	156.4	6.1	25.7
4	2004	2004	1991	Base	Base	Base		1	756.5	140.5	6.2	22.7
5	2020				Base	Optim.			832.7			
6	1998	1998	1985	Base	Base	Optim.		5	729.3	103.4	6.3	16.4
7	2000	2000	1987	Base	Base	Optim.		5	732.7	100.0	6.1	16.4
8	2004	2004	1991	Base	Base	Optim.		5	742.9	89.8	6.2	14.5
9	2020				Base	Pessim.			973.2			
10	1998	1998	1985	Base	Base	Pessim.		9	744.2	229.0	6.3	36.3
11	2000	2000	1987	Base	Base	Pessim.		9	757.9	215.3	6.1	35.3
12	2004	2004	1991	Base	Base	Pessim.		9	788.7	184.5	6.2	29.8
13	2020				-20%(a)	Base			755.9			
14	1998	1998	1985	Base	-20%(a)	Base		13	638.7	117.2	6.3	18.6
15	2000	2000	1987	Base	-20%(a)	Base		13	642.8	113.1	6.1	18.5
16	2004	2004	1991	Base	-20%(a)	Base		13	659.1	96.8	6.2	15.6
17	2020				+20%(b)	Base			1042.0			
18	1998	1998	1985	Base	+20%(b)	Base		17	832.2	209.8	6.3	33.3
19	2000	2000	1987	Base	+20%(b)	Base		17	838.1	203.9	6.1	33.4
20	2004	2004	1991	Base	+20%(b)	Base		17	860.8	181.2	6.2	29.2

Footnotes listed at end of tables.

Table IV.D-3 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 5% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			Benefit/Cost Ratio
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	
21	2000	2000	1987	+\$50(f)	Base	Base		1	766.9	130.1	6.1	21.3
22	2000	2000	1987	Base	Base	Base	(d)	1	744.8	152.2	6.1	25.0
23	2000	2000	1987	Base	Base	Base	(d)(e)	1	769.0	128.0	6.1	21.0
24	2000	2000	1987	Base	+20%(b)	Base	(d)	17	846.7	195.3	6.1	32.0
25	1998	1998	1985	Base	Base	Base	(e)	1	749.1	147.9	6.3	23.6
26	2000	2000	1987	Base	Base	Base	(e)	1	753.1	143.9	6.1	23.7
27	2004	2004	1991	Base	Base	Base	(e)	1	770.9	126.1	6.2	20.3
28	2000	2000	1987	Base	+20%(b)	Base	(e)	17	857.7	184.3	6.1	30.2
29	2000				Base	Base			850.7			
(3)	2000	2000	1987	Base	Base	Base		29	740.6	110.1	6.1	18.0
30	(none)				Base	Base			830.1			
31	(none)	2000	1987	Base	Base	Base		30	736.2	93.9	6.1	15.4
32	(h)				Base	Base	(h)		920.3			
33	(h)	2000	1987	Base	Base	Base	(h)	32	740.7	179.6	6.1	29.4
34	2020				Base	Base	(i)		1433.0			
35	(h)				Base	Base	(h)(i)		1339.5			
36	2000	2000	1987	Base	Base	Base	(i)	34	1178.6	254.4	6.1	41.7
								35		160.9	6.1	26.4

Footnotes listed at end of tables.

Table IV.D-3 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 5% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
37	2020				A	Base	A		522.6			
38	2000	2000	1988	Base	A	Base	A	37	474.4	48.2	6.1	7.9
39	2020				B	Base	B		907.5			
40	2000	2000	1988	Base	B	Base	B	39	757.3	150.2	6.1	24.7
41	2020				C	Base	C		1073.1			
42	2000	2000	1988	Base	C	Base	C	41	883.1	190.0	6.1	31.3
43	2020				D	Base	D		747.2			
44	2000	2000	1988	Base	D	Base	D	43	644.1	103.1	6.1	17.0
45	(none)				Base	Optim.			793.0			
46	(none)	2000	1987	Base	Base	Optim.		45	731.4	61.6	6.1	10.1
47	(none)	(none)	1987	Base	Base	Optim.		45	729.5	63.5	6.1	10.5
47B	(none)	(none)	1987	Base	Base	Base		30	737.6	92.5	6.1	15.2
48	2020				-50%(c)	Optim.	(c)		513.7			
49	(none)				-50%(c)	Optim.	(c)		501.3			
50	(none)	2000	1987	Base	-50%(c)	Optim.	(c)	49	477.9	35.8	6.1	5.9
51	(none)	(none)	1987	Base	-50%(c)	Optim.	(c)	49	476.3	37.4	6.1	6.2
52	2000	2000	1987	Base	-50%(c)	Optim.	(c)	48	478.5	35.2	6.1	5.8

Footnotes listed at end of tables.

Table IV.D-3 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 5% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
53	(none)	2000	1987	+\$100(g)	Base	Optim.	(g)	45	782.9	10.1	6.1	1.7
54	(none)	(none)	1987	+\$100(g)	Base	Optim.	(g)	45	779.8	13.2	6.1	2.2
55	2000	2000	1987	+\$100(g)	Base	Optim.	(g)	5	784.6	48.1	6.1	7.9
56	(none)	2000	1987	+\$100(g)	-50%(c)	Optim.	(c)(g)	49	502.2	0.0	6.1	0.0
57	(none)	(none)	1987	+\$100(g)	-50%(c)	Optim.	(c)(g)	49	496.8	4.5	6.1	0.7
58	2000	2000	1987	+\$100(g)	-50%(c)	Optim.	(c)(g)	48	503.1	10.6	6.1	1.7
59	(none)				Base	Pessim.			882.4			
60	(none)	2000	1987	Base	Base	Pessim.		59	750.9	131.5	6.1	21.6
61	(none)	(none)	1987	Base	Base	Pessim.		59	745.3	137.1	6.1	22.6
62	2020				-50%(c)	Pessim.	(c)		569.7			
63	(none)				-50%(c)	Pessim.	(c)		536.9			
64	(none)	2000	1987	Base	-50%(c)	Pessim.	(c)	63	486.7	50.2	6.1	8.3
65	(none)	(none)	1987	Base	-50%(c)	Pessim.	(c)	63	483.1	53.8	6.1	8.9
66	2000	2000	1987	Base	-50%(c)	Pessim.	(c)	62	488.6	81.1	6.1	13.4

Footnotes listed at end of tables.

Table IV.D-3 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 5% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
67	(none)	2000	1987	+\$100(g)	Base	Pessim.	(g)	59	806.7	75.7	6.1	12.5
68	(none)	(none)	1987	+\$100(g)	Base	Pessim.	(g)	59	805.1	77.3	6.1	12.7
69	2000	2000	1987	+\$100(g)	Base	Pessim.	(g)	9	806.7	166.5	6.1	27.4
70	(none)	2000	1987	+\$100(g)	-50%(c)	Pessim.	(c)(g)	63	512.5	24.4	6.1	4.0
71	(none)	(none)	1987	+\$100(g)	-50%(c)	Pessim.	(c)(g)	63	512.8	24.1	6.1	4.0
72	2000	2000	1987	+\$100(g)	-50%(c)	Pessim.	(c)(g)	62	515.6	54.1	6.1	8.9
73	2020				Base	Base	(j)		982.1			
74	2000	2000	1987	Base	Base	Base	(j)	73	768.2	213.9	6.1	35.2
75	(none)				Base	Base	(j)		887.9			
76	(none)	2000	1987	Base	Base	Base	(j)	75	763.7	124.2	6.1	20.4

Footnotes listed at end of tables.

Table IV.D-4

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 7.5% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
1	2020				Base	Base			408.3			
2	1998	1998	1985	Base	Base	Base		1	352.3	56.0	5.5	10.1
3	2000	2000	1987	Base	Base	Base		1	354.4	53.9	5.3	10.2
4	2004	2004	1991	Base	Base	Base		1	361.1	47.2	5.4	8.8
5	2020				Base	Optim.			384.8			
6	1998	1998	1985	Base	Base	Optim.		5	349.2	35.6	5.5	6.4
7	2000	2000	1987	Base	Base	Optim.		5	350.6	34.2	5.3	6.5
8	2004	2004	1991	Base	Base	Optim.		5	355.1	29.7	5.4	5.5
9	2020				Base	Pessim.			439.8			
10	1998	1998	1985	Base	Base	Pessim.		9	349.7	90.1	5.5	16.3
11	2000	2000	1987	Base	Base	Pessim.		9	361.7	78.1	5.3	14.8
12	2004	2004	1991	Base	Base	Pessim.		9	374.8	65.0	5.4	12.1
13	2020				-20%(a)	Base			354.2			
14	1998	1998	1985	Base	-20%(a)	Base		13	313.5	40.7	5.5	7.4
15	2000	2000	1987	Base	-20%(a)	Base		13	315.4	38.8	5.3	7.3
16	2004	2004	1991	Base	-20%(a)	Base		13	322.3	31.9	5.4	6.0
17	2020				+20%(b)	Base			464.6			
18	1998	1998	1985	Base	+20%(b)	Base		17	391.2	73.4	5.5	13.3
19	2000	2000	1987	Base	+20%(b)	Base		17	393.6	71.0	5.3	13.4
20	2004	2004	1991	Base	+20%(b)	Base		17	402.7	61.9	5.4	11.5

Footnotes listed at end of tables.

Table IV.D-4 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 7.5% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			Benefit/Cost Ratio
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	
21	2000	2000	1987	+\$50(f)	Base	Base		1	364.4	43.9	5.3	8.3
22	2000	2000	1987	Base	Base	Base	(d)	1	356.3	52.0	5.3	9.8
23	2000	2000	1987	Base	Base	Base	(d)(e)	1	362.0	46.3	5.3	8.8
24	2000	2000	1987	Base	+20%(b)	Base	(d)	17	396.9	67.7	5.3	12.8
25	1998	1998	1985	Base	Base	Base	(e)	1	356.4	51.9	5.5	9.4
26	2000	2000	1987	Base	Base	Base	(e)	1	359.1	49.2	5.3	9.3
27	2004	2004	1991	Base	Base	Base	(e)	1	365.4	42.9	5.4	8.0
28	2000	2000	1987	Base	+20%(b)	Base	(e)	17	399.3	65.3	5.3	12.3
29	2000				Base	Base			393.4			
(3)	2000	2000	1987	Base	Base	Base		29	354.4	39.0	5.3	7.4
30	(none)				Base	Base			384.6			
31	(none)	2000	1987	Base	Base	Base		30	353.9	30.7	5.3	5.8
32	(h)				Base	Base	(h)		417.2			
33	(h)	2000	1987	Base	Base	Base	(h)	32	354.8	62.4	5.3	11.8
34	2020				Base	Base	(i)		699.8			
35	(h)				Base	Base	(h)(i)		665.2			
36	2000	2000	1987	Base	Base	Base	(i)	34	610.3	89.5	5.3	16.9
								35		54.9	5.3	10.4

Footnotes listed at end of tables.

Table IV.D-4 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 7.5% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
37	2020				A	Base	A		257.1			
38	2000	2000	1988	Base	A	Base	A	37	241.4	15.7	5.3	3.0
39	2020				B	Base	B		411.8			
40	2000	2000	1988	Base	B	Base	B	39	359.6	52.2	5.3	9.9
41	2020				C	Base	C		482.9			
42	2000	2000	1988	Base	C	Base	C	41	416.8	66.1	5.3	12.5
43	2020				D	Base	D		349.4			
44	2000	2000	1988	Base	D	Base	D	43	315.1	34.3	5.3	6.5
45	(none)				Base	Optim.			371.4			
46	(none)	2000	1987	Base	Base	Optim.		45	350.2	21.2	5.3	4.0
47	(none)	(none)	1987	Base	Base	Optim.		45	349.4	22.0	5.3	4.2
47B	(none)	(none)	1987	Base	Base	Base		30	352.6	32.0	5.3	6.0
48	2020				-50%(c)	Optim.	(c)		259.8			
49	(none)				-50%(c)	Optim.	(c)		255.7			
50	(none)	2000	1987	Base	-50%(c)	Optim.	(c)	49	247.6	8.1	5.3	1.5
51	(none)	(none)	1987	Base	-50%(c)	Optim.	(c)	49	247.0	8.7	5.3	1.6
52	2000	2000	1987	Base	-50%(c)	Optim.	(c)	48	248.1	11.7	5.3	2.2

Footnotes listed at end of tables.

Table IV.D-4 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 7.5% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
53	(none)	2000	1987	+\$100(g)	Base	Optim.	(g)	45	368.6	2.8	5.3	0.5
54	(none)	(none)	1987	+\$100(g)	Base	Optim.	(g)	45	366.7	4.7	5.3	0.9
55	2000	2000	1987	+\$100(g)	Base	Optim.	(g)	5	369.4	15.4	5.3	2.9
56	(none)	2000	1987	+\$100(g)	-50%(c)	Optim.	(c)(g)	49	256.5	0.0	5.3	0.0
57	(none)	(none)	1987	+\$100(g)	-50%(c)	Optim.	(c)(g)	49	253.8	1.9	5.3	0.4
58	2000	2000	1987	+\$100(g)	-50%(c)	Optim.	(c)(g)	48	257.1	2.7	5.3	0.5
59	(none)				Base	Pessim.			405.7			
60	(none)	2000	1987	Base	Base	Pessim.		59	359.4	46.3	5.3	8.8
61	(none)	(none)	1987	Base	Base	Pessim.		59	356.3	49.4	5.3	9.3
62	2020				-50%(c)	Pessim.	(c)		281.5			
63	(none)				-50%(c)	Pessim.	(c)		269.4			
64	(none)	2000	1987	Base	-50%(c)	Pessim.	(c)	63	252.3	17.1	5.3	3.2
65	(none)	(none)	1987	Base	-50%(c)	Pessim.	(c)	63	250.8	18.6	5.3	3.5
66	2000	2000	1987	Base	-50%(c)	Pessim.	(c)	62	253.2	28.3	5.3	5.4

Footnotes listed at end of tables.

Table IV.D-4 (Continued)

SUMMARY OF COST-BENEFIT STUDY RESULTS DISCOUNTED AT 7.5% TO MID-1974

Case	Constraints Imposed Until		LMFBR Introduction Date	LMFBR Capital Costs	Energy Demand	Uranium Supply	Notes	Comparison With Case No.	Billions of Dollars			
	(HTGR)	(LMFBR)							Energy ^(k) Cost	Gross Benefit	R&D Cost	Benefit/Cost Ratio
67	(none)	2000	1987	+\$100(g)	Base	Pessim.	(g)	59	379.0	26.7	5.3	5.0
68	(none)	(none)	1987	+\$100(g)	Base	Pessim.	(g)	59	378.0	27.7	5.3	5.2
69	2000	2000	1987	+\$100(g)	Base	Pessim.	(g)	9	379.3	60.5	5.3	11.4
70	(none)	2000	1987	+\$100(g)	-50%(c)	Pessim.	(c)(g)	63	261.2	8.2	5.3	1.6
71	(none)	(none)	1987	+\$100(g)	-50%(c)	Pessim.	(c)(g)	63	260.9	8.5	5.3	1.6
72	2000	2000	1987	+\$100(g)	-50%(c)	Pessim.	(c)(g)	62	262.7	18.8	5.3	3.6
73	2020				Base	Base	(j)		447.2			
74	2000	2000	1987	Base	Base	Base	(j)	73	370.5	76.7	5.3	14.5
75	(none)				Base	Base	(j)		413.9			
76	(none)	2000	1987	Base	Base	Base	(j)	75	369.9	44.0	5.3	8.3

Footnotes listed at end of tables.

Footnotes for Tables IV.D-1 through IV.D-4

- ^aReduced energy demand; 20% below probable demand in 2020.
- ^bIncreased energy demand; 20% higher than probable demand in 2020.
- ^cGreatly reduced demand; 50% lower than probable demand in 2020.
- ^d365 day post-irradiation cooling time assumed for LMFBR fuel.
- ^eCarbide-fueled breeder assumed not to be available.
- ^fLMFBR capital costs remain \$50/kW higher than LWR costs after 2000.
- ^gLMFBR capital costs remain \$100/kW higher than LWR costs after 2000.
- ^hNo HTGR's assumed to be introduced past 1982.
- ⁱFossil fueled plants included.
- ^jSeparative work charge of \$75/SWU assumed.
- ^kEnergy costs include accumulated costs of electrical energy from 1974 to 2020, plus costs to end-of-life of plants in service in 2020. Taxes on property, income, and gross revenue are excluded. Energy costs are discounted to mid-1974 at the discount rate indicated in the table heading.
- ^lLMFBR capital costs are \$200/kW higher than LWR costs at introduction; decrease to a \$50/kW differential in 2000 and afterward.

- A Data from alternate energy projection A, WASH-1139 (74)
- B Data from alternate energy projection B, WASH-1139 (74)
- C Data from alternate energy projection C, WASH-1139 (74)
- D Data from alternate energy projection D, WASH-1139 (74)