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The Economics and Utilization of Thorium in Nuclear Reactors

Technical Annexes 1 and 2

Prepared by
Resource Planning Associates, Inc.
44 Brattle Street
Cambridge, Massachusetts 02138
Subcontract No. 7233

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THE ECONOMICS AND UTILIZATION
OF THORIUM IN NUCLEAR REACTORS

TECHNICAL ANNEXES 1 AND 2

Prepared by

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44 Brattle Street
Cambridge, Massachusetts 02138

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Department of Energy
Washington, D. C. 20545

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ANNEX 1

THORIUM ASSESSMENT PROGRAM SYSTEMS STUDIES

D. R. Haffner, W. E. Black, W. G. Jolly,
T. M. Helm, R. W. Hardie, and R. P. Omberg

February 27, 1978

HANFORD ENGINEERING DEVELOPMENT LABORATORY

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THORIUM ASSESSMENT PROGRAM SYSTEMS STUDIES

D. R. Haffner, W. E. Black, W. G. Jolly, T. M. Helm,
R. W. Hardie, and R. P. Omberg

A. INTRODUCTION

An assessment of the impact of utilizing the U-233/thorium fuel cycle in the U.S. nuclear economy is strongly dependent upon several decisions involving nuclear energy policy. These decisions include: (1) to recycle or not recycle fissile material; (2) if fissile material is recycled, to recycle plutonium, U-233, or both; and (3) to deploy or not to deploy advanced reactor designs such as Fast Breeder Reactors (FBR's), High Temperature Gas Reactors (HTGR's), and Canadian Deuterium Uranium Reactors (CANDU's). This report examines the role of thorium in the context of the above policy decisions while focusing special attention on economics and resource utilization.

The analysis was performed at the Hanford Engineering Development Laboratory (HEDL) using the ALPS mathematical model of the electrical energy system. The scenarios selected for investigation were developed in a series of meetings attended by Combustion Engineering (CE), Resource Planning Associates (RPA), Oak Ridge National Laboratory (ORNL), Nuclear Research and Applications (NRA/ERDA), and HEDL. The input data, including both reactor design characteristics and nuclear energy system economic parameters, were developed as a result of a cooperative effort by ORNL, United Engineers and Constructors (UE & C), Argonne National Laboratory (ANL), General Atomic (GA), Uranium Resources and Evaluation (URE/ERDA), CE, RPA, NRA/ERDA and HEDL.

B. DESCRIPTION OF ANALYTICAL MODEL

The basic components of the ALPS mathematical model⁽¹⁾ of the electrical energy system are shown in Figure B.1. The model is based on the linear programming technique and evaluates the effect of nuclear policy decisions by computing nuclear and fossil power growth patterns. Given a nuclear energy policy, the model determines the nuclear and fossil power growth pattern which minimizes the total cost of generating electricity over the planning horizon. In addition to minimizing the electrical generation cost, the following set of constraints are also satisfied.

Total Energy Demand

The total number of nuclear plus fossil plants built must be sufficient to meet the total energy demand.

HEDL 7703-067

FIGURE B.1: THE ALPS ELECTRICAL POWER ECONOMY SUPPLY MODEL

Regional Energy Demand and Fossil Fuel Costs

The U.S. is divided into nine regions, each with a unique fossil fuel cost. Nuclear units are thereby forced to compete directly against localized fossil energy sources.

Uranium Ore Supply

The long-run marginal cost of uranium ore is computed as a piecewise-constant function of the cumulative amount of ore mined. This accounts for the increasing cost of ore as the lower grade ore is consumed.

Fissile Fuel Supply

A nuclear unit cannot be built unless an adequate supply of fissile fuel (fissile Pu and U233) is available throughout the lifetime of the unit.

Introduction Constraint for a New Technology

A nuclear plant design which differs from established technology can only be introduced at a limited rate. A typical maximum introduction rate is 1 plant during the first biennium, 2 plants during the second biennium, 4 during the third, 8 during the fourth, etc.

Market Loss Constraint for an Established Technology

If the manufacturing capability to produce a particular reactor type has been established, the rate at which this reactor type will lose its share of the market is limited to a specified percent/year. A typical maximum phase-out rate is 10%/year. This reflects the fact that some utilities will continue to purchase plants of an established technology, even though a new technology may be more economical.

A schematic diagram of the nuclear fuel cycle model contained in ALPS is shown in Figure B.2. Charge and discharge data are required for

HEDE 7511-83.2

FIGURE B.2: NUCLEAR FUEL CYCLE MODEL

each reactor in each year of operation for the following six nuclear fuel items:

- Th232
- U233
- U235
- U238
- Fissile Pu
- Total Heavy Metal.

The demand for uranium ore (U₃O₈) and separative work (SWU) is computed from the U-235 and U-238 charge information. Likewise, the U₃O₈ and SWU spent fuel credits are computed from the discharge information. Fabrication and reprocesssing costs are calculated utilizing the total heavy metal entries

and the unit fabrication and reprocessing costs in the input data. U-233 and fissile plutonium charge requirements deplete the U-233 and fissile plutonium stockpiles, while U-233 and fissile plutonium discharges increase the stockpiles.

For fossil plants, the fuel cycle model consists simply of the product of the amount of coal purchased per year times the unit price of coal.

The capacity factor of the fossil and nuclear plants is assumed to vary over the lifetime of the plants, and consequently the six nuclear fuel cycle items and the coal usage per year will also vary.

The total levelized power cost and its components are calculated by ALPS for each power plant available. The components which are calculated are:

Capital

The capital cost component includes both depreciating and non-depreciating capital costs and also takes salvage value, if any, into account.

Fixed Charges

Capital replacements, property insurance, and property taxes are contained in the fixed charge component.

Operation and Maintenance

The operation and maintenance component includes both fixed and variable O & M charges, as well as nuclear liability insurance for nuclear plants.

Gross Revenue Tax

The gross revenue tax is simply the gross revenue tax rate times the total revenue.

Income Tax

The income tax component is obtained by multiplying the income tax rate by the non-deductible expenses.

Fuel

For nuclear plants, the fuel costs are further divided into ThO_2 , U_3O_8 , U-233, fissile plutonium, enrichment, fabrication, and reprocessing components. The fuel cost for fossil units is limited to the cost of purchasing coal.

C. DESCRIPTION OF REACTOR DATA

The reactor characteristics for this study were supplied by CE, GA, ANL, and HEDL. Four general types of reactors were included-- LWR's, represented by Pressurized Water Reactors (PWR's); HWR's, represented by Canadian Deuterium Uranium Reactors (CANDU's); High Temperature Gas Reactors (HTGR's); and Fast Breeder Reactors (FBR's). CE and HEDL provided the data for the PWR's. ANL supplied the data for the CANDU's, GA supplied the data for the HTGR's, and HEDL supplied the data for the FBR's. A list of the reactors included in this study, the power level, and the organization providing the reactor data is shown in Table C.1. Reference 2 contains detailed design data for most of the reactors in this study. The report also includes fuel inventory data used by the ALPS model.

The PWR designs included low-enriched and denatured U-235 fueled reactors, denatured U-233 fueled reactors, and Pu fueled reactors. The diluent consisted of either U-238 or Th, or both for the denatured designs.

In addition to the above PWR designs, three spectral-shift control PWR designs (SSCR's) were included. These were a low-enriched U-235 fueled reactor, a denatured U-233 fueled reactor, and a Pu/Th fueled reactor.

Table C.1

DESCRIPTION OF REACTORS IN THORIUM ASSESSMENT PROGRAM

Name	Power Level (MWe)	Introduction Date	RDC* Label	Fuel Cycle Description	Organization Providing Data
LWR-U5 (LE)/U	1150	1969	PWR-U5 (LE)/U	Low-enriched U-235/U-238 fuel	HEDL
-U5 (LE)/U-T	1150	1981	PWR-U5 (LE)/U-T	Low-enriched U-235/U-238 fuel; optimized for throwaway	HEDL
-U5 (DE)/U/Th	1150	1987	PWR-U5 (DE)/U/Th-20%	Denatured U-235 fuel (20%) in U-238 with thorium feed	HEDL
-U3 (DE)/U/Th	1150	1991	PWR-U3 (DE)/U/Th-12%	Denatured U-233 fuel (12%) in U-238 with thorium feed	HEDL
-Pu/U	1150	1991	PWR-Pu/U	Recycled plutonium fuel in natural uranium diluent	HEDL
-Pu/Th	1300	1991	PWR-Pu/Th	Recycled plutonium fuel in thorium diluent	CE
SSCR-U5 (LE)/U	1300	1991	PWR-U5 (LE)/U-SS	Low-enriched U-235/U-238 fuel with Spectral Shift Control Reactor	CE
-U3 (DE)/U/Th	1300	1991	PWR-U3 (DE)/U/Th-SS, 12% [†]	Denatured U-233/U-238 (12%) plus Th-232 feed, Spectral Shift Con- trol Reactor	CE
-Pu/Th	1300	1991	PWR-Pu/Th-SS [†]	Pu/Th-232 feed, Spectral Shift Control Reactor	CE
HWR-U5 (NAT)/U	1000	1995	CANDU-U5 (NAT)/U	Natural uranium fuel	ANL
-U5 (SEU)/U	1000	1995	CANDU-U5 (SE)/U	Slightly enriched uranium fuel (~1% U-235)	ANL
-U5 (DE)/U/Th	1000	1995	CANDU-U5 (DE)/U/Th-20%	Denatured U-235/U-238 fuel (20%) plus thorium	ANL
-U3 (DE)/U/Th	1000	1995	CANDU-U3 (DE)/U/Th-12%	Denatured U-233 fuel (12%) in U-238 plus thorium with U-233 self-generated recycle	ANL
-Pu/U	1000	1995	CANDU-Pu/U	Plutonium fuel in natural uranium	ANL
-Pu/Th	1000	1995	CANDU-Pu/Th	Plutonium fuel in thorium	ANL

Table C.1

DESCRIPTION OF REACTORS IN THORIUM ASSESSMENT PROGRAM
(CONT'D.)

Name	Power Level (MWe)	Introduction Date	RDC* Label	Fuel Cycle Description	Organization Providing Data
HTGR-U5(LE)/U-T	1344	1995	HTGR-U5(LE)/U-T	Low-enriched U-235/U-238 fuel; optimized for throwaway	GA
-U5(LE)/U	1344	1995	HTGR-U5(LE)/U	Low-enriched U-235/U-238 fuel; optimized for recycle	GA
-U5(DE)/U/Th	1344	1995	HTGR-U5(DE)/U/Th-20%	Denatured U-235 fuel (20%) in U-238 plus thorium; optimized for recycle	GA
-U5(HE)/Th	1344	1995	HTGR-U5(HE)/Th	High-enriched U-235 fuel plus thorium	GA
-U3(DE)/U/Th	1344	1995	HTGR-U3(DE)/U/Th-15%	Denatured U-233 fuel (15%) in U-238 plus thorium; optimized for recycle	GA
-U3/Th	1344	1995	HTGR-U3/Th	U-233 and thorium fuel with U-233 self-generated recycle	GA
-Pu/Th	1344	1995	HTGR-Pu/Th	Plutonium plus thorium fuel	GA
FBR-Pu-U/U	1200	2001	LMFBR-Pu/U/U/U-LT	Pu/U-238 core feed and U-238 blanket feed; low temperature design, oxide fuel	HEDL
-Pu-U/Th	1200	2001	LMFBR-Pu/U/Th/Th-LT	Pu/U-238 core feed and Th-232 blanket feed; low temperature design, oxide fuel	HEDL

*Reactor design documented in "Reactor Design Characteristics and Fuel Inventory Data", HEDL-TC-971, (Oct. 1977)

†Reactor data not received in time for inclusion in original RDC document

The CANDU designs were represented by three U-235 fueled reactors (natural, slightly-enriched, and denatured), a denatured U-233 fueled reactor, a Pu/U-238 reactor, and a Pu/Th reactor.

HTGR designs consisted of low-enriched, denatured, and high-enriched U-235 fueled reactors, denatured and high-enriched U-233 fueled reactors, and a Pu/Th reactor.

The FBR designs included two plutonium fueled versions, one having a uranium blanket and the other a thorium blanket.

Introduction dates for each reactor type are also given in Table C.1. A slight modification to an existing PWR fuel design, such as a thicker fuel pin cladding to increase discharge exposure, was introduced in 1981. A more extensive modification, such as a denatured U-235 PWR fuel pin, was delayed until 1987. The remaining PWR designs, including the spectral-shifts, were introduced in 1991. The HWR's and HTGR's were all introduced in 1995 while the FBR's were not introduced until 2001.

Finally, Table C.2 presents the key nuclear characteristics for each reactor design included in the study. In particular, lifetime U_3O_8 and separative work requirements and equilibrium fabrication requirements, discharge exposures, conversion ratios, fissile plutonium flows, and fissile U-233 flows are given. The table shows that, for the throwaway cycle, low-enriched HTGR's offer significant (almost 20%) uranium ore savings compared to low-enriched PWR's. Similarly, slightly-enriched CANDU's reduce uranium ore requirements by an additional 25% over HTGR's and more than 35% over PWR's. Although low-enriched PWR's and HTGR's, have roughly the same enrichment requirements, the slightly enriched CANDU's require 5-6 times less enrichment. Core discharge exposures for

Table C.2

Reactor	REACTOR CHARACTERISTICS								
	Lifetime Reactor U ₃ O ₈ Requirements (tons U ₃ O ₈ /GWe)			Lifetime Reactor Enrichment Requirements (10 ⁶ Kg SWU/GWe)			Equilibrium Fabrication Requirements (MT 1M/GWe-yr)	Equilibrium Core Dschr. Exposure (MWD/Kg)	Equilibrium Breeding or Conversion Ratio
	Charge	Discharge	Net	Charge	Discharge	Net			
LMR-US (LE)/U	5183	1169	4014	3.08	0.17	2.91	25.8	30	0.60
US (LE)/U-T	4855	0	4855	3.08	0	3.08	18.2	43	0.54
US (DE)/U/Th	8753	3341	4911	7.95	3.23	4.71	24.1	33	0.66
U3 (DE)/U/Th	0	0	0	0	0	0	24.1	32	0.80
Pu/U	941	0	941	0	0	0	25.7	30	0.70
Pu/Th	0	0	0	0	0	0	22.6	33	-
SSCR-US (LE)/U	4352	917	3435	2.40	0.05	2.35	25.3	30	-
U3 (DE)/U/Th	0	0	0	0	0	0	23.0	33	-
Pu/Th	0	0	0	0	0	0	23.0	33	-
LMR-US (NAT)/U	4114	0	4114	0	0	0	114.9	7.5	-
US (SEU)/U	3155	0	3155	0.59	0	0.59	53.9	16	-
US (DE)/U/Th	7264	2426	4837	6.59	1.95	4.64	53.9	16	-
U3 (DE)/U/Th	0	0	0	0	0	0	53.9	16	-
Pu/U	2010	0	2010	0	0	0	53.9	16	-
Pu/Th	0	0	0	0	0	0	53.9	16	-
LMR-US (LE)/U-T	4272	0	4272	3.32	0	3.32	8.2	80	0.55
US (LE)/U	4040	563	3477	3.19	0.18	3.01	7.2	91	0.53
US (DE)/U/Th	4269	812	3457	3.87	0.59	3.28	6.3	104	0.60
US (DE)/Th	3864	564	3300	3.85	0.56	3.30	8.9	74	0.67
U3 (DE)/U/Th	0	0	0	0	0	0	10.4	63	0.76
U3/Th	0	0	0	0	0	0	14.0	47	0.86
Pu/Th	0	0	0	0	0	0	3.4	196	0.62
FBR-Pu-U/U	0	0	0	0	0	0	12.7/5.1/7.1*	62	1.36
Pu-U/Th	0	0	0	0	0	0	12.7/4.6/6.4	62	1.34

*Core/Rad. Blkt./Ax. Blkt.

Table C.2
(CONT'D)

REACTOR CHARACTERISTICS

Reactor	Average* Fissile Plutonium Mass Flows (Kg/GWe-yr)			Average* U-233 Mass Flows (Kg/GWe-yr)		
	Charge	Discharge	Net	Charge	Discharge	Net
LMR-US (LE)/U	0	146.8	146.8	0	0	0
U5 (LE)/U-T	0	0	0	0	0	0
U5 (DE)/U/Th	0	77.8	77.8	0	256.2	256.2
U3 (DE)/U/Th	0	88.2	88.2	807.0	530.4	-276.6
Pu/U	700.6	472.2	-228.4	0	0	0
Pu/Th	1294.1	620.2	-673.9	0	239.0	239.0
SSCR-US (LE)/U	0	185.0	185.0	0	0	0
U3 (DE)/U/Th	0	72.9	72.9	619.9	426.2	-193.7
Pu/Th	1202.3	556.4	-645.9	0	281.2	281.2
LMR-US (NAT)/U	0	290.4	290.4	0	0	0
U5 (SEU)/U	0	159.8	159.8	0	0	0
U5 (DE)/U/Th	0	22.5	22.5	0	418.2	418.2
U3 (DE)/U/Th	0	26.9	26.9	765.8	664.7	-101.1
Pu/U	156.6	177.7	21.1	0	0	0
Pu/Th	895.5	234.4	-661.1	0	391.9	391.9
LMGR-US (LE)/U-T	0	0	0	0	0	0
U5 (LE)/U	0	52.4	52.4	0	0	0
U5 (DE)/U/Th	0	31.2	31.2	0	104.6	104.6
U5 (DE)/Th	0	1.0	1.0	0	186.9	186.9
U3 (DE)/U/Th	0	33.1	33.1	489.5	264.9	-224.6
U3/Th	0	0	0	501.5	389.0	-112.5
Pu/Th	637.0	126.7	-510.3	0	94.1	94.1
FBR-Pu-U/U	1253	1526	273.3	0	0	0
Pu-U/Th	1261	1283	21.9	0	237.5	237.5

*Lifetime average with 1% fabrication and 1% reprocessing losses.

FBR's are approximately twice the exposures of PWR's while CANDU's exposures are about half the PWR's exposures. HTGR discharge exposures are extremely large--nearly 200 MWd/Kg for the Pu/Th fuel design.

D. DESCRIPTION OF ECONOMIC DATA

The economic data base used in the thorium assessment program was jointly developed by CE, ORNL, UE & C, ANL, RPA, HEDL, URE/ERDA, and NRA/ERDA. The data base includes capital costs, operation and maintenance costs, fabrication and reprocessing costs, capacity factors, money costs, estimates of projected electrical generation, regional coal data, and construction cash flow data.

The deflated and present-valued capital costs excluding interest during construction for LWR's, SSCR's, HTGR's, CANDU's, and FBR's are shown in Table D.1. The same capital costs including interest during construction are shown in Table D.2. In either case, the stream of

Table D.1

CAPITAL COSTS
(7/1/76 \$/kWe not including IDC)

<u>Power Plant Type</u>	<u>Capital Costs</u>
LWR	500 ⁽¹⁾
LWR-spectral shift	520 + 38 (heavy water) = 558 ⁽²⁾
HTGR	560 to 580 ⁽¹⁾
CANDU	605 + 156 (heavy water) = 761 ⁽¹⁾
FBR	625 to 650 ⁽¹⁾

(1) Supplied by United Engineers and Constructors

(2) Supplied by Combustion Engineering

Table D.2

CAPITAL COSTS
(1/1/77 \$/kWe including IDC)

<u>Power Plant Type</u>	<u>Capital Cost</u>
LWR	625
LWR-spectral shift	$650 + 40 \text{ (heavy water)} = 690$
HTGR	715
CANDU	$755 + 160 \text{ (heavy water)} = 915$
FBR	800
Coal	
with scrubber	550
without scrubber	475

expenses incurred during the construction of the plant is discounted to the date of start-up and is measured in dollars of constant purchasing power. The capital cost of the SSCR--including the initial heavy water inventory--was assumed to be 10% greater than that of the standard LWR. The capital cost of the dry CANDU--i.e., excluding the initial heavy water inventory--was assumed to be 21% greater than that of the standard LWR, and the capital cost of the wet CANDU was assumed to be 46% greater than that of the standard LWR. The capital cost of the FBR was assumed to be 25% greater than that of the standard LWR. The capital cost of a coal unit without scrubbers was assumed to be 24% less than that of the standard LWR, while the capital cost of a coal unit with scrubbers was assumed to be 12% less than that of the standard LWR. The cost of scrubbers was assumed to be 75 \$/kwe and 5% of the power generated by the plant was assumed to be consumed in their operation.

The operation and maintenance costs for the same power plants are shown in Table D.3. The operation and maintenance costs for the SSCR and the CANDU are higher than the standard LWR because of the heavy water replacement requirement and because of the necessity to perform some maintenance in atmospheres containing tritium.

The fabrication costs for the PWR, SSCR, HTGR, CANDU, and FBR are shown in Table D.4. The fabrication costs for the PWR and the SSCR were based on the standard 17 x 17 pin assembly with a fuel pin of 374 mils in outer diameter. The fabrication costs for the HTGR were based on the standard carbon-coated uranium carbide fissile microsphere subsequently formed into cylindrical rods and located in a hexagonal graphite block. The fabrication costs for the CANDU were based on a 37 pin assembly approximately 20 inches long with a fuel pin of 531 mils in outer diameter. The fabrication costs for the FBR were based on a 217 pin assembly in a

Table D.3

OPERATION AND MAINTENANCE COSTS
(1/1/77 \$/kWe-year)

<u>Power Plant Type</u>	<u>Fixed</u>	<u>Variable*</u>
LWR	3.6	1.9
HTGR	3.6	1.9
CANDU	7.2	3.8
FBR	4.1	2.3
Coal		
with scrubber	4.2	11.7
without scrubber	4.0	4.8

*Must be multiplied by the capacity factor for given year

Table D.4
Fabrication Costs
(1/1/77 \$/kg HM)

Reactor Type	Cost (year) Schedule
PWR	
LE U5-U8	100 (1969 + 2089)
DE U5-U8-Th	230 (1987) + 140 (1997)
Pu-U	550 (1991) + 340 (2001)
Pu-Th	550 (1991) + 340 (2001)
DE U3-U8-Th	880 (1991) + 550 (2001)
SSCR	
LE U5-U8	100 (1991 + 2089)
DE U5-U8-Th	230 (1991) + 140 (2001)
Pu-U	550 (1991) + 340 (2001)
Pu-Th	550 (1991) + 340 (2001)
DE U3-U8-Th	880 (1991) + 550 (2001)
HTGR	
HE U5-U8-Th	
C/Th + U = 150	340 (1995) + 210 (2005)
C/Th + U = 238	500 (1995) + 300 (2005)
C/Th + U = 335	660 (1995) + 400 (2005)
C/Th + U = 400	760 (1995) + 470 (2005)
C/Th + U = 650	1220 (1995) + 770 (2005)
DE U5-U8-Th	
C/Th + U = 150	340 (1995) + 210 (2005)
C/Th + U = 238	500 (1995) + 300 (2005)
C/Th + U = 335	660 (1995) + 400 (2005)
C/Th + U = 400	760 (1995) + 470 (2005)
C/Th + U = 650	1220 (1995) + 770 (2005)
HE U3-U8-Th	
C/Th + U = 150	860 (1995) + 470 (2005)
C/Th + U = 238	1220 (1995) + 670 (2005)
C/Th + U = 335	1640 (1995) + 900 (2005)
C/Th + U = 400	2000 (1995) + 1100 (2005)
C/Th + U = 650	3200 (1995) + 1750 (2005)
DE U3-U8-Th	
C/Th + U = 150	860 (1995) + 470 (2005)
C/Th + U = 238	1220 (1995) + 670 (2005)
C/Th + U = 335	1640 (1995) + 900 (2005)
C/Th + U = 400	2000 (1995) + 1100 (2005)
C/Th + U = 650	3200 (1995) + 1750 (2005)
Pu-Th	
C/Th = 238	1220 (1995) + 670 (2005)
CANDU	
NAT U5-U8	60 (1995 + 2089)
SE U5-U8	60 (1995 + 2089)
HE U5-U8-Th	140 (1995) + 85 (2005)
DE U5-U8-Th	140 (1995) + 85 (2005)
Pu-U	320 (1995) + 200 (2005)
Pu-Th	320 (1995) + 200 (2005)
DE U3-U8-Th	560 (1995) + 350 (2005)
FBR	
Pu-U8 core (oxide)	1750 (2001) + 950 (2011)
Pu-Th core (oxide)	1750 (2001) + 950 (2011)
U3-U8 core (oxide)	3000 (2001) + 1650 (2011)
U8 axial blanket (oxide)	35 (2001) + 25 (2011)
U8 radial blanket (oxide)	250 (2001) + 150 (2011)
Th axial blanket (oxide)	35 (2001) + 25 (2011)
Th radial blanket (oxide)	250 (2001) + 150 (2011)

hexagonal duct with a fuel pin of 310 mils in outer diameter. The fabrication costs are shown for both the standard and alternate fuel designs, with a low-enriched fuel denoted by LE, a high-enriched fuel denoted by HE, and a denatured fuel denoted by DE. The costs are shown as a function of time beginning with the expected introduction date for a particular reactor and fuel design. If a particular reactor and fuel design should prove successful, fabrication costs should decrease as larger plants with higher throughput rates are constructed. The decrease in fabrication costs over the first decade after introduction as shown in Table D.4 is simply indicative of a transition from small fabrication plants with high unit costs to larger fabrication plants with lower unit costs. The fabrication costs in Table D.4 are a strong function of the fissile isotope and a weak function of the fertile isotope. The sensitivity to the fissile isotope is caused by either the spontaneous fission associated with high-exposure fissile plutonium or the gamma activity associated with high-exposure U-233. The costs are based on the assumption that fuels containing U-235 are fabricated on a line with contact operation and contact maintenance, while fuels containing fissile plutonium are fabricated on a line with remote operation and contact maintenance, and fuels containing U-233 are fabricated on a line with remote operation and remote maintenance.

The expected reprocessing costs are shown in Table D.5. These costs were obtained by estimating the capital and operating costs associated with each of five stages of the reprocessing process. The stages were: headend, solvent extraction, product conversion, off-gas treatment, and waste treatment. The costs are shown as a function of time reflecting the transition from a new industry consisting of small plants with high unit costs to a mature industry consisting of

Table D.5

Reprocessing Costs*
(\$/kg HM)

<u>Reactor Type</u>	<u>Cost (year) Schedule</u>
LWR	225 (1991) + 150 (2001)
SSCR	225 (1991) + 150 (2001)
HTGR	800 (1995) + 400 (2005)
CANDU	225 (1995) + 150 (2005)
FBR	500 (2001) + 200 (2011)

*Does not include spent fuel shipping costs, waste shipping costs, or waste storage costs.

larger plants with lower unit costs. The expected cost for spent fuel shipping, waste shipping, and waste storage is shown in Table D.6.

The sum of the reprocessing cost, the spent fuel shipping cost, the waste shipping cost, and the waste storage was defined as the total reprocessing cost, and this is shown in Table D.7. The cost of throwaway without reprocessing is also shown in Table D.7.

The long-run marginal cost of U_3O_8 as a function of the cumulative amount mined is shown in Table D.8. Two projections are shown in the table--viz, a small supply and a large supply. The small supply is based on the assumption that 2.3 million tons of U_3O_8 will be available from conventional uranium ore resources, while the large supply is based on the assumption that 4.2 million tons of U_3O_8 will be available from conventional resources. In either case, the shales are assumed to be mined after the conventional resources are depleted. The cost of extracting

Table D.6

SHIPPING AND WASTE STORAGE COSTS
(\$/kg HM)

<u>Reactor Type</u>	<u>Spent Fuel Shipping Costs*</u>	<u>Waste Shipping Costs</u>	<u>Waste Storage Costs</u>
LWR	15	10	40
HTGR	70	10	40
CANDU	15	10	40
FBR	45	10	40

*Throwaway includes shipping plus \$100/kg HM permanent spent fuel storage

Table D.7

TOTAL REPROCESSING COSTS*
(\$/kg HM)

<u>Reactor Type</u>	<u>Cost (year) Schedule</u>	<u>Throwaway Cost Schedule</u>
LWR	290 (2001) + 215 (2011)	125
HTGR	920 (2001) + 520 (2011)	180
CANDU	290 (2001) + 215 (2011)	125
FBR	545 (2001) + 295 (2011)	155

*Total reprocessing costs include spent fuel shipping costs, reprocessing costs (\$100/kg HM for throwaway cycle), waste shipping costs, and waste storage costs.

Table D.8
 U_3O_8 Assumptions

Large U_3O_8 Supply		Small U_3O_8 Supply	
Quantity of U_3O_8 10 ⁶ tons	Long-Run Marginal Cost \$/lb	Quantity of U_3O_8 10 ⁶ tons	Long-Run Marginal Cost \$/lb
0.0 - 0.25	14	0.0 - 0.25	14
0.25 - 0.75	23	0.25 - 0.75	24
0.75 - 1.25	33	0.75 - 1.25	35
1.25 - 1.75	44	1.25 - 1.75	54
1.75 - 2.5	53	1.75 - 2.25	84
2.5 - 3.5	61	2.25 - 2.75	128
3.5 - 4.25	80	2.75 - 3.25	158
4.25 - 4.75	107	3.25 - 3.75	173
4.75 - 5.25	128	3.75 - 4.25	180
5.25 - 5.75	143	4.25 - 4.75	180
5.75 - 8.5	165	4.75 - 6.5	210
above 8.5	180	above 6.5	240

the shales increases from 125 \$/lb to 240 \$/lb for the small supply case, while the cost of extracting the shales increases from 100 \$/lb up to 180 \$/lb for the large supply case.

The enrichment cost and tails composition assuming a continuation of the gaseous diffusion technology is shown in Table D.9. If the gaseous diffusion technology is continued, it was assumed that the tails composition will be stabilized at 0.0020 and that the cost of

enrichment will increase to 80 \$/SWU in 1987 and remain constant thereafter.

Additional data pertaining to fabrication, reprocessing, and minor reactor costs are shown in Table D.10. The first reprocessing

Table D.9
Enrichment Cost and Tails Composition

<u>Year</u>	<u>Tails Composition</u>	<u>Cost</u>
1969 to 1976	0.0020	50 \$/SWU
1977 to 1986	0.0020	75 \$/SWU
1987 to 2089.	0.0020	80 \$/SWU

Table D.10
Additional Data

Fabrication and Reprocessing

Reprocessing Introduction Data	1991
Out-of-Reactor Time (fabrication lead time + reprocessing lag time)	2 years with reprocessing, and extended to after 1991 prior to reprocessing
Fissile Storage Charges After Reprocessing	2 \$/g-yr for ^{233}U and fissile plutonium
Cost of Converting U_3O_8 to UF_6	\$3.50/kg of U

Minor Reactor Costs

Property Insurance Rate	0.0025
Capital Replacement Rate	0.0035
Nuclear Liability	580×10^3 \$/yr

plant is assumed to be in operation in 1991--provided a policy decision has been made to reprocess spent fuel. All fuel discharged from the reactor prior to reprocessing is assumed to be stored, and the spent fuel stockpile is reduced in an orderly manner after the advent of reprocessing. The out-of-reactor time required for reprocessing and refabrication is assumed to be two years after the spent fuel stockpile has been reduced to zero.

The capacity factor of a plant as a function of time throughout its thirty year life is shown in Table D.11. The capacity factor increases from 60% to 72% during the first three years of operation, and remains at 72% during the subsequent fourteen years. The capacity factor then decreases continuously as the forced outage rate increases and as the plant is shifted from a base-load unit to an intermediate-load unit.

The long-term real cost of money to the electric utility industry is shown in Table D.12. These costs were developed by analyzing the deflated cost of debt and equity to the industry over the past thirty years. The long-term deflated cost of debt has been 2.5 %/yr and the long-term deflated cost of equity has been 7.0 %/yr. Assuming the industry to be funded at approximately 55% debt and 45% equity, the long-term real money cost is approximately 4.5 %/yr.

The projected electrical generation from 1975 to 2030 including both nuclear and fossil is shown in Table D.13. The energy requirement is based on the assumption of a growth rate of 5.6 %/yr between 1975 and 1980 continuously decreasing thereafter to 2.5 %/yr between 2020 and 2030. This energy projection assumes 5% of the energy is produced by peaking generation plants.

Table D.11
Plant Capacity Factors

<u>Year</u>	<u>Capacity Factor, %</u>
1	60.0
2	66.0
3	72.0
4	72.0
.	.
.	.
.	.
15	72.0
16	72.0
17	70.4
18	68.9
19	67.3
20	65.7
21	64.1
22	62.6
23	61.0
24	59.4
25	57.9
26	56.3
27	54.7
28	53.1
29	51.6
30	50.0

Table D.12
Money Costs

Debt Interest	2.5%
Equity Interest	7.0%
Percent Debt	0.55
Percent Equity	0.45
Effective Interest Rate	4.525%

Table D.13

Projected Total Electrical Generation

<u>Year</u>	<u>Energy Demand (10¹² KWH)</u>	<u>Energy Growth Rate (%)</u>
1975	1.9	5.6
1980	2.5	
1990	4.1	5.1
2000	6.1	4.1
2010	8.6	3.5
2020	11.6	3.0
2030	14.9	2.5

The relative amount of electric energy consumed in the U.S. by geographical region is shown in Table D.14. This information, along with the average cost and heat content of the coal utilized in the same regions, is used to characterize the principal competitor to nuclear energy. The average cost and heat content of the coal utilized by region as a function of time are shown in Table D.15. The cost of coal ranges from a low value of 6.04 \$/ton at 6,600 Btu/lb in the West South Central Region to a high value of 33.89 \$/ton at 13,500 Btu/lb in the Northeast Region. The real cost of coal was assumed to be constant as a function of time.

Tables D.16 - D.18 are used for capital requirements analysis. Capital cost cash flows representing the stream of payments during the construction period are shown in Table D.16. Capital costs for fabrication, re-processing and enrichment facilities and for uranium and thorium mines are given in Tables D.17 and D.18.

Table D.14

Percent of Total U.S. Electrical Sales
by FPC Consuming Region

	<u>1975</u>	<u>1974</u>
New England (NE)	3.9	3.9
Middle Atlantic (MA)	13.1	13.5
East North Central (ENC)	19.5	19.7
West North Central (WNC)	6.6	6.4
South Atlantic (SA)	16.6	16.5
East South Central (ESC)	9.6	9.6
West South Central (WSC)	12.2	12.0
Mountain (MT)	4.9	4.9
Pacific (PA)	13.5	13.4

Table D.15

Projected Coal Costs and Heat Content by FPC Consuming Region

<u>Region</u>	<u>Coal Price*</u> <u>(1977 \$/ton)</u>	<u>Heat Content</u> <u>(BTU/lb)</u>
New England (NE)	33.89	13,500
Middle Atlantic (MA)	24.11	11,783
East North Central (ENC)	19.37	10,711
West North Central (WNC)	12.76	9,408
South Atlantic (SA)	24.36	11,855
East South Central (ESC)	19.83	11,006
West South Central (WSC)	6.04	6,583
Mountain (MT)	7.15	9,637
Pacific (PA)	12.35	8,101

*Assumed to be constant as a function of time.

Table D.16

CAPITAL COST CASH FLOWS
(Fraction of Capital Spent per Year)

Years Before Start-up Date	Industry				
	Fossil Plants	Nuclear Plants	Fabrication & Reprocessing Plants	Enrichment Plants	ThO ₂ & U ₃ O ₈ Mines
1	.080	.050	.10	.10	.10
2	.230	.090	.45	.20	.20
3	.372	.200	.30	.25	.25
4	.208	.240	.10	.20	.20
5	.085	.187	.05	.15	.15
6	.025	.128	.0	.10	.10
7	.0	.062	.0	.0	.0
8	.0	.029	.0	.0	.0
9	.0	.014	.0	.0	.0
10	.0	.0	.0	.0	.0

Table D.17

CAPITAL COSTS FOR FABRICATION AND REPROCESSING FACILITIES
(\$/Kg/Yr throughput)*

Reactor	Fabrication Plants (511 MT/Year)	Reprocessing Plants (1500 MT/Year)
LWR-US (LE)/U	127	533
US (LE)/U-T	127	533
US (DE)/U/Th	157	537
U3 (DE)/U/Th	886	537
Pu/U	507	533
Pu/Th	507	563
SSCR-US (LE)/U	127	533
U3 (DE)/U/Th	886	537
Pu/Th	507	563
LWR-US (NAT)/U	127	508
US (SEU)/U	127	508
US (DE)/U/Th	157	512
U3 (DE)/U/Th	886	512
Pu/U	507	508
Pu/Th	507	538
HTGR-US (LE)/U-T	235	1053
US (LE)/U	235	1053
US (DE)/U/Th	264	1053
US (DE)/Th	264	1053
U3 (DE)/U/Th	1237	1053
U3/Th	1237	1053
Pu/Th	1237	1053
FBR-Pu-U/U	1047/262	733
Pu-U/Th	1047/262	733

*Data provided by ORNL; costs do not include interest during construction.

Table D.18
Capital Costs for Enrichment Facilities,
Uranium and Thorium Mines*

<u>Facility Type</u>	<u>Capital Cost</u>
Enrichment	300 \$/Kg separative work unit per year
Uranium Mines	25 \$/lb U_3O_8 per year
Thorium Mines	25 \$/lb ThO_2 per year (62.6 \$/Kg Th per year)

*Data provided by Resource Planning Associates; costs do not include interest during construction.

E. DESCRIPTION OF CASES

Four sets of scenarios, each corresponding to a different fuel cycle option, were investigated in this study. The fuel cycle options are summarized below.

Once-Through (Throwaway) Cycle

The once-through cycle stores the spent fuel without reprocessing. Reactors optimized for a throwaway cycle include an extended exposure PWR and a low-enriched HTGR design.

U-233 and U-235 Recycle

The uranium isotopes are assumed to be recycled in this option and the plutonium is assumed to be discarded. All reactors are either natural uranium, low-enriched, or denatured designs.

Pu-U Recycle Restricted to Secure Centers (S) and Dispersed (D) Reactors
Restricted to "Denatured" Reactors

Nuclear non-proliferation considerations were addressed in this option. The plutonium fueled reactors were restricted to secure energy centers. All other reactors were either low-enriched or denatured, and therefore available to be built in dispersed areas.

Full Recycle

The full recycle option allows both fissile plutonium and U-233 recycle, with fissile plutonium being the dominant recycle material. All reactor types included in this scenario, with the exception of the HTGR's, are operating on the plutonium/uranium cycle. Nuclear non-proliferation is not an issue in this scenario. That is, denatured reactors are not available.

For each of the four fuel cycle options, five ALPS calculations, representing five different reactor strategies, were performed. Table E.1 presents the reactors available in each of these twenty cases. The first set of cases, denoted with an L, assumed that the only reactor type available, in addition to the FBR's mentioned above, are PWR's. The set of cases denoted with an S assumed that the throwaway PWR, the denatured U-233 fueled PWR, and the Pu/Th fueled PWR in set L are replaced with SSCR's on the same fuel cycle. The third set of cases, denoted with an H, assumed the availability of the CANDU's in addition to the standard LWR and the FBR's. The fourth set of cases, denoted with a G, assumed the availability of HTGR's, in addition to the standard LWR and the FBR's. Finally, the set of cases denoted with an A had all of the reactors that were included in sets L, S, H, and G available. Thus,

Table E.1

THORIUM ASSESSMENT PROGRAM REACTOR CASES
S = Secure Energy Center, D = Dispersed Area

Reactor	Once-Through (Throwaway) Cycle					U-233 & U-235 Recycle					Restricted Recycle					Full Recycle				
	L	S	H	G	A	L	S	H	G	A	L	S	H	G	A	L	S	H	G	A
LWR-U5 (LE) /U	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
LWR-U5 (LE) /U-T	D	-	-	-	D	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LWR-U5 (DE) /U/Th	-	-	-	-	-	D	D	-	-	D	D	D	-	-	D	-	-	-	-	-
LWR-U3 (DE) /U/Th	-	-	-	-	-	D	-	-	-	D	D	-	-	-	D	-	-	-	-	-
LWR-Pu/U	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S	-	-	S
LWR-Pu/Th	-	-	-	-	-	-	-	-	-	-	S	-	-	-	S	-	-	-	-	-
SSCR-U5 (LE) /U	-	D	-	-	D	-	D	-	-	D	-	D	-	-	D	-	D	-	-	D
SSCR-U3 (DE) /U/Th	-	-	-	-	-	-	D	-	-	D	-	D	-	-	D	-	-	-	-	-
SSCR-Pu/Th	-	-	-	-	-	-	-	-	-	-	-	S	-	-	S	-	-	-	-	-
HWR-U5 (NAT) /U	-	-	D	-	D	-	-	D	-	D	-	-	D	-	D	-	-	D	-	D
HWR-U5 (SEU) /U	-	-	D	-	D	-	-	D	-	D	-	-	D	-	D	-	-	D	-	D
HWR-U5 (DE) /U/Th	-	-	-	-	-	-	-	D	-	D	-	-	D	-	D	-	-	-	-	-
HWR-U3 (DE) /U/Th	-	-	-	-	-	-	-	D	-	D	-	-	D	-	D	-	-	-	-	-
HWR-Pu/U	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S	-	S
HWR-Pu/Th	-	-	-	-	-	-	-	-	-	-	-	-	S	-	S	-	-	-	-	-
HTGR-U5 (LE) /U-T	-	-	-	D	D	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HTGR-U5 (LE) /U	-	-	-	-	-	-	-	-	D	D	-	-	-	D	D	-	-	-	D	D
HTGR-U5 (DE) /U/Th	-	-	-	-	-	-	-	-	D	D	-	-	-	D	D	-	-	-	-	-
HTGR-U5 (HE) /Th	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S
HTGR-U3 (DE) /U/Th	-	-	-	-	-	-	-	-	D	D	-	-	-	D	D	-	-	-	-	-
HTGR-U3/Th	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S
HTGR-Pu/Th	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S	-	-	-	S	S
FBR-Pu-U/U	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S	S	S	S
FBR-Pu-U/Th	-	-	-	-	-	-	-	-	-	-	S	S	S	S	S	-	-	-	-	-

in this case, LWR's, SSCR's, CANDU's, HTGR's, and FBR's competed directly against each other (and against fossil plants) for a share of the market.

F. RESULTS

The results of this study are shown for the following key variables-- total system costs, levelized system power costs, total capacity built, coal consumption, uranium ore (U_3O_8) consumption, maximum enrichment requirements and U_3O_8 and enrichment utilization. Also reported are the installed nuclear capacity in year 2026 and levelized power costs in year 2025 for each reactor type available. Capital requirements for the various segments of the nuclear industry and the fossil generation plants are shown in the form of cash flow tables. Reactor and system material requirements are presented graphically in Appendix A to show the uranium ore, enrichment, fabrication, reprocessing, and fissile material requirements for the year 2035 per gigawatt of installed nuclear capacity. Because uranium ore availability and cost projections may vary, the above-mentioned results are presented for both small and large U_3O_8 supply assumptions.

Total Systems Costs

The first key variable shown in Tables F.1 through F.5 is the present-worth total system costs of electrical generation from 1977 through 2050. This variable which the ALPS model minimizes is reported for three discount rates--4 1/2, 7 1/2 and 10% per year. Comparison of all four fuel cycle options for the five different reactor strategies shows the same general trends. Note the slight decrease in systems cost at 4 1/2% discount rate (0-17 billion dollars) in choosing the U-233 and U-235 recycle option over the once-through (throwaway) option. Also, one can see that choosing either the restricted or the full recycle option over the throwaway option results

Table F.1
SUMMARY OF THORIUM ASSESSMENT PROGRAM STUDY RESULTS
SMALL U_3O_8 SUPPLY

	Fuel Cycle Options			
	Once-Through (Throwaway) Cycle	U-233 & U-235 Recycle	Restricted Recycle	Full Recycle
	(L)	(L)	(L)	(L)
System Costs (\$B) 1977 through 2050 Discounted at				
4 1/2%	1804	1806	1703	1701
7 1/2%	787	791	760	758
10%	479	483	469	468
Levelized System Power Costs in 2025 (mills/kwhr)	18.8	18.9	18.2	18.3
Cumulative Capacity Built (GWe) through 2050				
Nuclear	705 (13%)	933 (18%)	2597 (49%)	2663 (50%)
Fossil	4611 (87%)	4382 (82%)	2719 (51%)	2653 (50%)
Annual Coal Consump- tion in 2025 (10^6 tons)	5220	4790	2910	3150
Cumulative U_3O_8 Con- sumption (10^6 tons) through				
2026	2.92	2.88	3.68	3.56
2050	3.42	3.13	4.33	4.60
Maximum Annual Enrich- ment Requirement through 2050 (10^6 SWU/ yr)	54	72	80	73
U_3O_8 Utilization ⁽¹⁾ (ton U_3O_8 /GWe)	5033	3403	1684	1899
Enrichment Utilization ⁽²⁾ (10^6 SWU/GWe)	3.00	3.13	1.20	1.08

(1) Cumulative U_3O_8 consumed through 2050 (including forward commitment) per cumulative nuclear capacity built through 2050

(2) Cumulative enrichment requirements through 2050 per cumulative nuclear capacity built through 2050

Table F.2
SUMMARY OF THORIUM ASSESSMENT PROGRAM STUDY RESULTS
SMALL U_3O_8 SUPPLY

	Fuel Cycle Options			
	Once-Through (Throwaway) Cycle (S)	U-233 & U-235 Recycle (S)	Restricted Recycle (S)	Full Recycle (S)
System Costs (\$B)				
1977 through 2050				
Discounted at				
4 1/2%	1807	1797	1681	1688
7 1/2%	789	790	754	755
10%	480	483	467	468
Levelized System				
Power Costs in				
2025 (mills/kwhr)	18.9	18.9	17.8	18.0
Cumulative Capacity				
Built (GWe) through				
2050				
Nuclear	745 (14%)	1143 (22%)	3168 (60%)	3037 (57%)
Fossil	4571 (86%)	4173 (78%)	2148 (40%)	2279 (43%)
Annual Coal Consump-				
tion in 2025 (10^6 tons)	5170	4330	2340	2680
Cumulative U_3O_8 Con-				
sumption (10^6 tons)				
through				
2026	2.81	3.01	3.52	3.50
2050	3.40	3.27	4.34	4.75
Maximum Annual Enrich-				
ment Requirement				
through 2050 (10^6 SWU/ yr)	47	78	73	70
U_3O_8 Utilization ⁽¹⁾				
(ton U_3O_8 /GWe)	4892	2896	1392	1744
Enrichment Utilization ⁽²⁾				
(10^6 SWU/GWe)	2.65	2.39	0.96	0.94

(1) Cumulative U_3O_8 consumed through 2050 (including forward commitment) per cumulative nuclear capacity built through 2050

(2) Cumulative enrichment requirements through 2050 per cumulative nuclear capacity built through 2050

Table F.3
SUMMARY OF THORIUM ASSESSMENT PROGRAM STUDY RESULTS
SMALL U_3O_8 SUPPLY

	Fuel Cycle Options			
	Once-Through (Throwaway) Cycle	U-233 & U-235 Recycle	Restricted Recycle	Full Recycle
	(H)	(H)	(H)	(H)
System Costs (\$B)				
1977 through 2050				
Discounted at				
4 1/2%	1811	1810	1732	1716
7 1/2%	790	789	769	766
10%	480	481	473	473
Levelized System Power Costs in 2025 (mills/kwhr)	18.8	18.9	18.2	18.0
Cumulative Capacity Built (GWe) through 2050				
Nuclear	699 (13%)	830 (16%)	3108 (58%)	3598 (68%)
Fossil	4617 (87%)	4486 (84%)	2208 (42%)	1718 (32%)
Annual Coal Consump- tion in 2025 (10^6 tons)	5350	5030	3020	3090
Cumulative U_3O_8 Con- sumption (10^6 tons) through				
2026	2.79	2.76	3.23	3.24
2050	3.25	3.25	3.60	3.62
Maximum Annual Enrich- ment Requirement through 2050 (10^6 SWU/ yr)	49	58	70	70
U_3O_8 Utilization ⁽¹⁾ (ton U_3O_8 /GWe)	4942	4078	1164	1013
Enrichment Utilization ⁽²⁾ (10^6 SWU/GWe)	2.67	2.81	0.83	0.72

(1) Cumulative U_3O_8 consumed through 2050 (including forward commitment) per cumulative nuclear capacity built through 2050

(2) Cumulative enrichment requirements through 2050 per cumulative nuclear capacity built through 2050

Table F.4
SUMMARY OF THORIUM ASSESSMENT PROGRAM STUDY RESULTS
SMALL U_3O_8 SUPPLY

	Fuel Cycle Options			
	Once-Through (Throwaway) Cycle	U-233 & U-235 Recycle	Restricted Recycle	Full Recycle
	(G)	(G)	(G)	(G)
System Costs (\$B)				
1977 through 2050				
Discounted at				
4 1/2%	1810	1793	1697	1685
7 1/2%	790	787	760	757
10%	481	481	470	469
Levelized System Power Costs in 2025 (mills/kwhr)	18.9	18.7	18.0	17.7
Cumulative Capacity Built (GWe) through 2050				
Nuclear	701 (13%)	1301 (24%)	2791 (53%)	3212 (60%)
Fossil	4615 (87%)	4015 (76%)	2525 (47%)	2104 (40%)
Annual Coal Consump- tion in 2025 (10^6 tons)	5330	4090	2560	2330
Cumulative U_3O_8 Con- sumption (10^6 tons) through				
2026	2.74	3.01	3.63	3.41
2050	3.25	3.93	4.22	4.75
Maximum Annual Enrich- ment Requirement through 2050 (10^6 SWU/ yr)	49	76	80	79
U_3O_8 Utilization ⁽¹⁾ (ton U_3O_8 /GWe)	5005	3076	1524	1550
Enrichment Utilization ⁽²⁾ (10^6 SWU/GWe)	2.89	2.50	1.09	1.24

(1) Cumulative U_3O_8 consumed through 2050 (including forward commitment) per cumulative nuclear capacity built through 2050

(2) Cumulative enrichment requirements through 2050 per cumulative nuclear capacity built through 2050

Table F.5
SUMMARY OF THORIUM ASSESSMENT PROGRAM STUDY RESULTS
SMALL U_3O_8 SUPPLY

	Fuel Cycle Options			
	Once-Through (Throwaway) Cycle	U-233 & U-235 Recycle	Restricted Recycle	Full Recycle
	(A)	(A)	(A)	(A)
System Costs (\$B)				
1977 through 2050				
Discounted at				
4 1/2%	1802	1789	1676	1676
7 1/2%	786	788	752	752
10%	479	482	466	466
Levelized System Power Costs in 2025 (mills/kwhr)	18.9	18.8	17.8	17.8
Cumulative Capacity Built (GWe) through 2050				
Nuclear	773 (15%)	1342 (25%)	3181 (60%)	3159 (59%)
Fossil	4543 (85%)	3974 (75%)	2135 (40%)	2157 (41%)
Annual Coal Consump- tion in 2025 (10^6 tons)	5160	3980	2250	2230
Cumulative U_3O_8 Con- sumption (10^6 tons) through				
2026	2.94	3.05	3.58	3.49
2050	3.52	3.83	4.71	4.79
Maximum Annual Enrich- ment Requirement through 2050 (10^6 SWU/ yr)	52	76	74	78
U_3O_8 Utilization ⁽¹⁾ (ton U_3O_8 /GWe)	4863	2902	1524	1571
Enrichment Utilization ⁽²⁾ (10^6 SWU/GWe)	2.71	2.44	1.03	1.21

(1) Cumulative U_3O_8 consumed through 2050 (including forward commitment) per cumulative nuclear capacity built through 2050

(2) Cumulative enrichment requirements through 2050 per cumulative nuclear capacity built through 2050

in a much larger decrease in system costs of 100-125 billion dollars. Total system costs assuming a large U_3O_8 supply (Tables F.15 through F.19) exhibit the same relative differences, however, the less expensive uranium ore reduces all total systems costs by 60-70 billion dollars.

In comparing five different reactor strategies--L(LWR's only), S(LWR's and SSCR's), H(LWR's and CANDU's), G(LWR's and HTGR's) and A(all reactors), in addition to FBR's in the appropriate fuel cycle options, the economic benefits of deploying specific reactor types under the four different fuel cycle options become apparent. For the throwaway fuel cycle option, the LWR optimized for a throwaway cycle with extended exposure has a slight economic edge (≤ 7 billion dollars) over all other reactor strategies combined with the standard low-enriched LWR. For both the U-233 and U-235 recycle option and the full recycle option (includes FBR's), the HTGR reactor strategy provides slightly larger benefits (~ 15 billion dollars) than the LWR reactor strategy. The SSCR reactor strategy does, however, result in nearly the same benefits in the full recycle fuel option. For the restricted recycle option (includes FBR's), the SSCR reactor strategy provides the largest benefit of 22 billion dollars relative to the LWR reactor strategy. The CANDU reactors (reactor strategy H), although their fuel cycle costs are lower, are penalized by the higher capital costs associated with a heavy water inventory--resulting in higher total system costs than the LWR reactor strategy for all four fuel cycle options. As one might expect, the reactor strategy A employing all four reactor types (LWR, SSCR, CANDU, and HTGR), the total system costs are slightly less than any strategy employing only one reactor type.

Levelized System Power Costs

The levelized system power costs shown in the tables represent the average power costs in mills/kwhr for all nuclear and fossil power plants operating in the year 2025. Relative to the throwaway fuel cycle option, recycle of U-233 and U-235 without FBR's reduces power costs very slightly (0.1 mills/kwhr) if any at all. Results shown indicate that only through utilization of either restricted or full recycle with FBR's will the average power cost be reduced appreciably (1-2 mills/kwhr).

Cumulative Capacity Built

The split between nuclear and fossil cumulative capacity built through 2050 is also reported both in gigawatt of electrical capacity (GWe) and the percentage of the total generation market. The reduction in total system costs and average system power costs correlates very well with the changes in market penetration attained by nuclear power plants. Nuclear market penetration for small U_3O_8 supply increases from 15% to 25% if U-233 and U-235 recycle is employed instead of the throwaway cycle, and likewise from 20% to 40% for large U_3O_8 supply. If restricted or full recycle is employed nuclear market penetration increases for small U_3O_8 supply to 50% - 60% and for large U_3O_8 supply, as large as 60% - 70% nuclear market penetration results.

U_3O_8 Consumption and Utilization-Enrichment Utilization

Cumulative U_3O_8 consumption results reported in the tables show that for the throwaway and U-233 and U-235 recycle options 3-4 million tons of U_3O_8 are consumed. For restricted and full recycle options slightly more (4-5 million tons) U_3O_8 is consumed for production of fissile material to be used in FBR's. An important point to note is the behavior of U_3O_8

utilization which is a measure of the quantity of U_3O_8 required to support one gigawatt of electrical generating capacity. Although more U_3O_8 is consumed for both recycle options with breeders, the U_3O_8 utilization is reduced from 3000 - 5000 tons U_3O_8 per GWe to 1400 - 1900 tons U_3O_8 per GWe.

Enrichment utilization--the quantity of enrichment required per gigawatt--behaves similarly to U_3O_8 utilization. Enrichment requirements per gigawatt increases by a factor of 3-4 for fuel cycle options without FBR's.

Installed Nuclear Capacity - Levelized Power Costs

A "snapshot in time" of installed capacity (GWe) of each reactor in the year 2026 and the levelized power costs (mills/kwhr) for each reactor if startup occurs in year 2025 are presented in Tables F.6 through F.10 for small U_3O_8 supply and Tables F.20 through F.24 for large U_3O_8 supply.

Looking at the four fuel cycle options with the LWR reactor strategy (Table F.6), note that the LWR optimized for throwaway does take over the nuclear market but is still limited by high cost U_3O_8 in the later years. Allowing introduction of U-233 and U-235 recycle in LWR's nearly doubles nuclear capacity. Much larger changes (4-5 times as much nuclear capacity) result when either restricted or full recycle of Pu is allowed. The large increase in installed capacity of the standard low-enriched LWR provides adequate fissile Pu to be recycled in FBR's. About 15% of the generating capacity is also provided by LWR's recycling U-235 in the restricted recycle option. In the full recycle option about 17% of the nuclear capacity is provided by LWR's burning fissile Pu not required by FBR's.

If the SSCR reactor strategy is pursued, results shown in Table F.7 are obtained. The SSCR's because of their better fuel utilization increase

Table F.6
THORIUM ASSESSMENT PROGRAM RESULTS
Small U₃O₈ Supply
INSTALLED CAPACITY (GWe) in YEAR 2026/LEVELIZED POWER COSTS (Mills/Kwhr) in YEAR 2025

Reactor	Once-Through (Throwaway) Cycle (L)	U-233 & U-235 Recycle (L)	Restricted Recycle (L)	Full Recycle (L)
LWR-U5 (LE) /U	36/23.2	113/21.6	594/20.7	513/20.8
U5 (LE) /U-T	224/22.3	-	-	-
U5 (DE) /U/Th	-	189/22.5	0/23.2	-
U3 (DE) /U/Th	-	157/20.0	190/19.6	-
Pu/U	-	-	-	196/19.5
Pu/Th	-	-	52/22.1	-
SSCR-U5 (LE) /U	-	-	-	-
U3 (DE) /U/Th	-	-	-	-
Pu/Th	-	-	-	-
LWR-U5 (NAT) /U	-	-	-	-
U5 (SEU) /U	-	-	-	-
U5 (DE) /U/Th	-	-	-	-
U3 (DE) /U/Th	-	-	-	-
Pu/U	-	-	-	-
Pu/Th	-	-	-	-
HTGR-U5 (LE) /U-T	-	-	-	-
U5 (LE) /U	-	-	-	-
U5 (DE) /U/Th	-	-	-	-
U5 (HE) /Th	-	-	-	-
U3 (DE) /U/Th	-	-	-	-
U3/Th	-	-	-	-
Pu/Th	-	-	-	-
FBR-Pu-U/U	-	-	-	444/18.4
Pu-U/Th	-	-	408/19.4	-
Fossil	1934	1736	951	1042
Nuclear	261	459	1244	1153

Table F.7
THORIUM ASSESSMENT PROGRAM RESULTS
Small U₃O₈ Supply
INSTALLED CAPACITY (GWe) in YEAR 2026/LEVELIZED POWER COSTS (Mills/Kwhr) in YEAR 2025

Reactor	Once-Through (Throwaway) Cycle (S)	U-233 & U-235 Recycle (S)	Restricted Recycle (S)	Full Recycle (S)
LWR-U5 (LE) /U	95/23.1	82/22.1	170/20.9	161/21.6
U5 (LE) /U-T	-	-	-	-
U5 (DE) /U/Th	-	273/22.7	2/23.2	-
U3 (DE) /U/Th	-	-	-	-
Pu/U	-	-	-	207/19.6
Pu/Th	-	-	-	-
SSCR-U5 (LE) /U	197/21.8	0/21.3	495/19.5	454/20.0
U3 (DE) /U/Th	-	306/20.5	294/19.7	-
Pu/Th	-	-	72/20.8	-
IFWR-U5 (NAT) /U	-	-	-	-
U5 (SEU) /U	-	-	-	-
U5 (DE) /U/Th	-	-	-	-
U3 (DE) /U/Th	-	-	-	-
Pu/U	-	-	-	-
Pu/Th	-	-	-	-
IFGR-U5 (LE) /U-T	-	-	(5533)	-
U5 (LE) /U	-	-	-	-
U5 (DE) /U/Th	-	-	307/19.3	-
U5 (DE) /Th	-	-	-	-
U3 (DE) /U/Th	-	-	-	-
U3/Th	-	-	-	-
Pu/Th	-	-	-	-
FBR-Pu-U/U	-	-	-	511/18.5
Pu-U/Th	-	-	420/19.3	-
Fossil	1903	1534	742	862
Nuclear	292	661	1453	1333

Table F.8
THORIUM ASSESSMENT PROGRAM RESULTS
Small U₃O₈ Supply
INSTALLED CAPACITY (GWe) in YEAR 2026/LEVELIZED POWER COSTS (Mills/Kwhr) in YEAR 2025

Reactor	Once-Through (Throwaway) Cycle (H)	U-233 & U-235 Recycle (H)	Restricted Recycle (H)	Full Recycle (H)
LWR-U5 (LE)/U	195/22.4	349/21.6	442/21.0	448/21.0
U5 (LE)/U-T	-	-	-	-
U5 (DE)/U/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/U	-	-	-	-
Pu/Th	-	-	-	-
SSCR-U5 (LE)/U	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/Th	-	-	-	-
LWR-U5 (NAT)/U	0/25.1	0/27.2	0/24.9	0/25.0
U5 (SEU)/U	9/22.2	0/23.3	0/22.2	0/22.2
U5 (DE)/U/Th	-	0/26.7	0/30.0	-
U3 (DE)/U/Th	-	0/21.3	248/19.1	-
Pu/U	-	-	-	0/22.3
Pu/Th	-	-	0/24.8	-
HTGR-U5 (LE)/U-T	-	-	-	-
U5 (LE)/U	-	-	-	-
U5 (DE)/U/Th	-	-	-	-
U5 (DE)/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
U3/Th	-	-	-	-
Pu/Th	-	-	-	-
FBR-Pu-U/U	-	-	-	723/19.4
Pu-U/Th	-	-	537/20.9	-
Fossil	1991	1846	968	1024
Nuclear	204	349	1227	1171

Table F.9

THORIUM ASSESSMENT PROGRAM RESULTS

Small U_3O_8 Supply

INSTALLED CAPACITY (GWe) in YEAR 2026/LEVELIZED POWER COSTS (Mills/Kwhr) in YEAR 2025

Reactor	Once-Through (Throwaway) Cycle (G)	U-233 & U-235 Recycle (G)	Restricted Recycle (G)	Full Recycle (G)
LMR-U5 (LE)/U	141/22.5	125/22.7	566/20.6	230/21.2
U5 (LE)/U-T	-	-	-	-
U5 (DE)/U/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/U	-	-	-	-
Pu/Th	-	-	-	-
SSCR-U5 (LE)/U	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/Th	-	-	-	-
HWR-U5 (NAT)/U	-	-	-	-
U5 (SEU)/U	-	-	-	-
U5 (DE)/U/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/U	-	-	-	-
Pu/Th	-	-	-	-
ITGR-U5 (LE)/U-T	75/21.7	-	-	-
U5 (LE)/U	-	0/21.7	0/21.1	0/21.5
U5 (DE)/U/Th	-	487/20.9	0/20.7	-
U5 (HE)/Th	-	-	-	427/18.8
U3 (DE)/U/Th	-	136/20.9	273/19.6	-
U3/Th	-	-	-	291/19.1
Pu/Th	-	-	45/23.4	100/19.1
FBR-Pu-U/U	-	-	-	360/18.0
Pu-U/Th	-	-	493/21.1	-
Fossil	1979	1447	818	742
Nuclear	216	748	1377	1453

Table F.10

THORIUM ASSESSMENT PROGRAM RESULTS
Small U_3O_8 Supply

INSTALLED CAPACITY (GWe) in YEAR 2026/LEVELIZED POWER COSTS (Mills/Kwhr) in YEAR 2025

Reactor	Once-Through (Throwaway) Cycle (A)	U-233 & U-235 Recycle (A)	Restricted Recycle (A)	Full Recycle (A)
LWR-US (LE)/U	36/23.2	73/22.6	105/20.7	150/21.6
US (LE)/U-T	82/22.3	-	-	-
US (DE)/U/Th	-	116/23.0	2/22.8	-
U3 (DE)/U/Th	-	0/23.2	0/20.8	-
Pu/U	-	-	-	122/19.9
Pu/Th	-	-	41/21.2	-
SSCR-US (LE)/U	140/21.9	0/21.8	579/19.3	148/20.0
U3 (DE)/U/Th	-	0/21.1	227/19.3	-
Pu/Th	-	-	21/21.0	-
LWR-US (NAT)/U	0/25.7	0/28.1	0/23.8	0/24.7
US (SEU)/U	0/22.6	0/24.0	0/21.7	0/22.4
US (DE)/U/Th	-	0/23.6	0/24.4	-
U3 (DE)/U/Th	-	0/25.1	0/24.0	-
Pu/U	-	-	-	0/22.8
Pu/Th	-	-	0/22.8	-
INCR-US (LE)/U-T	0/22.3	-	-	-
US (LE)/U	-	0/21.7	0/21.1	0/21.8
US (DE)/U/Th	-	372/20.8	0/20.8	-
US (DE)/Th	-	-	-	444/19.1
U3 (DE)/U/Th	-	244/20.7	56/19.3	-
U3/Th	-	-	-	263/19.6
Pu/Th	-	-	6/20.4	30/19.8
FBR-Pu-U/U	-	-	-	353/18.3
Pu-U/Th	-	-	402/18.6	-
Fossil	1937	1390	756	685
Nuclear	258	805	1439	1510

Table F.11

CAPITAL CONSTRUCTION CASH FLOWS FOR
ONCE-THROUGH (Throwaway)
ALL REACTOR CASE--SMALL URANIUM SUPPLY
(Millions of \$/Year)

Year	Fossil Plants	Nuclear Plants	Fabrication Plants	Reprocessing* Plants	Enrichment Plants	U ₃ O ₈ Mines	ThO ₂ Mines
1970	5,380	3,450	27	-	133	213	-
1975	8,860	5,210	29	-	190	296	-
1980	7,270	9,000	72	-	354	554	-
1985	9,330	9,290	45	-	346	511	-
1990	7,330	11,520	65	240	420	612	-
1995	14,470	10,440	27	616	282	421	-
2000	19,910	8,780	48	269	447	370	-
2005	27,720	5,210	19	213	109	201	-
2010	36,820	3,060	43	141	106	194	-
2015	39,910	1,980	14	48	62	100	-
2020	44,910	2,040	15	24	97	133	-
2025	49,850	2,420	10	177	50	60	-
2030	56,960	2,640	13	120	69	104	-
2035	61,230	2,880	12	72	43	89	-
2040	70,290	2,460	20	72	85	172	-

*Reprocessing Plants in the throwaway options represent the facilities required for disposal of all spent fuel discharged.

Table F.12

CAPITAL CONSTRUCTION CASH FLOWS
 FOR CASE U-233 AND U-235 RECYCLE--ALL REACTOR
 CASE--SMALL URANIUM SUPPLY
 (Millions of \$/Year)

<u>Year</u>	<u>Fossil Plants</u>	<u>Nuclear Plants</u>	<u>Fabrication Plants</u>	<u>Reprocessing Plants</u>	<u>Enrichment Plants</u>	<u>U₃O₈ Mines</u>	<u>ThO₂ Mines</u>
1970	5,380	3,450	27	-	133	213	-
1975	8,870	5,130	29	-	189	292	-
1980	7,820	8,640	66	-	321	502	-
1985	7,440	9,430	92	-	384	552	2
1990	10,960	9,070	61	525	467	233	8
1995	13,190	11,580	75	139	453	636	12
2000	14,800	18,180	175	218	555	455	14
2005	13,760	20,170	338	336	431	472	10
2010	26,450	15,680	167	211	305	326	7
2015	27,860	15,570	169	195	327	418	8
2020	36,620	10,870	132	387	189	21	6
2025	44,690	7,530	72	191	0	21	4
2030	53,900	6,170	132	185	67	0	7
2035	59,530	4,330	179	227	0	44	1
2040	70,290	2,550	17	5	39	117	0

Table F.13
CAPITAL CONSTRUCTION CASH FLOWS
FOR RESTRICTED RECYCLE--ALL REACTOR CASE--
SMALL URANIUM SUPPLY
(Millions of \$/Year)

<u>Year</u>	<u>Fossil Plants</u>	<u>Nuclear Plants</u>	<u>Fabrication Plants</u>	<u>Reprocessing Plants</u>	<u>Enrichment Plants</u>	<u>U₃O₈ Mines</u>	<u>ThO₂ Mines</u>
1970	5,380	3,450	27	-	133	213	-
1975	8,870	5,130	29	-	189	292	-
1980	7,820	9,020	66	-	321	502	-
1985	3,940	13,870	134	-	531	781	2
1990	4,600	15,140	135	642	424	359	6
1995	8,730	17,760	159	514	341	541	8
2000	8,200	24,570	252	525	511	742	7
2005	7,950	30,000	453	592	439	608	16
2010	9,300	37,110	813	714	292	348	30
2015	15,110	32,530	622	788	277	354	23
2020	17,410	35,490	750	834	233	134	27
2025	21,690	37,030	798	787	93	146	24
2030	27,110	36,720	516	644	117	133	14
2035	36,110	31,750	531	630	48	114	16
2040	48,620	26,870	575	498	26	57	18

Table F.14
CAPITAL CONSTRUCTION CASH FLOWS
FOR FULL RECYCLE--ALL REACTOR CASE--
SMALL URANIUM SUPPLY
(Millions of \$/Year)

<u>Year</u>	<u>Fossil Plants</u>	<u>Nuclear Plants</u>	<u>Fabrication Plants</u>	<u>Reprocessing Plants</u>	<u>Enrichment Plants</u>	<u>U₃O₈ Mines</u>	<u>ThO₂ Mines</u>
1970	5,380	3,450	27	-	133	213	-
1975	8,870	5,130	29	-	189	292	-
1980	7,820	9,000	66	-	321	502	-
1985	4,090	13,700	128	-	514	763	-
1990	5,970	13,500	106	640	395	318	1
1995	8,470	18,570	174	416	372	595	2
2000	8,640	24,310	216	507	619	653	11
2005	7,890	30,920	467	518	471	483	15
2010	8,870	37,300	820	665	304	319	15
2015	15,140	32,850	489	768	490	511	17
2020	17,410	35,580	654	822	388	203	23
2025	21,560	38,200	531	697	190	279	21
2030	27,900	35,160	551	734	218	168	24
2035	37,750	29,760	786	734	0	4	23
2040	49,930	25,130	670	615	0	45	16

Table F.15
SUMMARY OF THORIUM ASSESSMENT PROGRAM STUDY RESULTS
LARGE U_3O_8 SUPPLY

	Fuel Cycle Options			
	Once-Through (Throwaway) Cycle	U-233 & U-235 Recycle	Restricted Recycle	Full Recycle
	(L)	(L)	(L)	(L)
System Costs (\$B) 1977 through 2050 Discounted at				
4 1/2%	1732	1743	1624	1623
7 1/2%	759	770	735	734
10%	466	474	459	458
Levelized System Power Costs in 2025 (mills/kwhr)	18.8	18.5	17.2	17.3
Cumulative Capacity Built (GWe) through 2050				
Nuclear	1257 (24%)	1815 (34%)	3296 (62%)	3415 (64%)
Fossil	4059 (76%)	3501 (66%)	2020 (38%)	1901 (36%)
Annual Coal Consump- tion in 2025 (10^6 tons)	4130	3410	1820	1920
Cumulative U_3O_8 Con- sumption (10^6 tons) through				
2026	4.75	4.41	4.48	4.43
2050	6.10	5.75	5.75	6.29
Maximum Annual Enrich- ment Requirement through 2050 (10^6 SWU/ yr)	93	119	101	93
U_3O_8 Utilization ⁽¹⁾ (ton U_3O_8 /GWe)	4994	3271	1782	2022
Enrichment Utilization ⁽²⁾ (10^6 SWU/GWe)	3.02	2.63	1.25	1.16

(1) Cumulative U_3O_8 consumed through 2050 (including forward commitment) per cumulative nuclear capacity built through 2050

(2) Cumulative enrichment requirements through 2050 per cumulative nuclear capacity built through 2050

Table F.16
SUMMARY OF THORIUM ASSESSMENT PROGRAM STUDY RESULTS
LARGE U_3O_8 SUPPLY

	Fuel Cycle Options			
	Once-Through (Throwaway) Cycle (S)	U-235 & U-235 Recycle (S)	Restricted Recycle (S)	Full Recycle (S)
System Costs (\$B) 1977 through 2050 Discounted at				
4 1/2%	1738	1730	1608	1612
7 1/2%	762	768	731	731
10%	467	473	457	458
Levelized System Power Costs in 2025 (mills/kwhr)	18.8	18.3	16.7	16.9
Cumulative Capacity Built (GWe) through 2050				
Nuclear	1335(25%)	2136(40%)	3844(72%)	3580(67%)
Fossil	3981(75%)	3180(60%)	1472(28%)	1736(33%)
Annual Coal Consump- tion in 2025 (10^6 tons)	4050	3050	1490	1660
Cumulative U_3O_8 Con- sumption (10^6 tons) through				
2026	4.61	4.41	4.15	4.20
2050	6.12	5.75	5.81	6.34
Maximum Annual Enrich- ment Requirement through 2050 (10^6 SWU/ yr)	81	121	85	82
U_3O_8 Utilization ⁽¹⁾ (10^6 U_3O_8 /GWe)	4801	2856	1572	1964
Enrichment Utilization ⁽²⁾ (10^6 SWU/GWe)	2.64	2.24	1.05	1.07

(1) Cumulative U_3O_8 consumed through 2050 (including forward commitment) per cumulative nuclear capacity built through 2050

(2) Cumulative enrichment requirements through 2050 per cumulative nuclear capacity built through 2050

Table F.17
SUMMARY OF THORIUM ASSESSMENT PROGRAM STUDY RESULTS
LARGE U_3O_8 SUPPLY

	Fuel Cycle Options			
	Once-Through (Throwaway) Cycle	U-233 & U-235 Recycle	Restricted Recycle	Full Recycle
	(H)	(H)	(H)	(H)
System Costs (\$B)				
1977 through 2050				
Discounted at				
4 1/2%	1747	1749	1662	1645
7 1/2%	765	766	746	743
10%	468	470	463	462
Levelized System				
Power Costs in				
2025 (mills/kwhr)	18.8	18.7	17.3	16.9
Cumulative Capacity				
Built (GWe) through				
2050				
Nuclear	1058(20%)	1444(27%)	4238(80%)	4568(86%)
Fossil	4258(80%)	3872(73%)	1078(20%)	748(14%)
Annual Coal Consumption in 2025 (10^6 tons)	4420	3780	1830	1740
Cumulative U_3O_8 Consumption (10^6 tons) through				
2026	4.59	4.35	4.43	4.45
2050	5.75	5.75	5.25	5.29
Maximum Annual Enrichment Requirement through 2050 (10^6 SWU/yr)	84	97	101	101
U_3O_8 Utilization ⁽¹⁾ (ton U_3O_8 /GWe)	5652	4079	1252	1169
Enrichment Utilization ⁽²⁾ (10^6 SWU/GWe)	3.20	2.85	0.89	0.83

(1) Cumulative U_3O_8 consumed through 2050 (including forward commitment) per cumulative nuclear capacity built through 2050

(2) Cumulative enrichment requirements through 2050 per cumulative nuclear capacity built through 2050

Table F.18
SUMMARY OF THORIUM ASSESSMENT PROGRAM STUDY RESULTS
LARGE U_3O_8 SUPPLY

	Fuel Cycle Options			
	Once-Through (Throwaway) Cycle	U-233 & U-235 Recycle	Restricted Recycle	Full Recycle
	(G)	(G)	(G)	(G)
System Costs (\$B)				
1977 through 2050				
Discounted at				
4 1/2%	1745	1724	1619	1611
7 1/2%	764	762	735	733
10%	468	469	460	458
Levelized System				
Power Costs in				
2025 (mills/kwhr)	18.8	18.3	16.7	16.8
Cumulative Capacity				
Built (GWe) through				
2050				
Nuclear	1211(23%)	2143(40%)	3517(66%)	3811(72%)
Fossil	4105(77%)	3173(60%)	1799(34%)	1505(28%)
Annual Coal Consump-				
tion in 2025 (10^6 tons)	4320	2880	1520	1480
Cumulative U_3O_8 Con-				
sumption (10^6 tons)				
through				
2026	4.56	4.43	4.46	4.21
2050	5.81	6.39	5.75	6.17
Maximum Annual Enrich-				
ment Requirement				
through 2050 (10^6 SWU/				
yr)	86	123	101	101
U_3O_8 Utilization ⁽¹⁾				
(ton U_3O_8 /GWe)	5006	3099	1715	1721
Enrichment Utilization ⁽²⁾				
(10^6 SWU/GWe)	3.02	2.46	1.17	1.33

(1) Cumulative U_3O_8 consumed through 2050 (including forward commitment) per cumulative nuclear capacity built through 2050

(2) Cumulative enrichment requirements through 2050 per cumulative nuclear capacity built through 2050

Table F.19
SUMMARY OF THORIUM ASSESSMENT PROGRAM STUDY RESULTS
LARGE U_3O_8 SUPPLY

	Fuel Cycle Options			
	Once-Through (Throwaway) Cycle	U-233 & U-235 Recycle	Restricted Recycle	Full Recycle
	(A)	(A)	(A)	(A)
System Costs (\$B) 1977 through 2050 Discounted at				
4 1/2%	1731	1717	1602	1602
7 1/2%	759	763	728	729
10%	465	471	456	456
Levelized System Power Costs in 2025 (mills/kwhr)	18.6	18.2	16.6	16.7
Cumulative Capacity Built (GWe) through 2050				
Nuclear	1339(25%)	2263(43%)	3680(69%)	3725(70%)
Fossil	3977(75%)	3053(57%)	1636(31%)	1591(30%)
Annual Coal Consump- tion in 2025 (10^6 tons)	4030	2610	1490	1460
Cumulative U_3O_8 Con- sumption (10^6 tons) through				
2026	4.74	4.43	4.18	4.07
2050	6.23	6.18	5.92	6.22
Maximum Annual Enrich- ment Requirement through 2050 (10^6 SWU/ yr)	89	125	87	106
U_3O_8 Utilization ⁽¹⁾ (ton U_3O_8 /GWe)	4864	2838	1666	1774
Enrichment Utilization ⁽²⁾ (10^6 SWU/GWe)	2.82	2.37	1.12	1.36

(1) Cumulative U_3O_8 consumed through 2050 (including forward commitment) per cumulative nuclear capacity built through 2050

(2) Cumulative enrichment requirements through 2050 per cumulative nuclear capacity built through 2050

Table F.20

THORIUM ASSESSMENT PROGRAM RESULTS

Large U₃O₈ Supply

INSTALLED CAPACITY (GWe) in YEAR 2026/LEVELIZED POWER COSTS (Mills/kwhr) in YEAR 2025

Reactor	Once-Through (Throwaway) Cycle (L)	U-233 & U-235 Recycle (L)	Restricted Recycle (L)	Full Recycle (L)
LWR-U5 (LE)/U	61/22.4	235/20.6	874/19.2	827/19.4
U5 (LE)/U-T	675/21.6	-	-	-
U5 (DE)/U/Th	-	489/21.6	0/21.3	-
U3 (DE)/U/Th	-	336/20.4	219/19.6	-
Pu/U	-	-	-	269/18.7
Pu/Th	-	-	63/20.8	-
SSCR-U5 (LE)/U	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/Th	-	-	-	-
HWR-U5 (NAT)/U	-	-	-	-
U5 (SEU)/U	-	-	-	-
U5 (DE)/U/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/U	-	-	-	-
Pu/Th	-	-	-	-
HFGR-U5 (LE)/U-T	-	-	-	-
U5 (LE)/U	-	-	-	-
U5 (DE)/U/Th	-	-	-	-
U5 (HE)/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
U3/Th	-	-	-	-
Pu/Th	-	-	-	-
FBR-Pu-U/U	-	-	-	516/17.3
Pu-U/Th	-	-	486/19.2	-
Fossil	1459	1135	553	583
Nuclear	736	1060	1642	1612

Table F.21

THORIUM ASSESSMENT PROGRAM RESULTS
 Large U₃O₈ Supply
 INSTALLED CAPACITY (GWe) in YEAR 2026/LEVELIZED POWER COSTS (Mills/Kwhr) in YEAR 2025

Reactor	Once-Through (Throwaway) Cycle (S)	U-233 & U-235 Recycle (S)	Restricted Recycle (S)	Full Recycle (S)
LWR-U5 (LE)/U	205/22.3	128/21.0	298/19.2	283/19.5
U5 (LE)/U-T	-	-	-	-
U5 (DE)/U/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/U	-	525/21.4	0/21.1	344/18.1
Pu/Th	-	-	-	-
SSCR-U5 (LE)/U	568/21.2	29/20.4	650/18.2	603/18.4
U3 (DE)/U/Th	-	506/20.1	306/18.2	-
Pu/Th	-	-	114/19.1	-
HWGR-U5 (NAT)/U	-	-	-	-
U5 (SEU)/U	-	-	-	-
U5 (DE)/U/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/U	-	-	-	-
Pu/Th	-	-	-	-
HWGR-U5 (LE)/U-T	-	-	-	-
U5 (LE)/U	-	-	-	-
U5 (DE)/U/Th	-	-	-	-
U5 (HE)/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
U3/Th	-	-	-	-
Pu/Th	-	-	-	-
FBR-Pu-U/U	-	-	-	475/17.5
Pu-U/Th	-	-	385/17.7	-
Fossil	1422	1007	442	490
Nuclear	773	1188	1753	1705

Table F.22

THORIUM ASSESSMENT PROGRAM RESULTS
Large U_{308} Supply

INSTALLED CAPACITY (GWe) in YEAR 2026/LEVELIZED POWER COSTS (Mills/Kwhr) in YEAR 2025

Reactor	Once-Through (Throwaway) Cycle (H)	U-233 & U-235 Recycle (H)	Restricted Recycle (H)	Full Recycle (H)
LWR-US (LE)/U	617/21.8	883/21.0	785/19.2	792/19.3
US (LE)/U-T	-	-	-	-
US (DE)/U/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/U	-	-	-	-
Pu/Th	-	-	-	-
SSCR-US (LE)/U	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/Th	-	-	-	-
LWR-US (NAT)/U	0/24.6	0/26.8	0/23.8	0/23.8
US (SEU)/U	0/21.8	0/22.9	0/21.1	0/21.1
US (DE)/U/Th	-	0/26.8	0/28.8	-
U3 (DE)/U/Th	-	0/20.6	158/17.8	-
Pu/U	-	-	-	0/21.1
Pu/Th	-	-	0/22.2	-
IFGR-US (LE)/U-T	-	-	-	-
US (LE)/U	-	-	-	-
US (DE)/U/Th	-	-	-	-
US (HE)/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
U3/Th	-	-	-	-
Pu/Th	-	-	-	-
FBR-Pu-U/U	-	-	-	886/17.6
Pu-U/Th	-	-	704/18.2	-
Fossil	1578	1312	548	517
Nuclear	617	883	1647	1678

Table F.23

THORIUM ASSESSMENT PROGRAM RESULTS
Large U_3O_8 Supply

INSTALLED CAPACITY (GWe) in YEAR 2026/LEVELIZED POWER COSTS (Mills/Kwhr) in YEAR 2025

Reactor	Once-Through (Throwaway) Cycle (G)	U-233 & U-235 Recycle (G)	Restricted Recycle (G)	Full Recycle (G)
LWR-U5 (LE)/U	446/22.1	342/21.5	811/18.6	474/19.5
U5 (LE)/U-T	-	-	-	-
U5 (DE)/U/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/U	-	-	-	-
Pu/Th	-	-	-	-
SSCR-U5 (LE)/U	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/Th	-	-	-	-
IMWR-U5 (NAT)/U	-	-	-	-
U5 (SEU)/U	-	-	-	-
U5 (DE)/U/Th	-	-	-	-
U3 (DE)/U/Th	-	-	-	-
Pu/U	-	-	-	-
Pu/Th	-	-	-	-
HTGR-U5 (LE)/U-T	218/21.4	-	-	-
U5 (LE)/U	-	0/20.8	0/19.3	0/20.0
U5 (DE)/U/Th	-	723/19.9	0/18.9	-
U5 (HE)/Th	-	-	-	480/17.7
U3 (DE)/U/Th	-	179/19.7	278/18.2	-
U3/Th	-	-	-	275/17.7
Pu/Th	-	-	74/19.8	168/17.7
FBR-Pu-U/U	-	-	-	363/17.1
Pu-U/Th	-	-	554/19.1	-
Fossil	1531	951	478	435
Nuclear	664	1244	1717	1760

nuclear market penetration by about 200 GWe (mostly with converter reactors) in the year 2026 over the LWR strategy except in the throwaway option where the SSCR available was not optimized for throwaway.

The CANDU reactors made available in the H reactor strategy (Table F.8) did very poorly in competing with LWR's with and without FBR's. The only fuel cycle option in which CANDU's were built was the restricted recycle option where the only U-233 burner was a CANDU design.

The installed capacity of HTGR's shown in Table F.9 indicates their ability to compete when operating on the Th/U-233 fuel cycle. The HTGR optimized for throwaway and fueled with low-enriched U-235 did not compete nearly as well as the LWR optimized for throwaway. However, with the U-233 and U-235 recycle option, the denatured U-235 and U-233 burning HTGR's comprised 83% of the nuclear market and in the full recycle option the highly enriched HTGR's comprised 59% of the nuclear market. Note that in the restricted recycle option fissile Pu produced by primarily LWR's was recycled in FBR's whereas the U-233 was restricted to recycle in HTGR's.

If all reactors strategies are allowed to compete directly, the results are as shown in Table F.10. The SSCR and HTGR advanced converters as expected, win out over the LWR's with the CANDU's losing out completely due to high costs of heavy water inventories. The SSCR out-competes the LWR slightly in the throwaway option and dominates in the restricted cycle option. The HTGR, however, is the predominant converter design chosen in the U-233 and U-235 option and the full recycle option.

Similar results shown in Tables F.20 through F.28 are obtained if a large U_3O_8 supply is assumed. In general, all installed nuclear capacities are larger due to increased supply of low cost uranium ore.

Table F.24

THORIUM ASSESSMENT PROGRAM RESULTS
Large U₃O₈ Supply

INSTALLED CAPACITY (GWe) in YEAR 2026/LEVELIZED POWER COSTS (Mills/Kwhr) in YEAR 2025

Reactor	Once-Through (Throwaway) Cycle (A)	U-233 & U-235 Recycle (A)	Restricted Recycle (A)	Full Recycle (A)
LWR-U5 (LE)/U	59/21.7	128/21.4	294/18.9	228/19.5
U5 (LE)/U-T	483/20.9	-	-	-
U5 (DE)/U/Th	-	248/21.6	0/20.6	-
U3 (DE)/U/Th	-	0/21.3	0/18.9	-
Pu/U	-	-	-	209/17.6
Pu/Th	-	-	71/19.2	-
SSCR-U5 (LE)/U	237/20.7	0/20.8	707/17.9	114/18.3
U3 (DE)/U/Th	-	35/19.6	238/17.9	-
Pu/Th	-	-	25/19.3	-
IFWR-U5 (NAT)/U	0/24.6	0/27.1	0/22.7	0/23.2
U5 (SEU)/U	0/21.8	0/23.1	0/20.6	0/21.0
U5 (DE)/U/Th	-	0/22.5	0/23.1	-
U3 (DE)/U/Th	-	0/23.5	0/22.7	-
Pu/U	-	-	-	0/21.4
Pu/Th	-	-	0/21.6	-
HTGR-U5 (LE)/U-T	0/21.1	-	-	-
U5 (LE)/U	-	0/20.7	0/19.5	0/20.0
U5 (DE)/U/Th	-	582/19.8	0/19.2	-
U5 (HE)/Th	-	-	-	628/17.7
U3 (DE)/U/Th	-	362/19.4	42/17.9	-
U3/Th	-	-	-	320/17.7
Pu/Th	-	-	15/18.7	50/17.4
FBR-Pu-U/U	-	-	-	219/16.3
Pu-U/Th	-	-	361/17.9	-
Fossil	1416	840	442	427
Nuclear	779	1355	1753	1768

Table F.25
CAPITAL CONSTRUCTION CASH FLOWS
FOR ONCE-THROUGH (Throwaway)--ALL REACTOR CASE
Large U Supply
(Millions of \$/Year)

<u>Year</u>	<u>Fossil Plants</u>	<u>Nuclear Plants</u>	<u>Fabrication Plants</u>	<u>Reprocessing* Plants</u>	<u>Enrichment Plants</u>	<u>U₃O₈ Mines</u>	<u>ThO₂ Mines</u>
1970	5,380	3,450	27	-	133	213	-
1975	8,860	5,210	29	-	190	296	-
1980	7,270	9,350	72	-	534	554	-
1985	6,470	12,170	80	-	469	712	-
1990	4,360	15,280	77	632	560	824	-
1995	7,370	18,330	76	323	670	956	-
2000	10,810	18,750	90	328	625	894	-
2005	17,960	15,070	50	362	400	608	-
2010	26,600	14,130	98	168	375	630	-
2015	31,600	9,890	48	256	253	458	-
2020	40,750	5,810	39	402	151	244	-
2025	48,310	3,460	15	232	152	213	-
2030	56,940	2,590	11	93	96	102	-
2035	61,230	2,870	4	75	21	30	-
2040	69,970	2,850	31	96	79	168	-

*Reprocessing plants in the throwaway options represent the facilities required for disposal of all spent fuel discharged.

Table F.26
CAPITAL CONSTRUCTION CASH FLOWS
FOR U-233 AND U-235 RECYCLE--ALL REACTOR CASE
Large U Supply
(Millions of \$/Year)

<u>Year</u>	<u>Fossil Plants</u>	<u>Nuclear Plants</u>	<u>Fabrication Plants</u>	<u>Reprocessing Plants</u>	<u>Enrichment Plants</u>	<u>U₃O₈ Mines</u>	<u>ThO₂ Mines</u>
1970	5,380	3,450	27	-	133	213	-
1975	8,870	5,130	29	-	187	292	-
1980	7,820	9,020	66	-	321	502	-
1985	3,960	13,520	135	-	555	790	2
1990	6,630	13,240	107	632	617	481	8
1995	7,140	19,040	157	340	103	1,244	25
2000	8,420	24,160	277	459	747	604	21
2005	8,000	28,690	469	380	512	527	20
2010	14,890	29,090	264	383	687	716	15
2015	15,690	29,860	286	330	737	802	16
2020	24,730	23,470	246	506	407	205	11
2025	34,450	20,380	307	381	315	383	16
2030	45,890	14,250	238	354	118	37	3
2035	53,100	11,070	409	295	0	18	5
2040	66,350	6,640	15	163	14	82	1

Table F.27

CAPITAL CONSTRUCTION CASH FLOWS
FOR RESTRICTED RECYCLE--ALL REACTOR CASE
Large U Supply
(Millions of \$/Year)

<u>Year</u>	<u>Fossil Plants</u>	<u>Nuclear Plants</u>	<u>Fabrication Plants</u>	<u>Reprocessing Plants</u>	<u>Enrichment Plants</u>	<u>U₃O₈ Mines</u>	<u>ThO₂ Mines</u>
1970	5,383	34,510	27	-	133	213	-
1975	8,870	51,270	29	-	189	292	-
1980	7,819	90,390	66	-	321	502	-
1985	3,564	14,680	131	-	545	810	1
1990	3,272	16,850	144	674	480	447	6
1995	4,663	23,180	204	597	507	794	11
2000	4,970	26,970	267	635	574	766	9
2005	5,675	32,910	500	546	481	641	19
2010	6,847	39,400	726	733	821	567	25
2015	8,054	39,390	611	838	524	721	21
2020	11,400	41,560	838	1,031	372	266	28
2025	16,790	43,550	922	892	208	285	29
2030	22,060	44,350	611	760	152	106	19
2035	29,610	39,270	529	706	38	70	19
2040	45,840	29,730	531	564	28	59	16

Table F.28
CAPITAL CONSTRUCTION CASH FLOWS
FOR FULL RECYCLE--ALL REACTOR CASE
Large U Supply
(Millions of \$/Year)

<u>Year</u>	<u>Fossil Plants</u>	<u>Nuclear Plants</u>	<u>Fabrication Plants</u>	<u>Reprocessing Plants</u>	<u>Enrichment Plants</u>	<u>U₃O₈ Mines</u>	<u>ThO₂ Mines</u>
1970	5,380	3,450	27	-	133	213	-
1975	8,870	5,130	29	-	189	292	-
1980	7,820	9,040	66	-	321	502	-
1985	3,560	14,670	131	-	548	810	-
1990	3,270	16,760	126	677	517	525	1
1995	5,130	22,470	189	565	478	752	2
2000	4,970	26,950	329	640	532	567	7
2005	5,680	33,260	471	550	526	540	16
2010	6,850	39,420	622	696	612	625	23
2015	7,240	41,070	643	730	791	802	31
2020	11,090	42,680	713	912	649	448	33
2025	13,420	46,660	765	851	505	637	35
2030	21,020	44,140	740	927	316	242	34
2035	31,170	36,430	691	965	29	48	30
2040	46,930	28,820	760	782	22	71	26

Finally, yearly capital construction cash flows were calculated. The cash flows required for constructing fossil plants, nuclear plants, fabrication plants, reprocessing plants, enrichment plants, U_3O_8 mines and ThO_2 mines are presented in Tables F.11 through F.14 for small uranium supply and Tables F.25 through F.28 for large uranium supply.

Nuclear Plant Levelized Power Costs

The components of the levelized power cost for a plant starting up in 2007 is given in Table F.29. In addition to the standard components--capital, fixed charges, O & M, income tax, and fuel--the fuel cycle components are further subdivided into U-233, fissile plutonium, U_3O_8 , enrichment, fabrication, and reprocessing. These components were obtained from a single ALPS calculation in which all reactors were allowed to compete. The total levelized costs vary from 17.2 mills/kwhr for an FBR with a plutonium/thorium core and a thorium blanket to 24.0 mills/kwhr for a U-233 denatured CANDU. Although the CANDU's have a 3.6 mills/kwhr disadvantage in capital charge plus income tax with respect to the PWR, their fuel cycle was often significantly lower. Most reactors which rely entirely on uranium ore as a source of fissile fuel show a very high U_3O_8 cost--over 9 mills/kwhr for most plants. The slightly-enriched CANDU had the lowest fuel cycle cost (6.7 mills/kwhr), followed by the high-enriched HTGR (7.2 mills/kwhr) and the low-enriched spectrum-shift PWR (7.7 mills/kwhr). The naturally-enriched CANDU had a fuel cycle cost of 8.8 mills/kwhr, while the standard low-enriched PWR had a fuel cycle cost of 9.9 mills/kwhr.

The denatured reactors in general had higher fuel cycle costs than the comparable conventional design. This is in part due to a higher

Table F.29

COMPARISON OF LEVELIZED POWER COSTS (Mills/kwhr) FOR PLANTS STARTING UP IN YEAR 2025
All Reactor Case--Large Uranium Supply

Reactor	Total Cost Components						Fuel Cost Components					
	Total	Capital	Fixed Charges	Operation and Maintenance	Income Tax	Fuel	U233	Fissile Pu	U ²³⁸	Enrichment	Fabrication	Reprocessing
LWR-US(LE)/U	19.3	6.4	.6	.9	1.4	9.9	0.0	-1.5	8.6	1.5	.5	.8
LWR-US(LE)/U-T	21.2	6.4	.6	.9	1.4	11.9	0.0	0.0	9.6	1.6	.4	.3
LWR-US(DE)/U/Th	20.7	6.4	.6	.9	-1.4	11.3	-3.8	-0.8	11.7	2.8	.7	.8
LWR-US(DE)/U/Th	20.8	6.4	.6	.9	1.4	11.5	9.0	-0.9	0.0	0.0	2.6	.8
LWR-Pu/U	19.2	6.4	.6	.9	1.4	9.9	0.0	5.6	1.9	.0	1.6	.8
LWR-Pu/Th	19.6	6.4	.6	.8	1.4	10.4	-3.7	12.0	0.0	0.0	1.5	.7
SSCR-US(LE)/U	18.2	7.1	.7	1.1	1.6	7.7	0.0	-1.9	7.2	1.2	.5	.8
SSCR-US(DE)/U/Th	19.3	7.1	.7	1.1	1.6	8.9	6.4	-0.7	0.0	0.0	2.4	.7
SSCR-Pu/Th	19.6	7.1	.7	1.1	1.6	9.2	-4.4	11.4	0.0	0.0	1.5	.7
IMR-US(NAT)/U	22.8	9.3	.9	1.7	2.1	8.8	0.0	-3.1	7.8	.0	1.1	3.0
IMR-US(SRU)/U	20.8	9.3	.9	1.7	2.1	6.7	0.0	-1.7	6.1	.3	.6	1.4
IMR-US(DE)/U/Th	22.5	9.3	.9	1.7	2.1	8.4	-6.8	-0.2	10.7	2.6	.8	1.4
IMR-US(DE)/U/Th	24.0	9.3	.9	1.7	2.1	9.9	5.4	-0.3	0.0	0.0	3.4	1.4
IMR-Pu/U	21.8	9.3	.9	1.7	2.1	7.7	0.0	0.5	3.9	.0	1.9	1.4
IMR-Pu/Th	21.6	9.3	.9	1.7	2.1	7.5	-6.4	10.6	0.0	0.0	1.9	1.4
HTGR-US(LE)/U-T	21.3	7.3	.7	.9	1.6	10.8	0.0	0.0	8.2	1.7	.6	.2
HTGR-US(LE)/U	19.9	7.3	.7	.9	1.6	9.4	0.0	-0.5	7.1	1.5	.7	.6
HTGR-US(DE)/U/Th	19.4	7.3	.7	.9	1.6	8.8	-1.5	-.3	7.7	1.9	.6	.5
HTGR-US(DE)/Th	17.7	7.3	.7	.9	1.6	7.2	-2.7	-.0	6.8	1.8	.5	.7
HTGR-US(DE)/U/Th	19.3	7.3	.7	.9	1.6	8.8	6.6	-0.3	0.0	0.0	1.7	0.9
HTGR-US/Th	17.9	7.3	.7	.9	1.6	7.4	4.8	-.0	0.0	0.0	1.4	1.2
HTGR-Pu/Th	19.0	7.3	.7	.9	1.6	8.4	-1.1	8.3	0.0	0.0	1.1	.2
FBR-Pu-U/U	18.9	8.2	.8	1.0	1.8	7.1	0.0	3.1	0.0	0.0	2.4	1.6
FBR-Pu-U/Th	17.7	8.2	.8	1.0	1.8	5.9	-3.5	5.5	0.0	0.0	2.4	1.5

enrichment component of the fuel cycle cost. The denatured U-235 fueled PWR's have the highest enrichment component--2.8 mills/kwhr.

The cost penalty for fabricating fuels containing U-235 is reflected in significantly higher fabrication cost components for reactors loading this fuel. On the other hand, the reprocessing cost component was in general about 1 mill/kwhr for most reactors. The exception to this was the CANDU, where the lower discharge exposure results in a higher reprocessing cost component.

The fuel cycle component which varied the most from reactor to reactor was the fissile fuel component. The U-235 component varied from a cost of 12.6 mills/kwhr to a credit of 11.3 mills/kwhr. The fissile plutonium component varied from 13.1 to -5.0 mills/kwhr.

Appendix A

THORIUM ASSESSMENT PROGRAM SYSTEM STUDIES (Material Flows and Nuclear Power Growth Patterns)

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MATERIAL FLOWS AND GROWTH PATTERNS

Material flows diagrams for all cases of the Thorium Assessment Program Systems Study are presented in the following figures to show the impact of various fuel cycle policy decisions and reactor strategy options on uranium ore requirements and enrichment requirements. Fissile isotopes, thorium and heavy metal flows and relative market penetration by reactor type are also presented. The summation of heavy metal flows into reactors indicates fabrication plant requirement and out of reactors the reprocessing (or waste disposal for throwaway cycle) plant requirements. The year 2035 was chosen as a time when the system appeared to be in quasi-equilibrium--that is, U-233 and fissile plutonium stockpiles are near zero. All the above-mentioned material flows have been normalized to a total system capacity of 1 GWe.

The installed nuclear capacity table following each material flow diagram presents nuclear capacity information for four specific years--2000, 2030, 2035 and 2040--to show the trends of 1) total installed nuclear capacity (GWe), 2) the percent of that capacity in dispersed areas outside secure energy centers, and 3) the market penetration by each reactor type available in each particular case.

ONCE-THROUGH (THROWAWAY) - LWR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	459	197	145	113
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-U5(LE)/U	53	12	10	7
LWR-U5(LE)/U-T	47	88	90	93

THORIUM ASSESSMENT PROGRAM
U-233 and U-235 Recycle - LWR Reactors
(Small Uranium Supply)

U-233 AND U-235 RECYCLE - LWR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	490	369	280	202
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-US(LE)/U	79	20	19	20
LWR-US(DE)/U/Th	20	36	28	23
LWR-U3(DE)/U/Th	1	44	53	57

RESTRICTED RECYCLE - LWR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	584	1249	1255	1243
PERCENT IN DISPERSED AREA	95	59	52	46
PERCENT EACH REACTOR				
LWR-US(LE)/U	95	39	27	16
LWR-US(DE)/U/Th	-	20	25	30
LWR-Pu/Th	5	3	3	7
FBR-Pu-U/Th	-	38	44	46

FULL RECYCLE - LWR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	589	1291	1280	1295
PERCENT IN DISPERSED AREA	94	34	24	14
PERCENT EACH REACTOR				
LWR-U5(LE)/U	94	34	24	14
LWR-Pu/U	6	23	33	43
FBR-Pu-U/U	-	42	43	42

THORIUM ASSESSMENT PROGRAM
Once-Through (Throwaway) - SSCR Reactors
(Small Uranium Supply)

ONCE-THROUGH (THROWAWAY) - SSCR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	409	243	173	140
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-U5(LE)/U	99	26	21	16
SSCR-U5(LE)/U	10	74	79	84

U-233 AND U-235 RECYCLE - SSCR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	471	575	457	347
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-U5(LE)/U	73	9	7	5
LWR-U5(DE)/U/Th	25	34	25	20
SSCR-U3(DE)/U/Th	2	57	68	75

RESTRICTED RECYCLE - SSCR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	558	1536	1605	1626
PERCENT IN DISPERSED AREA	94	64	58	54
PERCENT EACH REACTOR				
LWR-U5(LE)/U	85	7	4	2
LWR-U5(DE)/U/Th	1	-	-	-
SSCR-U5(LE)/U	7	31	24	15
SSCR-U3(DE)/U/Th	1	25	30	37
SSCR-Pu/Th	6	3	6	9
FBR-Pu-U/Th	-	33	36	37

FULL RECYCLE - SSCR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	543	1453	1552	1556
PERCENT IN DISPERSED AREA	93	37	26	16
PERCENT EACH REACTOR				
LWR-U5(LE)/U	86	7	4	2
LWR-Pu/U	7	22	33	43
SSCR-U5(LE)/U	7	30	22	13
FBR-Pu-U/U	-	40	41	41

ONCE-THROUGH (THROWAWAY) - HWR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	443	158	129	121
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-U5(LE)/U	100	87	69	49
HWR-U5(SEU)/U	-	13	31	51

U-233 AND U-235 RECYCLE - LWR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	484	273	199	150
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-US(LE)/U	100	100	100	100

THORIUM ASSESSMENT PROGRAM
Restricted Recycle - HWR Reactors
(Small Uranium Supply)

RESTRICTED RECYCLE - HWR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	548	1297	1400	1540
PERCENT IN DISPERSED AREA	100	54	52	52
PERCENT EACH REACTOR				
LWR-U5(LE)/U	100	25	14	7
HWR-U5(DE)/U/Th	-	29	30	45
FBR-Pu-U/Th	-	46	48	48

FULL RECYCLE - HWR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	548	1230	1367	1603
PERCENT IN DISPERSED AREA	100	27	14	7
PERCENT EACH REACTOR				
LWR-US(LE)/U	100	27	14	7
FBR-Pu-U/U	-	73	86	93

ONCE-THROUGH (THROWAWAY) - HTGR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	427	175	137	124
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-US(LE)/U	99	52	40	26
HTGR-US(LE)/U-T	1	48	60	74

THORIUM ASSESSMENT PROGRAM
U-233 and U-235 Recycle - HTGR Reactors
(Small Uranium Supply)

U-233 AND U-235 RECYCLE - HTGR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	417	749	708	560
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-US(LE)/U	98	11	7	5
HTGR-US(LE)/U	-	-	1	3
HTGR-US(DE)/U/Th	2	68	66	57
HTGR-U3(DE)/U/Th	-	21	26	36

RESTRICTED RECYCLE - HTGR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	568	1411	1428	1453
PERCENT IN DISPERSED AREA	98	58	53	48
PERCENT EACH REACTOR				
LWR-U5(LE)/U	98	32	21	12
HTGR-U3(DE)/U/Th	-	26	32	36
HTGR-Pu/Th	2	3	5	10
FBR-Pu-U/Th	-	39	42	41

FULL RECYCLE - HTGR
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	539	1592	1744	1807
PERCENT IN DISPERSED AREA	97	9	5	3
PERCENT EACH REACTOR				
LWR-US(LE)/U	97	9	5	3
HTGR-US(HE)/Th	2	33	30	25
HTGR-U3/Th	-	24	29	34
HTGR-Pu/Th	2	7	10	15
FBR-Pu-U/U	-	26	25	24

ONCE-THROUGH (THROWAWAY) - ALL REACTORS
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWE	445	235	167	137
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-US(LE)/U	55	10	8	6
LWR-US(LE)/U-T	40	33	27	20
SSCR-US(LE)/U	6	57	64	74

U-233 AND U-235 RECYCLE - ALL REACTORS
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWE	426	777	688	542
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-US(LE)/U	78	6	4	3
LWR-US(DE)/U/Th	19	10	7	5
HTGR-US(LE)/U	-	-	-	2
HTGR-US(DE)/U/Th	2	50	51	48
HTGR-U3(DE)/U/Th	2	34	38	43

THORIUM ASSESSMENT PROGRAM
Restricted Recycle - All Reactors
(Small Uranium Supply)

FULL RECYCLE - ALL REACTORS
INSTALLED NUCLEAR CAPACITY
(SMALL URANIUM SUPPLY)

* YEAR	2000	2030	2035	2040
TOTAL GWE	555	1627	1734	1743
PERCENT IN DISPERSED AREA	90	13	7	4
PERCENT EACH REACTOR				
LWR-U5(LE)/U	83	6	3	2
LWR-Pu/U	6	6	3	2
SSCR-U5(LE)/U	7	7	4	2
HTGR-U5(HE)/TH	2	30	27	22
HTGR-U3/TH	0	21	26	31
HTGR-Pu/TH	2	5	11	15
FBR-Pu-U/U	0	25	25	25
HWR-U3(NAT)/U	-	-	-	-
HWR-U5(SEU)/U	-	-	-	-
HWR-Pu/U	-	-	-	-
HWR-U5(LE)/U	-	-	-	-

THORIUM ASSESSMENT PROGRAM
Full Recycle - All Reactors
(Small Uranium Supply)

RESTRICTED RECYCLE - ALL REACTORS
INSTALLED NUCLEAR CAPACITY
(SMALL-URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	564	1615	1722	1748
PERCENT IN DISPERSED AREA	92	65	61	55
PERCENT EACH REACTOR				
LWR-US(LE)/U	83	7	4	2
LWR-US(DE)/U/Th	1	-	-	-
LWR-Pu/Th	4	2	1	1
SSCR-US(LE)/U	7	36	29	21
SSCR-U3(DE)/U/Th	1	15	15	14
SSCR-Pu/Th	3	1	0	0
HTGR-U3(DE)/U/Th	-	7	12	18
HTGR-Pu/Th	1	1	6	12
FBR-Pu-U/Th	-	31	32	32

ONCE-THROUGH (THROWAWAY) - LWR INSTALLED NUCLEAR CAPACITY (LARGE URANIUM SUPPLY)				
YEAR	2000	2030	2035	2040
TOTAL GWe	573	618	456	323
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-US(LE)/U	52	7	5	4
LWR-US(LE)/U-T	48	93	95	96

TRIUMF ASSESSMENT PROGRAM
U-233 and U-235 Recycle - LWR Reactors
(Large Uranium Supply)

U-233 AND U-235 RECYCLE - LWR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	537	1001	893	758
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-U5(LE)/U	76	23	26	30
LWR-U5(DE)/U/Th	23	40	33	25
LWR-U3(DE)/U/Th	1	37	41	44

RESTRICTED RECYCLE - LWR INSTALLED NUCLEAR CAPACITY (LARGE URANIUM SUPPLY)				
YEAR	2000	2030	2035	2040
TOTAL GWe	634	1683	1708	1675
PERCENT IN DISPERSED AREA	95	62	56	51
PERCENT EACH REACTOR				
LWR-US(LE)/U	95	46	34	23
LWR-U3(HE)/U/Th	-	17	22	27
LWR-Pu/Th	5	3	5	8
FBR-Pu-U/Th	-	35	39	41

FULL RECYCLE - LWR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	634	1709	1798	1775
PERCENT IN DISPERSED AREA	94	42	32	23
PERCENT EACH REACTOR				
LWR-US(LE)/U	94	42	32	23
LWR-Pu/U	6	24	33	42
FBR-Pu-U/U	-	34	35	35

THORIUM ASSESSMENT PROGRAM
Once-Through (Throwaway) - SSCR Reactors
(Large Uranium Supply)

ONCE-THROUGH (THROWAWAY) - SSCR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	540	695	545	388
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-U5(LE)/U	93	19	15	12
SSCR-U5(LE)/U	7	81	85	88

U-233 AND U-235 RECYCLE - SSCR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	576	1104	1175	987
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-U5(LE)/U	75	7	4	3
LWR-U5(DE)/U/Th	24	37	28	22
SSCR-U3(DE)/U/Th	1	48	52	53
SSCR-U5(LE)/U	-	8	16	23

THORIUM ASSESSMENT PROGRAM
Restricted Recycle - SSCR Reactors
(Large Uranium Supply)

RESTRICTED RECYCLE - SSCR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	626	1864	1987	2073
PERCENT IN DISPERSED AREA	94	69	63	60
PERCENT EACH REACTOR				
LWR-U5(LE)/U	87	11	6	3
SSCR-U5(LE)/U	6	37	32	26
SSCR-U3(DE)/U/Th	-	21	25	31
SSCR-Pu/Th	6	5	7	10
FBR-Pu-U/Th	-	26	30	30

THORIUM ASSESSMENT PROGRAM
Full Recycle - SSCR Reactors
(Large Uranium Supply)

FULL RECYCLE - SSCR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	543	1453	1964	1556
PERCENT IN DISPERSED AREA	94	44	36	28
PERCENT EACH REACTOR				
LWR-US(LE)/U	88	10	6	3
LWR-Pu/U	6	27	35	43
SSCR-US(LE)/U	7	34	30	25
FBR-Pu-U/U	-	29	29	29

THORIUM ASSESSMENT PROGRAM
Once-Through (Throwaway) - LWR Reactors
(Large Uranium Supply)

ONCE-THROUGH (THROWAWAY)- LWR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	563	507	356	265
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-US(LE)/U	100	100	96	89
LWR-US(SEU)/U	-	-	4	11

U-233 AND U-235 RECYCLE - INWR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	573	791	635	456
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-U5(LE)/U	100	100	100	100

THORIUM ASSESSMENT PROGRAM
Restricted Recycle - HWR Reactors
(Large Uranium Supply)

RESTRICTED RECYCLE - HWR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	634	1802	2008	2187
PERCENT IN DISPERSED AREA	100	56	55	53
PERCENT EACH REACTOR				
LWR-US(LE)/U	100	35	21	12
HWR-U3(DE)/U/Th	-	21	33	42
FBR-Pu-U/Th	-	44	45	47

THORIUM ASSESSMENT PROGRAM
Full Recycle - LWR Reactors
(Large Uranium Supply)

FULL RECYCLE - LWR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	634	1775	1927	2166
PERCENT IN DISPERSED AREA	100	36	22	12
PERCENT EACH REACTOR				
LWR-US(LE)/U	100	36	22	12
FBR-Pu-U/U	-	64	78	88

ONCE-THROUGH (THROWAWAY) - HTGR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	563	556	409	318
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-U5(LE)/U	100	59	47	36
HTGR-U5(LE)/U-T	-	41	53	64

U-233 AND U-235 RECYCLE - HTGR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	561	1265	1234	1096
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-U5(LE)/U	98	19	12	8
HTGR-U5(LE)/U	-	-	1	5
HTGR-U5(DE)/U/Th	2	63	65	59
HTGR-U3(DE)/U/Th	-	18	22	29

THORIUM ASSESSMENT PROGRAM
Restricted Recycle - HTGR Reactors
(Large Uranium Supply)

RESTRICTED RECYCLE - HTGR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030
TOTAL GWe	634	1814
PERCENT IN DISPERSED AREA	99	62
PERCENT EACH REACTOR		
LWR-U5(LE)/U	99	39
HTGR-U3(DE)/U/Th	-	23
HTGR-Pu/Th	1	4
FBR-Pu-U/Th	-	34

FULL RECYCLE - HTGR
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	626	1903	2046	2140
PERCENT IN DISPERSED AREA	98	18	10	5
PERCENT EACH REACTOR				
LWR-U5(LE)/U	98	18	10	5
HTGR-U5(HE)/Th	1	31	31	29
HTGR-U3/Th	-	20	26	32
HTGR-Pu/Th	1	11	12	14
FBR-Pu-U/U	-	21	21	19

ONCE-THROUGH (THROWAWAY) - ALL REACTORS
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	571	670	508	380
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-US(LE)/U	52	6	4	4
LWR-US(LE)/U-T	43	56	45	35
SSCR-US(LE)/U	-	38	51	61

U-233 AND U-235 RECYCLE - ALL REACTORS
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)-

YEAR	2000	2030	2035	2040
TOTAL GWe	561	1359	1285	1140
PERCENT IN DISPERSED AREA	100	100	100	100
PERCENT EACH REACTOR				
LWR-U5(LE)/U	77	6	4	3
LWR-U5(DE)/U/Th	20	13	8	5
SSCR-U3(DE)/U/Th	-	2	1	1
HTGR-U5(LE)/U	-	-	1	4
HTGR-U5(DE)/U/Th	2	47	51	50
HTGR-U3(DE)/U/Th	1	31	35	37

THORIUM ASSESSMENT PROGRAM
Restricted Recycle - All Reactors
(Large Uranium Supply)

RESTRICTED RECYCLE - ALL REACTORS
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	626	1615	2000	2077
PERCENT IN DISPERSED AREA	91	70	63	58
PERCENT EACH REACTOR				
LWR-US(LE)/U	84	11	6	4
LWR-Pu/Th	5	3	2	1
SSCR-US(LE)/U	6	39	34	28
SSCR-U3(DE)/U/Th	1	14	13	11
SSCR-Pu/Th	3	1	-	-
HTGR-U3(DE)/U/Th	-	6	10	16
HTGR-Pu/Th	1	1	6	11
FBR-Pu-U/Th	-	25	28	28

THORIUM ASSESSMENT PROGRAM
Full Recycle - All Reactors
(Large Uranium Supply)

FULL RECYCLE - ALL REACTORS
INSTALLED NUCLEAR CAPACITY
(LARGE URANIUM SUPPLY)

YEAR	2000	2030	2035	2040
TOTAL GWe	620	1923	2065	2127
PERCENT IN DISPERSED AREA	91	12	6	3
PERCENT EACH REACTOR				
LWR-US(LE)/U	85	8	4	2
LWR-Pu/U	6	10	5	3
SSCR-US(LE)/U	6	4	2	1
HTGR-US(HE)/Th	2	38	38	35
HTGR-U3/Th	-	23	30	37
HTGR-Pu/Th	2	4	7	9
FBR-Pu-U/U	-	13	13	12

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ANNEX 2

TECHNICAL ASPECTS OF THORIUM UTILIZATION

by
Norton L. Shapiro
Combustion Engineering, Inc.

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TECHNICAL ASPECTS OF THORIUM UTILIZATION

2.1 INTRODUCTION

The possibility of utilizing thorium as a fuel for nuclear reactors has been recognized since 1946 when it was discovered that Th-232 could be transmuted into the fissile isotope U-233, and interest in utilizing thorium-based fuels in thermal reactors has persisted over the years because of the superior nuclear characteristics of U-233. Although thorium fuels have been employed in experimental and demonstration programs, large-scale commercial utilization of thorium has not evolved for a number of reasons. The U.S. Nuclear Power Development Program, from its inception, has been predicated on the development of breeder reactors toward the latter part of the 20th century. Thermal reactors, such as those currently employed throughout the U.S., were viewed as an interim source of electrical power and as a means of developing the technology and of generating the fissile material required for the eventual deployment of the fast breeder reactor. The superior performance in fast reactors of the plutonium bred from uranium fuels, and the more extensive development of the uranium fuel cycle for military applications led to a decision to develop nuclear reactors based on the uranium fuel cycle. Subsequent assessments of thorium utilization, performed in the 60s, identified a number of incentives for thorium utilization, but concluded that the uranium cycle would be more economical, under the economic conditions of the time, for the light-water-moderated reactors (LWR) being deployed.

A number of economic and political changes have occurred since the decision was initially made to develop nuclear reactors based on uranium fuels and since the last comprehensive review of thorium utilization was performed by the AEC in 1969. Foremost of these has been the developing concern of the proliferation of nuclear weapons, which has resulted in a decision to postpone indefinitely plutonium utilization and the deployment of the plutonium-fueled fast breeder reactor in the U.S., and to encourage other nations to adopt a similar policy. As a result of this decision, thermal converter

reactors will have to play a more significant and longer-term role in the generation of nuclear power than had previously been anticipated, thus placing an increased emphasis on the potential of alternate fuel cycles for uranium resource conservation. The changed economic climate, in particular the significant increase in uranium price over the past few years, has also increased the incentive to consider the development of alternatives, such as thorium fueling, which reduce uranium demand. In this chapter, the technical, economic and resource utilization aspects of thorium utilization are reviewed to establish the advantages and disadvantages of thorium utilization with respect to the changed political and economic considerations mentioned above.

2.2 RESULTS OF PREVIOUS STUDIES

An examination of the most recent comprehensive assessment of thorium utilization performed by the AEC in June 1969, WASH 1097¹, highlights some of the reasons why thorium has not received a high level of support for commercial development. An essential ground rule used in this earlier report is a supposition that the primary incentive for the development of nuclear power was economic--more specifically, the reduction in the cost of power. Whether a specific reactor uses a thorium or uranium cycle was viewed to depend upon the expected economics of the respective cycles for the applicable financial and technological conditions, and on the impact of the specific fuel strategies selected upon the overall electric system economics. The report did consider the efficiency of natural resource utilization, that is, how much electrical power can be produced from a given ton of mined uranium ore, but the key conclusions with respect to the potential for commercial deployment were primarily based on the economic incentive. Key conclusions from this report are summarized briefly below.

1. The possibility of utilizing thorium fueling in the light-water-moderated reactor (LWR), the heavy-water-moderated reactor (HWR), the high-temperature gas-cooled reactor (HTGR), the molten salt breeder reactor (MSBR), and the fast-breeder reactor (FBR) were assessed with the conclusion that thorium fueling could be used in each type.

2. Under the economic ground rules employed in the study (e.g., \$8/lb U_3O_8), the uranium cycle was viewed to be more economical than the thorium cycle in the LWR or HWR.
3. The Indian Point PWR was operated initially with U-235 enriched thorium fuel. This plant successfully demonstrated the possibility of using the thorium fuel cycle in an LWR, as well as the ability of converting completely to the uranium fuel cycle in the same plant. (It should be noted, however, that irradiation demonstrations of the performance of thorium-based fuels in fuel rods of modern design will probably also be required). The report concluded, however, that there was no economic motivation to pursue the thorium cycle in presently-developed water reactors unless economic factors changed significantly from those prevalent at the time of the study.
4. The use of heavy water as a moderator permits the use of natural or slightly-enriched uranium as fuel. The resulting fuel inventory and make-up cost with the uranium cycle are so low that very large changes in the uranium ore cost were judged necessary to make the thorium cycle economically competitive.
5. The use of thorium fueling in such reactors as the high-temperature gas-cooled reactor (HTGR) and the molten-salt-breeder reactor (MSBR) appear to be more economic. Although more of the expensive, highly enriched U-235 is used, the increased fissile inventory cost is more than compensated by the savings in fuel depletion cost achieved with the thorium fuel cycle due to the higher fuel conversion ratio. In the future (after about the late 70s), the use of thorium in the HTGR indicated a potential levelized fuel cycle cost savings of up to 0.4 mils/kwhr, and in the more distant future (after about 1985) the use of the thorium cycle in the MSBR indicated potential fuel cycle cost savings of up to 1.0 mils/kwhr over those obtainable with LWRs operating on either the thorium or uranium cycles.

6. Since the fuel inventory costs of reactors using the thorium cycle are higher than those of reactors using the uranium cycle, high interest rates on the fuel inventory penalizes the thorium cycle more than uranium; conversely, lower interest rates favor the thorium cycle. Future increases in uranium ore cost and/or decreases in the cost of enrichment tend to favor the thorium cycle relative to the use of the uranium cycle.
7. Because thorium does not contain any natural occurring fissile material, U-235 is required for initial inventory and burnup, and therefore the requirements for both uranium and thorium ores must be evaluated when considering the use of the thorium fuel cycle.
8. The economic development of the thorium fuel cycle will significantly increase our economically exploitable resources of nuclear fuel. Although there is little incentive to develop the thorium fuel cycle solely to increase the supply of fertile material (because of the abundance of the fertile material U-238), the higher conversion ratios which can be obtained in thermal spectrum reactors using the bred U-233 instead of Pu-239, can result in significantly better utilization of natural uranium fuel resources in thorium-fueled reactors than with low-enrichment uranium fuel.
9. The economic utilization of nuclear resources is not necessarily consistent with optimal conservation of these resources.

Overall, WASH-1097 concluded in 1969 that although the thorium fuel cycle had certain inherent technical features, such as improved fuel utilization in thermal spectrum reactors, the fuel cycle economics were not sufficiently favorable to justify the commercial development of the thorium cycle in the U.S. at that time, at least for LWRs and FBRs. The report pointed out that, in general, various applications of the thorium fuel cycle appeared technically feasible, although some additional R&D would be required. Noting that the LWR and HTGR applications had been demonstrated, the

report concluded that technical feasibility would not prevent commercial deployment of the fuel cycle, at least in these reactor applications.

In addition to the WASH-1097 study, numerous other evaluations of thorium have been made over the past 10 - 15 years. A bibliography of the most relevant of these is provided.*

2.3 THE NEED FOR A REVISED ASSESSMENT OF THE THORIUM CYCLE

Although the conclusions reached in the 1969 WASH-1097 study, and in other previous evaluations, are generally valid today, a number of political and economic changes have evolved since the time of this study which necessitate a careful reevaluation of the incentives for thorium utilization. These current-day factors are discussed briefly below.

1. Conclusions as to the desirability of implementing the thorium option have, in the past, been viewed almost entirely within the context of the economic competition with the uranium fuel cycle. At the time of these previous studies, nuclear power was striving to compete economically with the then inexpensive fossil-fuel alternatives, and the deployment of alternate fuel cycles which might lead to a competitive disadvantage for nuclear power was unattractive. Although the cost of uranium ore and enrichment services has increased over the years, the cost of alternate energy sources has increased even more rapidly so that nuclear power now enjoys a significant cost advantage in most areas of the nation. Fuel cycle economics, of course, remains an important consideration in the selection of fueling options; in the absence of other mitigating considerations, the most economical alternative would undoubtedly be selected. However, alternatives such as thorium fueling can at least now be considered even though they may not represent the economic optimum alternative provided they contribute in other ways to the energy goals of the nation without seriously compromising the economics of nuclear power with respect to other alternatives. Such goals as a reduction in the potential for nuclear weapons

* See Appendix A, Volume 1.

proliferation and the conservation of uranium resources are considerations which are not necessarily reflected in the economic intercomparison of alternate fuel cycles.

2. At the time of previous studies, the breeder reactor, with the promise of inexpensive and essentially resource unlimited power, was perceived to be realizable in the not too distant future, and hence the uranium conservation aspects of alternate fuel cycles were of less importance. Relatively recently, concerns for the potential for nuclear weapons proliferation have received prominence, and have resulted in President Carter's April 7, 1977 decision to defer commercial reprocessing and the deployment of the plutonium-fueled LMFBR. The deferment of the LMFBR Program has contributed to growing concerns over the adequacy of uranium resources and production capacity, and has heightened interest in alternate fuel cycle and reactor concepts which might extend uranium resources in the absence of an LMFBR, or for use in conjunction with modified LMFBR concepts.
3. Since 1969, the price of uranium ore has risen from \$8/lb to current prices of \$30/lb or more. Although the price of uranium in the near term is difficult to predict, since it is subject to supply and demand considerations, the long-term trend should be for uranium prices to increase, reflecting the increasing scarcity of uranium as more economically recoverable deposits are consumed. Increases in uranium price will tend to make the thorium cycle more competitive with respect to uranium fueling. The cost of other fuel cycle components, such as the cost of enrichment services, have also increased and these increases will tend to reduce the incentive for thorium utilization; however, a number of technological innovations, such as centrifugal and eventually laser enrichment, are foreseen, which might provide further economic incentive for thorium fueling by reducing the cost of separative work. At any rate, it is clear that a number of economic factors have changed so significantly from those employed in the WASH-1097 evaluation, that a re-evaluation of the economic incentives for thorium utilization is required.

4. As mentioned above, many of the current investigations of alternate fuel cycles have been motivated by considerations of nuclear weapons proliferation. Central to most proliferation resistant fuel cycle alternatives is the reduction or elimination of plutonium utilization in non-weapons states. Although the once-through cycle which is currently employed achieves this objective, it is gained at the expense of uranium resource conservation and of an assured long-term fissile fuel supply. Certain thorium fuel cycles offer the potential of a more proliferation-resistant fuel cycle while providing an appreciably more efficient resource utilization. This incentive for the thorium fuel cycle is discussed in more detail in Section 2.4.

5. At the time the initial thorium utilization assessments were performed, the nuclear capacity on line, under construction, or committed was very small. The WASH-1097 analysis could then consider in an even-handed way a variety of alternate fuel cycles and reactor types, since the future U.S. nuclear economy was not committed to any particular path. Today, however, more than 45 Gwe of LWR capacity is in operation in the U.S. and more than 200 Gwe of LWRs are committed by 1990. Consequently, it is clear that the characteristics of the overall vs. nuclear economy will be dominated by the performance of the LWR until well into the 21st century. Consequently, an analysis of the impact of alternate fuel cycles or reactor types must consist of a systems analysis in which the existing and planned LWR capacity is represented along with any modified fuel cycles or reactor types contemplated for future deployment. Since a substantial fraction of our potential uranium resources will be required to fuel these LWRs, assessments performed today must address such questions as whether the remaining uranium base is sufficiently large to make worthwhile the deployment of alternate reactor types or fuel cycles, and questions of whether more efficient thorium fuel cycles can be backfit into planned LWR capacity.

2.4 FEATURES OF THE THORIUM CYCLE

2.4.1 Nuclear Characteristics

Thorium is a natural occurring element which is about three times more abundant in the earth's crust than uranium. Thorium occurs in nature as essentially pure Th-232 which, like U-238, is a fertile material. When irradiated by neutrons in a reactor, Th-232 is converted into a fissile isotope of uranium, U-233, in a manner analogous to the conversion of U-238 into Pu-239.

The isotopic buildup in thorium and uranium is compared in Figure 2.1. The capture of a neutron in Th-232 or U-238 leads, after the β decay of an intermediate isotope, to the production of a fissile isotope, U-233 in the case of thorium and Pu-239 in the case of uranium. Absorption of a neutron by these fissile isotopes leads either to fission or to the fertile isotopes U-234 or Pu-240 which in turn can be transmuted to the fissile isotopes U-235 or Pu-241 by the capture of an additional neutron. Neutron absorption in either of these fissile isotopes lead either to fission or to the production of parasitic neutron absorbers.

The U-235 component of uranium is the only fissile material present in any significant quantity in nature. Since natural thorium contains no fissile component comparable to U-235, the use of a thorium fuel cycle does not preclude the need for uranium. U-235 from uranium ore must either be used directly with thorium to start the cycle or indirectly in a uranium cycle to produce plutonium which, in turn, would provide the initial fissile component in a thorium cycle. For reactors other than the breeder reactor (converter reactors) annual additions of fissile material are required to supplement the fissile material bred during the cycle. Here again, U-235 obtained from uranium ore or plutonium produced in the uranium cycle is necessary for continued operation. In this sense, the thorium cycle is coupled to the uranium cycle and the availability of uranium ore.

As mentioned above, thorium consists of the fertile material Th-232 and consequently thorium is an alternative to the fertile component of uranium

Figure 2.1 THE ISOTOPIC BUILDUP IN THORIUM AND URANIUM

U-238, rather than a replacement for uranium ore itself. The large quantities of uranium required for our nuclear industry are not needed for the U-238 content, but for the U-235 which is also present in small quantities in uranium ore. Since thorium, unlike uranium, does not contain a fissile component, thorium, per se, adds nothing significant to our nuclear fuel resources; there is no need for quantities of fertile material larger than those already available as U-238 in our natural uranium resources. The fissile isotope U-233 produced from thorium, however, does have somewhat different characteristics from the fissile plutonium produced from U-238, which result in superior performance when utilized in thermal reactors. The superior performance in thermal reactors of the U-233 bred from thorium, as compared to the characteristics of plutonium bred from uranium, provides the incentive for use of thorium fueling.

In particular, the number of excess neutrons available from fission ($\eta-1$) of U-233 is larger than that of Pu-239 or U-235 in thermal-spectrum reactors. Representative values of η are given for a typical PWR thermal spectrum in Table 2.1, and illustrates a greater neutron production per neutron absorbed in U-233, particularly with respect to Pu-239. Because of a larger number of excess neutrons from U-233, more neutrons are available to breed additional quantities of fissile material. When recycle is performed, these

TABLE 2.1
REPRESENTATIVE η (η) VALUES FOR
(Thermal Spectra (Ref. 4))

	U-233	U-235	Pu-239	Pu-241
η (0.025 eV)	2.30	2.07	2.11	2.15
η (Typical PWR Thermal Spectrum)	2.27	2.06	1.84	2.17
η epi (Typical PWR Epithermal Spectrum)	2.16	1.67	1.88	2.49

differences mean that a smaller amount of uranium is needed to produce a given amount of energy if thorium is used as the fertile material (i.e., the thorium cycle) than if U-238 is used as the fertile material (i.e., the uranium cycle).

Although the η values of U-233 are higher than those of Pu-239 in the thermal spectra characteristic of converter reactors, a different situation exists in the spectra characteristic of liquid metal or gas-cooled fast breeder reactors. Representative η values for the fast breeder reactor are given in Table 2.2. As this table illustrates, the η value of Pu-239 is somewhat higher than that of U-233 in a fast spectrum and that the η value of Pu-241 is significantly higher than that of U-235, the corresponding isotope in the thorium isotopic build-up sequence. Consequently, it can be concluded that U-233 is a preferred fissile fuel for thermal spectrum reactors, but that superior performance is obtained in fast breeder reactors using plutonium fueling.

Within the context of thermal reactors, the η value of U-233 is also much less sensitive to neutron spectrum than that of plutonium which exhibits a

TABLE 2.2
REPRESENTATIVE η (η) VALUES FOR
Fast Breeder Spectra (Reference 1)

<u>Nuclide</u>	<u>η</u>
U-233	2.31
U-235	1.93
Pu-239	2.49
Pu-241	2.72
Th-232	0.076
U-238	0.411
Pu-240	1.315

decrease in the number of neutrons produced per fission in a hard (higher energy) thermal spectrum. This characteristic is illustrated in Table 2.3. This attribute of U-233 is important in maintaining the nuclear performance high temperature concepts, such as the HTGR.

Another nuclear attribute which is worth noting is that thorium has a higher absorption cross section than does U-238. As Table 2.4 illustrates, the thermal capture cross section of Th-232 is about three times larger than the value of U-238, while the Th-232 infinitely dilute resonance integral is about three times smaller than the U-238 value. In thermal reactors, lumping of the fuel into rods reduces the effective resonance capture through self-shielding of the resonances, and results in effective resonance capture integrals which are roughly comparable in Th-232 and U-238. The effect of the larger thermal cross section of Th-232, however, leads to the need for higher initial fissile enrichments for thorium cycles.

Overall, the nuclear properties of U-233 provide an advantage to the uranium cycle, primarily by reducing the fissile requirements for criticality in heterogeneous thermal reactors. The superior performance of U-233 on the other hand, provides an advantage to thorium fueling primarily by increasing the conversion ratio of thermal reactors and

TABLE 2.3
TYPICAL THERMAL-SPECTRUM-AVERAGED ETA VALUES
(Reference 1)

<u>Temp., °C</u>	<u>Eta</u>		
	U-233	U-235	Pu-239
0	2.29	2.06	1.87
300	2.29	2.05	1.82
600	2.29	2.04	1.79
900	2.28	2.03	1.77

TABLE 2.4
CROSS SECTIONS FOR U-238 and Th-232
(Reference 4)

	Thermal (0.025 eV)		Infinitely Dilute Resonance Integral	
	<u>Th-232</u>	<u>U-238</u>	<u>Th-232</u>	<u>U-238</u>
Absorption, σ_a	7.40	2.73	85.78	273.57
Capture, σ_c	7.40	2.73	85.20	272.37
Fission, σ_f	0	0	0.58	1.20

hence reducing the quantities of fissile material required to supplement that bred during operation. This competition between the higher initial loadings required with thorium refueling and the reduced annual fissile makeup requirement is discussed in greater detail in Section 2.6.

2.4.2 Fuel Cycles

basic fuel cycle alternatives are shown in Figure 2.2 for the uranium cycle and in Figure 2.3 for the thorium cycles. Figure 2.2 (a) illustrates the fuel cycle currently in place today where spent fuel is stored either for eventual reprocessing or permanent disposal. Figure 2.2 (b) illustrates the case where uranium and plutonium recycle are performed; the recycle of uranium only could also be contemplated with the plutonium either stored for future use or diverted to the waste stream. Figure 2.2 (c) illustrates a similar recycle mode in which plutonium is utilized in reactors dedicated for that purpose.

A basic thorium fuel cycle is illustrated in Figure 2.3 (a). The initial fissile loading and makeup fissile requirements are provided by highly-enriched (93 w/o U-235) uranium. The U-235 remaining in the fuel at end of cycle and the bred U-233 can be recycled as illustrated, while alternately the spent fuel can be stored for future reprocessing or ultimate

Figure 2.2
Simplified Uranium Fuel Cycles

3.2(a) Once Through Cycle

3.2(b) U and Pu Recycle

3.2(c) Pu Recycle AT Energy Centers

* LEU < 20% U-235

Figure 2.3
Simplified Thorium Fuel Cycles

3.3(a) Highly Enriched Cycle

3.3(b) Pu Enriched Thorium Cycle

Figure 2.3 (Continued)

3.3(c) Denatured Fuel Cycle

3.3(d) Denatured Fuel Cycle with FBR

- * MEU > 20% U-235 or > 12% U-233
- * LEU < 20% U-235 or < 12% U-233
- * MEU (denatured fuel) ≤ 20% U-235 or ≤ 12% U-233

waste disposal. Figure 2.3 (b) illustrates the thorium fuel cycle in which plutonium is used in place of U-235 for enrichment. This fuel cycle, of course, requires the operation of reactors on the uranium fuel cycle to produce the required quantities of plutonium. Figure 2.3 (c) illustrates the "denatured" thorium fuel cycle. This fuel cycle is similar to the highly enriched case illustrated in Figure 2.3 (a) with the exception that uranium enriched to less than 20 w/o U-235 or less than 12 w/o U-233 is employed for enrichment rather than the 93 w/o U-235 material of the highly-enriched thorium fuel cycle. Because of the U-238 content of the denatured fuel, some plutonium will be produced. This plutonium could either be stored as a future natural energy asset as illustrated in the figure, or utilized directly to fuel thorium-based converter reactors (similar to that illustrated in Figure 2.3 (b)), or to fuel thorium-blanketed fast breeder reactors as indicated in Figure 2.3 (d).

2.4.3 Non-Proliferation Considerations²

The objective of this report is to assess the technical and economic feasibility of thorium utilization rather than to discuss in detail proliferation aspects of the various alternative fuel cycles. Nonetheless, it is necessary to give some qualitative consideration to non-proliferation aspects in order to establish potential incentives for thorium utilization, and to include in the technical options under consideration those thorium refueling alternatives which might contribute to the safeguarding of the nuclear fuel cycle. In reviewing non-proliferation considerations, it is important to recognize that no fuel cycle alternative can completely eliminate the possibility of proliferation. Rather, the objective of proliferation-resistant fuel cycles is to increase the difficulty and length of time required to obtain nuclear weapons materials, so that developing nuclear weapons through power reactor programs becomes unattractive in comparison to other potential technologies. In particular, the objective is to identify fuel cycles which would allow the resource conservation possible with recycle, and eventually with the breeder reactor, to be obtained without increasing the potential for nuclear weapons proliferation.

U-233, like U-235 or plutonium, can be used to make nuclear weapons. The critical masses of fully reflected spheres of various fissile materials are given in Table 2.5. These critical masses are indicative of the quantities of fissile material required to construct a nuclear weapon. As the table illustrates, roughly the same quantity of U-233 is required as Pu-239. Since the spontaneous fission rate of power reactor grade U-233 is significantly lower than power reactor plutonium, U-233 is probably a more useful material for rapid assembly into prompt critical configurations.

TABLE 2.5

CRITICAL MASS OF FISSILE SPHERES
REFLECTED BY NATURAL URANIUM²

Major Isotope	Critical Mass (kg)
U-233 (98%)	5.63
U-235 (93%)	17.86
Pu-239 (95%)	5.91

Since U-235 and U-233 can be chemically separated from thorium, just as plutonium can be chemically separated from uranium, the thorium cycles illustrated in Figure 2.3 (a) provide as simple a source for diversion of weapons material as the plutonium cycle itself; indeed, greater quantities of weapons-grade material are present in the fuel cycle because of the use of highly-enriched uranium for initial inventories. The plutonium used in the fuel cycle illustrated in Figure 2.3 (b), can also be chemically separated, and it presents a situation analogous to the use of plutonium in uranium fuels.

It should be noted that of primary concern is the presence of weapons-grade material either in pure form or in fresh unirradiated fuel. Weapons material in a pure form, such as may be present at a reprocessing plant, could most easily be utilized in a nuclear weapon; however, a high degree of safeguards can be obtained by applying adequate accountability and physical security

asures at the reprocessing facility. The concepts of international and multinational reprocessing centers are currently the subject of investigation, and it appears likely that an acceptable degree of safeguards can be applied to reprocessing facilities within the context of these concepts. Less amenable to physical security measures is the presence of weapons-grade material in fresh unirradiated fuel, since such fuel would have to be shipped to diverse reactor sites. Of less concern is the fissile material contained in spent highly irradiated reactor fuel. Although this material can be chemically separated, the highly radioactive fission products necessitate that these chemical operations be performed in elaborate and specially designed facilities. This contrasts to fresh fuel where reprocessing operations would be much simpler because of the absence of the radioactive fission products.

One point worth noting is that recycled U-233, although suitable for use in weapons, contains trace quantities of U-232, which is produced during irradiation in the reactor and which cannot be chemically separated from the fissile U-233. U-232 has daughter nuclides that emit high energy gamma rays. Although the irradiations from U-232 would in general be insufficient to preclude assembling a nuclear device, the U-232 contamination does lead to the following non-proliferation advantages:

- a. As a result of the gamma ray emissions from the daughters of U-232, the sensitivity of special nuclear material detection instruments is significantly greater for U-233 than for plutonium U-239 or uranium U-235. For example, commercially available special nuclear material monitors, which can detect 0.5 gms of Pu-239, should be able to detect less than 0.05 gms of U-233 fuel that has not been chemically cleaned for a period of one month or longer.
- b. One daughter of U-232, Tl-208, emits a 2.6 Mev gamma ray. This high energy gamma has high penetrability in all shielding materials because the minimum mass absorption coefficients for all shields occur near this energy. As a consequence, search and recovery operations for U-233 materials can be assisted by aerial scanning units similar to those used for environmental monitoring.

- c. For bulk quantities of U-233, the gamma ray emissions are of an intensity that requires moderate (2 to 3 feet of concrete) shielding for processing operations. Thus, access to U-233 is necessarily restricted throughout processing. The dose rates anticipated without shielding are high by occupational exposure standards; however, they are well below dose rates that would cause near-term health effects.

Overall, Th/U-233 fuels are thought to be significantly better than Th/U-235 or plutonium-bearing fuels, but much worse than the low-enrichment uranium fuel currently employed in providing inherent domestic and international safeguards against a possible terrorist explosive threat. This advantage results from the increased detectability of U-233 and from the limited access to U-233 necessitated by the shielding required for processing. From the standpoint of international proliferation, U-233-bearing fuels are only marginally better than plutonium-bearing fuels because the processing technologies are well within the reach of most nations.

The denatured thorium fuel cycles, illustrated in Figure 2.3 (c and d), offer a more significant barrier against nuclear material diversion and weapons proliferation. Such denatured thorium fuel employs uranium enriched to either less than 20 w/o U-235 or less than 12 w/o U-233 to provide the required fissile materials. Although the uranium can be chemically separated from the thorium, the resulting U-235 or U-233 content is sufficiently small to make construction of a nuclear device impractical. Sophisticated isotopic concentration facilities would be required to concentrate the U-233 or U-235 sufficiently for use in a nuclear weapon. This contrasts with the use of plutonium or highly-enriched uranium which can be more easily separated from the uranium or thorium diluent using chemical techniques. Because of the mass difference between U-233 and U-238 and the enrichments used in denatured fuels, the concentration of fissile material would be easier (requires less SWU) than U-235 enrichment of natural or slightly enriched uranium. However, although fewer enrichment stages would be required to upgrade denatured U-233 to enrichments suitable for use in nuclear weapons, isotopic separation equipment would still be required, and the development of such equipment is at

least currently beyond the capabilities of most lesser developed nations; at any rate, if such isotopic separation equipment were deployed, weapons material could be obtained by the enrichment of natural uranium so that the presence of denatured fuel in the fuel cycle might not necessarily contribute materially to the possibility of obtaining weapons materials.

Overall, the use of denatured fuels might eliminate both domestically and internationally the possibility of terrorist groups constructing a nuclear device. From the standpoint of international proliferation, the use of denatured fuels would impose a significant delay in proliferation because of the necessity of constructing enrichment facilities to concentrate the U-233, or of constructing reprocessing facilities to extract plutonium from the spent fuel. Except for the smaller enrichment capacities needed to enrich U-233 fuel, as mentioned above, the effort required to obtain weapons-grade material is equivalent to that which would be required using the low-enrichment cycle currently employed. Consequently, this fuel is judged as significantly better for use in unsecured power reactor plants than either the plutonium-uranium cycle or the highly-enriched thorium cycle, assuming that processing is controlled and performed in safeguarded facilities.

2.4.4 Thorium Supply and Demand

Thorium is about three times more abundant in the earth's crust than uranium, reflecting the difference in the half lives of Th-232 (1.4×10^{10} yrs) and U-238 (4.5×10^9 yrs). However, the recoverable resources of thorium are highly uncertain, because, unlike uranium, the demand and exploration for thorium has been very limited. Total U.S. thorium consumption, in all forms, in 1974 was estimated at 80 ST³. Only small quantities of this thorium were consumed for energy purposes. Except where thorium can be produced as a by-product of uranium mining, the principal source of thorium is monazite, a by-product of beach-sand mining. Monazite is recovered for its rare earth content; after these rare earths are recovered, the residues may be processed for thorium. In addition to the monazite beach sands, deposits in sedimentary rocks, conglomerates or quartz sites enriched in thorium and uranium may be thorium sources. Table 2.6 presents

TABLE 2.6
 ASSESSMENT OF WORLD THORIUM RESOURCES³
 (Thousand Short Tons)

	Reserves	Other Resources	Total Resources
North America:			
United States	140	160	300
Canada	<u>230</u>	<u>440</u>	<u>670</u>
Total:	370	600	970
South America:			
Brazil	60	100	160
Other	<u>10</u>	<u>20</u>	<u>30</u>
Total	70	120	190
Africa:			
Nigeria	15	20	35
Republic of South Africa	5	15	20
Other	<u>20</u>	<u>25</u>	<u>45</u>
Total	40	60	100
Europe: USSR	40	80	120
Asia:			
India	200	250	450
Other	<u>20</u>	<u>30</u>	<u>50</u>
Total	220	280	500
Oceania: Australia	<u>40</u>	<u>100</u>	<u>140</u>
World Total	780	1,240	2,020

an assessment of known world thorium resources. Although these resources are significant, they are only a fraction of those identified for uranium. However, the discovery of additional thorium deposits would seem likely, should the demand for thorium increase; based on the relative abundance of thorium to uranium, an assumption that thorium resources are at least as large, the projected uranium ore resources seem reasonable.

The requirements for thorium, on the other hand, are only a small fraction of the requirements for uranium ore. As was noted in Section 2.4.1, thorium is an alternative fertile material for U-238. A large fraction of uranium ore is mined to obtain the fissile component U-235 which constitutes only about 0.7% of the uranium. Less than 20% of the mined ore is actually used as slightly-enriched uranium in reactors, with the remaining 80% going into diffusion plant tails. Of the 20% placed into reactors, only a small fraction is consumed during operation; if uranium recycle is performed, the majority of the discharged uranium ends up as diffusion plant tails when the fuel is re-enriched. Since thorium is mined strictly as a replacement for the fertile U-238, the demand for thorium would be less than about 20% of the total uranium ore demand, if discharged thorium were not recycled and even if all reactors were to employ thorium fueling. Recycle of thorium would further reduce demands to about 5 to 7% of the uranium demand for a reactor lifetime of 40 years. The considerably lower demand for thorium, together with a relatively large abundance, leads to the conclusion that the size of the thorium resource should not be a limiting factor in the use of the thorium fuel cycle for any reasonable projection of installed nuclear capacity.

2.5 REACTOR CHARACTERISTICS

Reviews of thorium utilization indicated that thorium fuel can be employed in most reactor concepts currently deployed commercially or under development. Thus, a variety of reactor applications have been considered in the Thorium Assessment Program (TAP) to evaluate and intercompare the relative merits of thorium utilization in these alternate systems. These reactor systems are summarized briefly below with particular emphasis placed on those aspects which are important to the timely introduction of thorium

utilization. The discussion of reactor types is followed in Section 2.6 by a discussion of the fuel cycle characteristics. The reactor and fuel cycle characteristics were utilized in systems analysis calculations to determine the overall economics and fuel utilization of nuclear economies containing various mixes of reactor types and fuel cycles. These system analyses, as well as a more detailed discussion of the reactor parameters employed, are discussed in Annex 1.

2.5.1 Light Water Reactor (LWR)

Conventional LWRs - Light-water-moderated reactors of both the boiling (BWR) and pressurized water (PWR) types are utilized extensively in the U.S. and throughout much of the world. These reactors have almost universally been fueled with slightly-enriched uranium fuel, although thorium fuel was initially used in the Indian Point Plant of Consolidated Edison. Since the fuel cycle and economic characteristics of the BWR and PWR are very similar in principle, the PWR has been used exclusively in this report as representative of the light-water reactor.

The Combustion Engineering System 80TM reactor design and operating characteristics were employed in the analysis of alternate fuel cycles in unmodified LWRs, since evaluations of thorium utilization had previously been performed in this reactor design⁴. The 3800 Mw(th), 1300 Mw(e) System 80TM PWR is representative of the large capacity reactors currently under construction. The reactor design and operating characteristics employed are summarized in Table 2.7.

Characteristic of LWRs, a regular array of square fuel assemblies is employed within a pressure vessel containing water which serves both as moderator and coolant. For the majority of the cases evaluated, the reference reactor and fuel design as described in this table was unaltered so as to determine the characteristics of thorium utilization in PWRs currently in operation or under construction. The results of the preliminary evaluation of thorium utilization in the System 80 reactor confirm the suitability of this reactor design for thorium fueling⁴. In considering methods to improve

Table 2.7
SYSTEM 80TM CORE PARAMETERS

Core Power, Mwt	3800
Nominal Electrical Output, Mwe	1300
Fuel Assemblies	241
Fuel Rods Per Assembly	236
Control Rod Channels Per Assembly	4
Instrumentation Channels Per Assembly	1
Active Fuel Length (in.)	150
Specific Power (w/cm ³)	94.9
Average Linear Heat Rate (kw/ft)	5.34

OPERATING PARAMETERS

Primary System Pressure, psia	2250
Reactor Coolant Average Temperature (°F)	592
Nominal Fuel Temperature (°F)	1500

FUEL ASSEMBLIES (Dimensions at 68°F)

Fuel Rod Array	16x16
Assembly Pitch (in.)	8.18
Fuel Cell Pitch (in.)	0.5063
Fuel Pellet Diameter (in.)	0.325
Zr Clad Thickness (in.)	0.025
Gap Thickness (in.)	0.00350
Water Channel Between Assemblies (half width) (in.)	0.0394
CEA/Instrumentation Channel Zr Guide Tube: ID/OD (in.)	0.901/0.972
Coolant to Fuel Pellet Volume Ratio	
Fuel Cell Ratio	1.714
Assembly Ratio	2.041

FUEL LOADINGS

Full UO ₂ Core (TeM)	102.78
Full ThO ₂ Core (TeM)	93.50
Fuel Stack Density (gm/cm ³)	
UO ₂ Fuel	10.054
ThO ₂ Fuel	9.173

fuel utilization within the PWR concept, parameter studies were also performed by varying the basic lattice dimensions or operating characteristics given in the table. These parametric studies illustrated the general rule that annual uranium requirements can be reduced but at the expense of higher initial fissile loadings; alternately, initial loadings can be reduced by lattice modifications but at the expense of higher annual requirements. The thirty-year average uranium requirements prove largely insensitive to lattice design; however, in the longer term, optimized designs can reduce total U_3O_8 demand for a given installed nuclear capacity.

The primary incentive for evaluating thorium utilization in LWRs is the potential for rapid and widespread deployment of thorium fuel. The LWR is the only reactor type currently commercially available in the U.S., and essentially all of the nearly 50 Gw(e) of nuclear capacity currently operating in the U.S. are reactors of this type. In view of construction lead times and the period required to commercialize alternate concepts, reactors of this type will dominate the nuclear economy for at least the next several decades. An LWR base of about 125 Gw(e) is projected for 1985 and the great majority of the additional approximately 200 Gw(e) capacity operating or planned worldwide will be LWRs. Thus, if the thorium fuel cycle is to have a significant impact within the century, it must be implemented in light water reactors.

Spectrum-Shift-Controlled Reactor - The spectrum-shift-controlled reactor consists of a conventional PWR, as described above, in which the soluble poison control system is replaced with spectrum-shift control to adjust reactivity during normal reactor operation. Spectrum-shift control employs a mixture of heavy and light water in the primary coolant. The introduction of heavy water shifts the neutron spectrum to higher energies and enhances the absorption of neutrons in fertile material; consequently, excess neutrons are utilized to produce additional quantities of fissile material rather than being wasted by absorption in control poisons. Enhanced fuel utilization is achieved by eliminating losses to parasitic captures in control materials in a fashion similar to the improvements in resource utilization achieved with on-line refueling in the CANDU concept or by the relative movement of fertile and fissile fuel regions in the LWBR.

The spectrum-shift-control concept has been demonstrated by the Vulcain reactor experiment in the BR-3 nuclear power plant at Mol, Belgium.⁵ The BR-3 power plant, after two years of operation as a conventional PWR was modified for spectrum-shift operation and successfully operated with this mode of control between 1966 and 1968. The Vulcain core operated to a core average burnup of 23,000 Mwd/T (a peak burnup of around 50,000 Mwd/T) and achieved an average load factor and primary plant availability factor of 91.2 and 98.6%, respectively.⁶ The leakage rate of primary water from the high pressure reactor systems to the atmosphere was found to be negligible, about 30 kg of D₂O/H₂O mixture per year.⁵

Since the spectrum-shift-controlled reactor is based upon existing light-water-reactor technology, with modifications required to realize spectrum shift control limited largely to modifications to auxiliary systems, the SSCR has the advantage of potentially early introduction; as demonstrated by the Vulcain experiment, there is also the possibility of backfitting spectrum-shift control to existing PWRs. Another and potentially more attractive alternative is the possibility of modifying plants that are in the early phases of construction; this alternative would avoid the potentially costly down-time required to modify operating reactors for spectral shift control. The risk of implementing this concept is also reduced since the reactor could always be operated in the poison-control mode. The BR-3 reactor, after completing the Vulcain experiment, was subsequently returned to poison control. Because the financial risk of implementing this concept is limited to the additional cost required to realize spectrum-shift control, a more rapid introduction rate could be contemplated than for a completely new reactor system; in the latter case, the entire cost of the reactor and the generating capacity of the plant are at risk. The primary technical difficulties with realizing this concept are the heavy water supply and problems with the control of primary coolant leakage and refueling.

Other Light-Water-Reactor Concepts - Two other light-water-reactor concepts, although not discussed in detail in this report, should be mentioned. The first of these is the light-water-breeder reactor (LWBR) concept developed

at Bettis. A demonstration of this concept is scheduled to begin in late 1977 at the Shippingport reactor.

The design of the LWBR is made unusual by the need to avoid parasitic neutron losses. In the Shippingport demonstration, the necessary reactivity adjustment to compensate for fission product buildup is provided by an arrangement for moving highly reproducing fuel within a blanket region. In addition, the spacing of fuel rods is much closer than in conventional LWRs to attain high conversion.

The LWBR is fueled with thorium enriched with U-233. A conversion or a breeding ratio 1 to 2% in excess of unity is anticipated with the thorium fuel cycle, which, in principle, would allow unlimited continued operation without addition of fissile material once the initial inventory is provided. With these fuel cycle characteristics, the fuel demand becomes closely related to the installed nuclear capacity rather than to annual energy output. The fuel for new breeder reactors is assumed to be produced entirely from normal LWRs, with fuel assemblies especially designed to perform efficient thorium to U-233 conversion. Thus the system is composed of two separate components--the pre-breeder to produce the initial inventories and the hold-own breeder itself.

The primary attraction of the LWBR concept is the very high long-term uranium ore utilization possible within the context of the well-developed light-water reactor technology. Utilization of existing LWRs as pre-breeder appears feasible and, as the Shippingport project is to demonstrate, it is possible to convert existing LWRs to LWBR operation. Although conversion to LWBR operation appears possible, there remains a question of whether such conversion can be achieved without seriously derating the power output of the reactor and hence compromising the power cost economics. A second consideration is the high fissile inventory required for such operation. Seven to fourteen years of pre-breeder operation are required to produce the U-233 inventories necessary to start up the LWBR.

TABLE 2.8CANDU-PHWR CORE PARAMETERS

Core Power, Mwt.	2510
Nominal Electrical Output, Mwe	750
Thermal Efficiency, %	29.8
Number of Fuel Channels	480
Specific Power, kw/kg	22
Average Linear Heat Rate, kw/ft	6.69
Discharge Exposure (Nat UO ₂), Mwd/TeM	8000
Fuel Management	Continuous Refueling

Operating Parameters

Primary System Pressure, psia	1420
Reactor Coolant Average Temperature, °F	542

Fuel Assemblies

Geometry	Cylindrical
Orientation	Horizontal
Active Length, in.	19.5
Bundle Diameter, in.	4.03
Number of Fuel Rods/Bundle	37
Fuel Rod Diameter, in.	0.516
Fuel Pellet Diameter, in.	0.479
Fuel Pellet Density, g/cm ³	10.55
Fuel Rod Clad	Zr

Fuel Loading

Fuel Loading/Bundle, kgU	18.3
Number of Fuel Assemblies	6240

Consequently, the LWBR seems more suited to periods when low electrical growth is anticipated.

In the seed-and-blanket reactor, fissile material is bred in the blanket from neutrons which leak from the enriched seed material. As fissile material is bred in the blanket, power generation in the blanket increases as the fissile material is consumed in situ. At the end of its useful reactivity lifetime, the enriched seed material is replaced with fresh fuel (the seed can be placed into the blanket region to achieve a more complete burnup of the contained material), while the blanket material remains in core for a number of cycles in order to achieve high burnup and to more efficiently utilize in situ its bred fissile content.

The primary problem with realizing economic performance in the seed and blanket concept is the imbalance in power which can result between the low enriched blanket region and the highly enriched seed material. Because of this imbalance in power, the average power densities achieved are usually significantly lower than those in conventional LWRs; as a result, capital costs are increased. Additional evaluations of this concept are required in order to establish its resource utilization characteristics and the anticipated fuel and power costs. Since the resource requirements for the LWBR are very closely approximated by those of the CANDU reactor operating on a self-sufficient cycle, the LWBR concept was not included explicitly in the systems analysis performed for this study; very similar resource utilization results would have been obtained had the LWBR been substituted for the self-sufficient CANDU reactor.

2.5.2 Heavy Water Reactors (HWR)

The CANDU-PHWR (Pressurized Heavy Water Reactor) served as the reference HWR concept for the thorium assessment program. Typical core parameters for the CANDU PHWR are given in Table 2.8. A number of reactors of this type are already in operation in Canada and have been exported to a number of other nations. CANDU PHWRs are considered to be the only reactor type

besides the LWR for which a significant commercial manufacturing base presently exists; the British and French gas-cooled reactors have not gained acceptance outside their countries of origin.

The PHWR is characterized as having cylindrical fuel assemblies located in pressure tubes through which flows heavy-water coolant. The pressure tubes are arranged in a widely-spaced array in the calandria (tank) containing heavy-water moderator. CANDU plants employ on-line refueling and current designs use natural uranium fuel, although operation with slightly-enriched uranium or thorium fuels is also possible.⁷

Two CANDU reactors were considered in the TAP evaluations: the first was a 600 Mw(e) Gentilly II plant currently under construction in Quebec; the second was a conceptual design for a "Middletown," U.S.A. plant which was similar to Gentilly II, but increased in size to 3800 Mw(th) (1140 Mw(e)) and modified as much as necessary to meet U.S. licensing criteria.

The primary advantage of the CANDU PHWR is the improved resource utilization which results from the better neutron economy possible with heavy water and on-line fueling. On the thorium cycle, self-sufficient breeding (i.e., no uranium ore required in the equilibrium cycle) is possible, although discharge burnups are relatively low; economic considerations may favor higher burnups for which supplementary uranium ore is required. The highly successful operation of the CANDU reactors deployed in Canada offers the potential for the rapid introduction in other areas of the world, including the U.S.

The main difficulty with introducing CANDU into the U.S. is the lack of domestic manufacturing experience and questions of design modifications which might be dictated by U.S. licensing criteria and traditions. A large 3800 Mw(th) plant, upon which the economic analysis contained in this report is predicated, would also have to be developed and demonstrated. U.S. heavy water production capacity would also have to be increased if a significant rate of CANDU introduction were to be supported.

There are also a number of heavy-water reactor concepts in addition to the PHWR. The Gentilly I plant employs light water as a reactor coolant while

retaining heavy-water moderation (CANDU-BLR) and utilizes natural uranium fueling. The steam-generating heavy-water reactor (SGHWR), exemplified by the prototype operating at Winfrith in Great Britain, is a similar concept which utilizes low-enrichment uranium fuel. In general, the resource utilization of these light-water-cooled reactors are intermediate between that of the PHWR and the LWR; the main incentive for this reactor type is the potential for reduced capital cost resulting from decreased reactor size and heavy-water inventory. Another member of the CANDU family of reactors is the organic-cooled heavy-water-moderated reactor (CANDU-OCR). The primary motivations for this reactor are the potential reduction in capital cost and the higher efficiency possible with organic coolant. Although a small demonstration reactor using organic coolant is in operation in Canada, significant additional research, development and demonstration will probably be required before this concept can be considered for widespread deployment. Heavy-water reactors of the pressure vessel type have also been constructed, for example the Atucha plant in Argentina, and resource utilization comparable to the CANDU PHWR have been obtained by employing on-line refueling in this plant.

2.5.3 High Temperature Gas-Cooled Reactor (HTGR)

The reference HTGR is based upon the conceptual design of a 1344 Mw(e) commercial plant developed by GA^{8,9}. Specifications for this plant are given in Table 2.9. The HTGR employs coated fuel particles contained in high integrity graphite fuel elements (prisms) through which the helium coolant flows. The reference HTGR has a nuclear conversion ratio of about 0.67 and provides a steam cycle with an efficiency of 40%. The higher efficiency compared to the 33% of the LWR, is the major reason that the reference HTGR achieves better uranium utilization than the LWR per unit of electrical energy output. Modifications, such as an increase in the thorium-to-carbon ratio, semi-annual refueling, reduced power density, and reduced discharge burnup, can also be made to increase the conversion ratio, and hence further improve resource utilization¹⁰ at some expense to capacity factor, reprocessing and capital costs.

TABLE 2.9HTGR CORE PARAMETERS

Core Power, Mwt.	3360
Nominal Electrical Output, Mwe	1344
Thermal Efficiency, %	40
Core Power Density, W/CC	7.1
Fuel Assembly Geometry	Hexagonal Blocks
Primary Pressure, psia	775
C/U or C/Th Ratio	150-650*
Discharge Burnup, Mwd/MTHM	47,000-196,000*

*Depends on Fuel Cycle

*Depends on Fuel Cycle. See Annex 1, Table C.2.

U.S. experience with high-temperature gas-cooled reactors dates to March 3, 1966 when the 40 Mw(e) Peach Bottom Atomic Power Station became operable. More recently, the 330 Mw(e) Fort St. Vrain Station has been completed and is currently undergoing low-power test operation. Extensive experience with gas-cooled reactors has also been obtained in Great Britain where 31 plants having a total capacity of 7738 Mw(e) are in operation.

Since thorium fueling has always been the reference fuel cycle for the HTGR, more extensive development of the HTGR thorium fuel cycle has been performed than in other reactor concept. The HTGR also takes advantage of the nuclear performance of U-233 (relative to U-235 or Pu-239) to obtain relatively high conversion ratios while operating at the elevated temperatures which result in increased thermal efficiency. Because of the HTGR fuel design, which consists of microspheres containing fissile and fertile fuel materials contained in fuel channels within graphite fuel elements, a wide latitude of fissile-to-fertile and heavy-metal-to-moderator atom

ratios are achievable without alteration of the basic concept of the fuel design. These parameters control, to a large extent, the conversion ratio of the reactor system, and thus the current-design HTGR is amenable to alterations in conversion ratio over a fairly large range. For this reason, the HTGR has the advantage of having a high degree of flexibility to tailor the reactor fuel cycle by varying the fuel loading and fuel exposures to meet changes in economic and resource availability conditions.

Real constraints on HTGR commercialization and deployment have been encountered in both the U.S. and Europe, and it is difficult to summarize the present situation and future expectations in any simple way; however, these difficulties are manifested by the history of attempts to commercialize the HTGR in the U.S.

2.5.4 Liquid Metal Fast Breeder Reactor (LMFBR)

The reference LMFBR (c.f. Table 2.10) employed in the Thorium Assessment Program is based upon the conceptual design of a large low temperature prototype breeder reactor developed by the Hanford Engineering Development Laboratory¹¹. The LMFBR employs a regular array of hexagonal fuel elements containing fuel rods clad with stainless steel, about which the liquid sodium coolant flows. The central region of the core contains enriched fuel, while the axial and radial blanket regions contain depleted uranium. The PLBR employs oxide fuel, has a specific inventory of about 5000 kg fissile plutonium per Gw(e), and exhibits a compound fissile doubling time of about 12.5 years when operated with the uranium blanket or about 13.1 years with thorium blankets.

The primary advantage of the LMFBR (or any real breeder concept) is that it produces a surplus of fissile material which can subsequently be used either to expand nuclear capacity or to supplement uranium requirements of converter reactors. Rather extensive development of the LMFBR concept has been performed both in the U.S. and overseas. LMFBRs are currently in operation in England (PFR - 250 Mw(e)), in France (Phoenix - 233 Mw(e)), and in the USSR (350 Mw(e)), and a larger 600 Mw(e) LMFBR is scheduled to begin operation in 1978 in the USSR.

TABLE 2.10

LMFBR CORE PARAMETERS

Core Power, Mwt	3736
Nominal Electrical Output, Mwe	1196
Thermal Efficiency, %	32
Average Linear Heat Rate, kw/ft Core/Axial Blanket/ Radial Blanket	8.9/0.4/1.3
Reactor Inlet/Outlet Temperature, °F	620/900
Refueling Interval	annual
Fuel Residence Time, FPD	525.6
Discharge Exposure, Mwd/kg (UO ₂)	61.6
<u>Fuel Assemblies</u>	
Number of Assemblies	380
Number of Fuel Rods/Assembly	271
Assembly Length, in.	120.9
Lattice Pitch, in.	6.22
Duct Wall Thickness, in.	0.084
Interduct Gap, in.	0.303
Pellet Diameter, in.	0.2565
Pellet Density, gm/cc	10.23
Cladding OD, in.	0.286
Cladding Thickness	0.012
Cladding Material	316 SS, 20% CW
Diametral Gap, in.	.0055

Beyond the normal technical development problems inherent in such a large undertaking, new difficulties have emerged, particularly in the U.S. for the LMFBR concept relating to the possibility of increased nuclear weapons proliferation potential should the plutonium-fueled LMFBR be deployed widely throughout the world. Intense growth of this concern has resulted in the postponement of U.S. plans to construct a facility which would demonstrate concepts and components necessary for the eventual construction of large

LMFBRs and the subsequent commercial deployment of this type of plant. In order to appraise the possibilities for reducing proliferation concerns associated with LMFBRs, a number of thorium-fueled cores have been included in the thorium assessment program to establish the characteristics and potential of these alternate fuel cycles.

2.5.5. Gas-Cooled Breeder Reactor (GCFR)

The gas-cooled breeder reactor consists of a four-enrichment zone core of PuO_2 and depleted uranium, surrounded by an axial blanket of depleted uranium and a radial blanket comprised of either uranium oxide or thorium oxide. The GCFR is basically a blend of HTGR and LMFBR technologies: the fuel element design technology developed for the LMFBR and the gas-coolant technology of the HTGR would be utilized in this concept, so as to minimize the required research and development effort. Evaluations of the GCFR have indicated that the fuel utilization performance of this reactor is comparable to the LMFBR¹². Consequently, both the LMFBR and the GCFR are represented in the thorium assessment study as a single category, the fast breeder reactor (FBR).

2.6 FUEL UTILIZATION

2.6.1 Fuel Cycle Options

Assessments are currently under way by ERDA and other agencies of the Federal Government to establish non-proliferation criteria against which various fuel cycle options can be evaluated. When these criteria are developed, they will provide important guidance to the selection of fuel cycles optimal from the standpoint of non-proliferation. In the Thorium Assessment Program, no attempt was made to judge these criteria by eliminating from consideration fuel cycle alternatives. However, in order to allow the fuel cycle alternatives developed in the Thorium Assessment Program to be employed in non-proliferation assessments, care has been taken to include alternatives which might have inherent non-proliferation advantages, and the cases evaluated were divided into fuel cycle

options which could be readily distinguished in terms of the degree of resistance to proliferation. These fuel cycle options are summarized below.

1. Once Through (Throwaway) Cycle

The Once-Through Cycle in which spent fuel is stored rather than reprocessed is the fuel cycle currently in place today. Reactor options with this fuel cycle which were considered included the standard PWR; modifications of the standard PWR, including both minor modifications and the implementation of more major changes, such as spectrum shift control or the seed and blanket concept; the standard CANDU utilizing both natural uranium and slightly enriched uranium fueling, the HTGR utilizing both low-enrichment uranium and denatured thorium fueling; and the use of the tandem PWR-HWR cycle. In the latter, spent PWR fuel is reinserted into a heavy-water reactor for an additional cycle of irradiation.¹³

2. U-233 and U-235 Recycle

This fuel cycle option allows only the recycle of uranium. Included are the highly-enriched thorium cycles in the PWR, FBR, HTGR and CANDU reactors, in addition to the conventional uranium cycle with uranium recycle.

3. Pu-U Recycle With Restricted Pu Utilization

In this fuel cycle option, Pu-U recycle is restricted to reactors located at secure energy centers. All reactors located outside of these secured areas (dispersed reactors) are restricted to the use of denatured fuels unsuitable for use in nuclear weapons: either low-enrichment uranium as currently employed, or denatured thorium. Denatured thorium consists of a mixture of thorium and uranium in which the uranium component is enriched to less than 20 w/o U-235 or less than 12 w/o U-233. Plutonium produced by dispersed reactors

TABLE 2.11
 THORIUM ASSESSMENT PROGRAM REACTOR CASES (6/22/77)

	FUEL CYCLE OPTIONS			
	ONCE-THROUGH (THROWAWAY) CYCLE	U-233 & U-235 RECYCLE	Pu-U RECYCLE RESTRICTED TO SECURE CENTERS ^(C) AND DIS- PERSED ^(D) REACTORS RESTRICTED TO "DENATURED" REACTORS	FULL RECYCLE
PWR-U5(LE)/U	X	X	D	X
PWR-U5(DE)/U/Th	X	-	D	-
PWR-U5(HE)+U3(RE)/Th	-	X	-	-
PWR-U3(DE)/U/Th	-	-	D	-
PWR-U3(HE)/Th	-	X	-	-
PWR-Pu/U	-	-	-	X
PWR-Pu/Th	-	-	C	-
PWR-U5(LE)/U-EE	X	-	-	-
PWR-U5(LE)/U-TAH	X	-	-	-
PWR-U5(LE)/U-SS	X	-	-	-
PWR-U5(HE)+U3(RE)/Th-SS	-	X	-	-
PWR-U5(DE)/U/Th-LWB(SB)	X	-	-	-
PWR-U5(DE)/U/Th-HWB(SB)	-	X	-	-
FBR-Pu/U/U/U	-	-	-	X
FBR-Pu/U/Th/Th	-	-	C	-
FBR-U3/U/Th/Th	-	-	D	-
FBR-U3/Th/Th/Th	-	X	-	-
HTGR-U5(DE)/U/Th-T	X	-	-	-
HTGR-U5(HE)/Th	-	X	C	X
HTGR-U5(LE)/U	X	-	-	-
HTGR-U3(HE)/Th	-	X	C	X
HTGR-U5(LE)/U/Th	-	-	-	-
HTGR-U3(DE)/U/Th	-	-	-	-
CANDU-U5(SEU)/U	X	-	-	-
CANDU-U5(NAT)/U	X	-	D	-
CANDU-U5(DIS)/U-TAH	X	-	-	-
CANDU-U5(DE)/U/Th-T	X	-	-	-
CANDU-U5(HE)/Th	-	X	C	-
CANDU-U3(HE)/Th	-	X	-	-

is utilized at the secured centers to fuel converter or breeder reactors which contain thorium in the blanket and/or core regions. U-233 produced by center reactors is denatured with U-238 and can then be employed in dispersed reactors. Also included in this option is the use of the highly-enriched thorium cycle at the secured centers. Reactors considered for deployment at energy centers consist of the PWR, the FBR, the HTGR and the CANDU reactor, while PWRs, FBRs and CANDU reactors operating on denatured fuel cycles were considered for dispersed-site use.

4. Full Recycle

The standard full recycle option was included in the thorium assessment program as a reference case against which the advantages and disadvantages of other alternatives can be compared. This fuel cycle, of course, has the advantage that reactors are currently operating with uranium fueling and producing the plutonium required for recycle in standard LWRs or to initiate the deployment of plutonium-fueled LMFBRs. Included in this option are the reference cases for most reactor types, i.e., the PWR with uranium and plutonium recycle, the FBR operating on the plutonium cycle, and the HTGR operating on the highly-enriched thorium cycle with recycle of uranium.

2.6.2 Fuel Cycle Characteristics

A comprehensive characterization of fuel utilization requires detailed consideration of the cycle-by-cycle fuel requirements for each alternative reactor concept and fuel cycle. Such detailed material flows were employed in the economics and resource evaluation.* In this section, a simplified characterization has been employed to summarize the fuel utilization of various alternatives, in which initial loading requirements, the equilibrium cycle uranium demand and the 30-year uranium requirements have been employed to characterize the performance of converter reactors.

*See HEDL, Reactor Design Characteristics and Fuel Inventory Data (September 1977).

This simplified characterization is useful since it does delineate life-time uranium requirements and provides a concise basis for inter-comparing alternatives; however, it must be recognized that the time-dependent (cycle-by-cycle) requirements are important in economic assessments and in the evaluation of annual uranium demands during periods of nuclear expansion.

For all cases discussed below, U_3O_8 requirements are given for a 1000 Mw(e) reactor having an assumed lifetime of 30 years. A 75% capacity factor and a 0.2 w/o diffusion plant tails assay were also assumed, along with a two-year out-of-reactor time for reprocessing and refabrication. The worth of fuel remaining in the reactor or in reprocessing and refabrication at the end of the assumed 30-year lifetime has been neglected. For breeder reactors, fuel utilization is tabulated in terms of the specific inventory and system doubling times, since these are more appropriate measures of system performance. Initial inventories have also been translated into the equivalent U_3O_8 requirements, based upon the uranium ore consumption of light-water reactors required to produce initial fissile loadings.

1. Light-Water Reactors

U_3O_8 requirements for the reference LWR design are summarized in Table 2.12. The requirements shown for reactor start-up include both the initial core and the first two reloads, i.e., total uranium utilized before recycle begins in the third reload core. Two cases are tabulated for the denatured thorium cycle. In the first case, only uranium recycle is performed, with the recovered plutonium stored for eventual use in the breeder reactor. The second option utilizes both uranium and plutonium recycle. Here plutonium is recycled into thorium fuel in plutonium enriched converter reactors of the reference System 80 design. These reactors would be located at secured energy centers and the U-233 which is produced is assumed to be denatured and returned to reactors located at dispersed sites. As Table 2.12 illustrates, the effect of thorium utilization is to reduce annual

TABLE 2.12

U_3O_8 REQUIREMENTS FOR LWRs (ST U_3O_8 / Gwe)*

	<u>Reactor Startup</u>	<u>Annual Requirement</u>	<u>30-Year Requirement</u>
Uranium Cycle			
Once Through	791	192	6000
U Recycle	791	154	4950
U and Pu Recycle	791	117	4100
Thorium Cycle			
Highly-Enriched U Recycle	1104	87	3450
Denatured U Recycle	1189	110	4100
Denatured U and Pu Recycle	1189	94	3750

*75% Capacity Factor, 0.2 w/o Tails Assay

U_3O_8 requirements to about 58% of that obtained on the once-through uranium cycle.

For all cases shown in Table 2.12, the reference PWR parameters have been utilized and the discharge burnup has been assumed to be 30,400 Mwd/T for UO_2 fuels and 33,400 Mwd/T for ThO_2 fuels.*

Figure 2.4 presents the cumulative U_3O_8 ore requirements as a function of years of reactor operation for the once-through uranium cycle, the

*The difference in burnup results from the difference in density of UO_2 and ThO_2 ; the burnups are selected so that the number of full power days between refuelings remains constant.

Figure 2.4 CUMULATIVE U_3O_8 ORE REQUIREMENTS vs REACTOR LIFETIME

uranium cycle with uranium and plutonium recycle, and the highly enriched thorium fuel cycle options. As this figure illustrates, reactor startup requirements are higher for the thorium cycle as compared to the uranium cycle. This results from the higher absorption cross section of thorium as compared to U-238. However, because of the higher conversion ratio possible in thorium-fueled systems, the annual ore requirements are lower than those of the uranium cases and within 6 to 10 years of operation (depending on whether the thorium cycle is compared to the throw-away uranium cycle or to the uranium cycle with U and Pu recycle), cumulative U_3O_8 ore consumption is lower with thorium fueling. Figure 2.5 illustrates cumulative separative work requirements as a function of years of reactor operation. Initial separative work requirements are higher with thorium fueling than for uranium fueling because of the higher initial loadings of thorium cores and the use of highly-enriched uranium. Over the reactor's 30-year lifetime, separative work consumption is higher than if uranium and plutonium recycle were performed, but roughly equivalent to the demand of the throw-away cycle. Although these curves of cumulative U_3O_8 and SWU requirements were generated for the light-water reactor, the trends illustrated here of higher initial uranium and SWU requirements and of lower annual U_3O_8 demand are also characteristic of the inter-comparison of thorium and uranium cycles in other reactor types.

For all cases shown in Table 2.12 and in Figures 2.4 and 2.5, the reference PWR parameters have been utilized and the discharge burnup has been assumed to be 30,400 Mwd/T (33,400 Mwd/T for ThO_2 fuel). Modifications of such fuel cycle parameters as discharge burnup can result in some improvement in resource utilization. Improvements such as this, which can be implemented without modifying reactor design, were included in the thorium assessment evaluation and are described in Annex 1. Further improvements in resource utilization could, of course, be achieved in the LWR by lattice optimization; however, these alterations to the LWR design would typically compromise the advantage of early implementation of the thorium cycle

Figure 2.5 CUMULATIVE SWU REQUIREMENTS vs REACTOR LIFETIME

and/or the economics of thorium utilization. Consequently, the fuel utilization parameters employed in the thorium assessment program were based upon the use of thorium fueling in a conventional PWR design without modification. In general, modifications could be utilized which would reduce the higher initial loading requirements of the thorium fuel cycle, but at the expense of a somewhat reduced conversion ratio and hence of higher annual U_3O_8 requirements; alternately, the conversion ratio could be improved somewhat, reducing annual U_3O_8 demand, but at the expense of higher initial loadings. This trade-off between initial U_3O_8 requirements and annual U_3O_8 requirements is a general characteristic of lattice optimization in any reactor system. The optimal design from a resource utilization standpoint will consequently depend not only upon the detailed reactor material inventory balances, but also upon the assumed rate of nuclear expansion. The establishment of optimal reactor design was beyond the scope of the Thorium Assessment Program.

The resource utilization for the reference pressurized water reactor modified for spectrum shift control is given in Table 2.13. This reactor consists of the standard System 80 PWR in which the poison control system has been replaced with spectrum-shift control achieved through the introduction of varying concentrations of heavy water. The lattice parameters and discharge burnups are unaltered from the reference uranium cycle case.

On the once-through uranium cycle, startup requirements and 30-year requirements are reduced somewhat from those required with poison control (5000 for the SSCR versus 6000 with poison control). On the thorium cycle requirements are reduced to between 2200 and 2500 ST, depending on the thorium fuel cycle option.

2. Heavy Water Reactors

U_3O_8 utilization in heavy-water reactors of the CANDU type is summarized in Table 2.14. Natural uranium fueling, the mode of fueling currently employed in CANDU reactors, is shown for reference. Improved

TABLE 2.13

SPECTRAL SHIFT REACTOR

 U_3O_8 REQUIREMENT, ST U_3O_8 /GWe *

	<u>Startup Requirements</u>	<u>Annual Equilibrium Cycles</u>	<u>30-Year Requirements</u>
Uranium Cycle			
Once Through	658	161	5010
Thorium Cycle			
Highly Enriched, U Recycle	1029	43	2185
Denatured; U Recycle	1120	48	2500
Denatured, U + Pu Recycle	1120	44	2200

*75% Capacity Factor, 0.2 w/o Tails Assay

resource utilization can be obtained by using slightly enriched uranium fuel, with a concomitant increase in discharge burnup. The case illustrated, which utilizes 1.2 w/o U-235 enrichment and achieves a burnup of about 20,600 Mwd/T is thought to be near optimal for the CANDU-PHWR, although only slightly higher uranium requirements result when higher enrichments and discharge exposures are utilized, as illustrated in Figure 2.6.

Also given in Table 2.14 are the U_3O_8 requirements for the highly enriched and denatured thorium fuel cycles. Annual uranium requirements for the HWR are, of course, dependent upon the conversion ratio achieved, and the conversion ratio, in turn, is dependent upon the discharge burnup. As the discharge burnup is decreased, less neutrons are lost to parasitic captures and fission products, resulting in an improved conversion

TABLE 2.14

U_3O_8 REQUIREMENTS FOR HWRs (ST U_3O_8 /Gwe) *

	<u>Reactor Startup</u>	<u>Annual Requirement</u>	<u>30-Year Requirement</u>
Uranium - Once Through			
Natural U	504	158	4770
LEU	359	112	3390
Thorium Cycle (Highly Enriched)			
Burnup = 27 Mwd/kg	760	38	1790
= 16 Mwd/kg	902	27	1631
= 8.5 Mwd/kg	1470	0	1470 **
Thorium Cycle (Denatured)	886	38	1912

* 75% Capacity Factor, 0.2 Tails Assay

**Indefinite Operation

ratio. This dependency of conversion ratio on discharge exposure is, in principle, applicable to other concepts besides the HWR; however, the on-line fueling employed in the HWR makes this concept uniquely suitable for efficient operation with low discharge burnups without jeopardizing the plant capacity factor. As Table 2.14 illustrates, the 30-year ore requirements are 1770 when a burnup of 27 Mwd/kg is employed. This burnup is roughly comparable to that of the LWR and hence the amount of fuel which must be reprocessed and refabricated is also comparable. As the burnup is decreased, the conversion ratio increases until at a burnup of between 8.5 and 10 Mwd/kg a conversion ratio of 1 is achieved. At this burnup a self-sufficient breeder is realized, i.e., there are no annual uranium requirements. Operation

Figure 2.6 Fuel Utilization Characteristics for Enriched Uranium Fueled CANDU (Ref. 14)

at this burnup, however, requires two to three times the volume of fuel to be reprocessed and refabricated relative to the LWR, with a concomitant increase in the fuel cycle cost for these services. The economic optimum for the HWR is, consequently, a tradeoff between the increased cost for fuel fabrication and reprocessing as the burnup is decreased and the reduction in uranium demand realized with reduced burnup.

As Table 2.14 illustrates, the 30-year uranium requirements for the denatured thorium fuel cycle in the HWR are roughly comparable to those for the highly-enriched thorium cycle.

2.6.3 High-Temperature Gas-Cooled Reactor

U_3O_8 resource utilization is summarized in Table 2.15 for the High-Temperature Gas-Cooled Reactor (HTGR). The once-through cycle, which employs a feed of highly-enriched uranium (93 w/o U-235) in thorium is tabulated for the reference HTGR design, which achieves a conversion ratio of 0.66; this design is considered optimum under current economic conditions. U_3O_8 resource utilization is also given for the low-enrichment, once-through uranium cycle and for the denatured thorium fuel cycle with U recycle. Resource utilization is roughly comparable between these three alternatives.

Fuel utilization parameters are also given for the highly enriched cycles where uranium is recycled, both for the reference design and for a high conversion ratio design. The high conversion ratio design employs an increase in thorium loading, semi-annual refueling, reduced power densities, and some modification to the fuel rod and/or fuel particle design. Conversion ratios intermediate between these two are, of course, possible.

2.6.4 Breeder Reactors

Table 2.16 summarizes the specific inventories and doubling times for breeder reactors. The reference breeder concept is the LMFBR containing a UO_2 blanket. This reactor is based upon HEDL's low-temperature oxide

TABLE 2.15

HIGH TEMPERATURE GAS COOLED REACTORS

 U_3O_8 REQUIREMENTS, ST U_3O_8 / GWe*

	<u>Startup Requirements</u>	<u>Annual Equilibrium Cycles</u>	<u>30-Year Requirements</u>
Thorium Cycles			
Highly Enriched Once Through	512	--	4300
Highly Enriched, U-Recycle			
CR = 0.66	512	79	2650
CR = 0.90	810	28	1575
Denatured, U Recycle	--	--	4100

* 75% Capacity Factor, 0.2 w/o Tails Assay

design, and its performance is considered to be characteristic of a number of alternate LMFBR designs. The introduction of thorium blankets in place of the UO_2 blankets presently employed in the reference design has little effect on the compound fissile system doubling time, increasing the doubling time from 12.5 to 13.1 years when both axial and radial uranium blankets are replaced with thorium. However, most of the breeding gain is in the form of U-233 production so that an exogenous source of plutonium is required to expand LMFBR capacity. With the use of thorium radial blankets and uranium axial blankets, a Pu fissile doubling time of about 26 years is achieved. The denatured LMFBR design employs the same type of denatured fuel as has been considered in converter reactors, i.e. a mixture of uranium and thorium with the uranium component enriched to 12 w/o U-233. Such breeder reactors could be deployed at dispersed sites without concern that fresh fuel would be diverted and processed into weapons material. Although

TABLE 2.16

BREEDER REACTOR

	<u>Specific Inventory</u>		<u>Doubling Time</u>
	kg fiss/GWe	Equivalent ²⁾ ST U_{308}	Years
LMFBR			
UO_2 blanket	4600	1500	12.5
ThO_2 blanket	4600	1500	26
Denatured	--	--	1)
GCFR			
UO_2 blanket	4600	1500	15.5
ThO_2 blanket	4600	1500	~ 25 ³⁾

1) Fissile Pu discarded - 410 kg/GW(e)-yr
 Net Feed Requirement - 250 kg U-233/GW(e)-yr

2) Increase in LWR requirements as a result of plutonium diversion to FBR;
 assumes 0.2 w/o tails assay

3) Pu fissile doubling time

the denatured LMFBR is a breeder reactor, producing more fissile material each year than consumed, a net feed of 250 kg U-233/GW(e)-yr is required. The excess fissile which is produced is in the form of plutonium, with 410 kg/GW(e)-yr produced. This material would either have to be discarded or used in secured energy centers.

Also given in Table 2.16 are the specific inventory and doubling times for similar UO_2 or thorium blanket GCFR designs. As Table 2.16 notes,

the performance of the GCFR is thought to be comparable with that of the LMFBR.

2.6.5 Fuel Cycle Characteristics Utilized in Thorium Assessment Program

As indicated in Section 2.6.2, a variety of fuel cycle performance characteristics can be obtained within the context of any one reactor design through reactor design optimization and through the modification of such operating parameters as discharge burnup. Further optimal economic performance is not necessarily consistent with optimal resource utilization; the optimum design from the standpoint of power cost economics depends on such parameters as the price of uranium ore, separative work, reprocessing fabrication, and the effective capital costs of each option in addition to the resource utilization performance. In order to reduce the number of cases to a manageable number, the thorium assessment program's evaluation was restricted to fuel cycle options considered representative of the various reactor types and fuel cycle alternatives. The lifetime performance characteristics of the reactors and fuel cycles included in the thorium assessment program evaluation is summarized in Table C.2 in Annex 1.

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