1000-MWe LMFBR FOLLOW-ON STUDY
— Task II and III Final Report —
Volume 5
Parametric Studies

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:
A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.
As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Approved by B. J. Goulding
Project Engineer

M. W. Croft
Project Manager

January 1969

ANL Contract No. 31-109-38-1998
B&W Contract No. 59-3102

Prepared for
ARGONNE NATIONAL LABORATORY
by
BABCOCK & WILCOX
Power Generation Division
P.O. Box 1260
Lynchburg, Virginia 24505

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

PREFACE

Babcock & Wilcox (B&W) is participating in the AEC's 1000-MWe Fast Breeder Reactor Follow-On Study Program under Argonne National Laboratory (ANL) Contract No. 31-109-38-1998. As stated by ANL,

"The over-all objective of the current 1000 MWe LMFBR Follow-On Study Program is to provide the AEC with information needed to establish research and development programs which will lead to the achievement of economic and safe LMFBR power plants by a viable nuclear industry. This information is to be developed through studies of 1000 MWe LMFBR power plant reference conceptual designs favored by the nuclear industry for further development and eventual sale to the electric utilities in the period of 1975 to 1985."

The B&W Follow-On Study consists of four tasks:

Task I — The development of four basic plant concepts based on the established ground rules and the estimated state of technology in 1980, and the selection of a preliminary reference design that incorporates the best features of each concept.

Task II — Detailed engineering work on the preliminary reference design, and, in parallel, the performance of in-depth engineering trade-off studies.

Task III — Parametric studies to identify and evaluate basic problem areas and to provide a basis for the selection of an optimized reference design.

Task IV — Preparation of a document outlining the research, development, and component testing required for the successful design and construction of the reference 1000-MWe LMFBR design.

This five-volume report describes the work performed under Tasks II and III. Volume 5 describes the parametric studies carried out under

Task III. Listed below are the titles of Volumes 1 through 4 and a brief description of the contents of each.

Volume 1 — Summary Description and Cost Estimate

Cost data and a description of the overall plant and the reference operating conditions and parameters.

Volume 2 — Conceptual System Design Descriptions (1 - 7)

Descriptions of land, structures, and conventional systems and the reactor and associated systems, such as shielding, control, and supports.

Volume 3 — Conceptual System Design Descriptions (8 - 14)

Descriptions of reactor auxiliary, intermediate coolant, steam generator, energy conversion, instrumentation and control, electrical, and safety systems.

Volume 4 — Trade-Off Studies

A compilation of the various trade-off studies that were carried out to evaluate alternate choices for the conceptual design.

CONTENTS

	Page
1. INTRODUCTION	1-1
1.1. Purpose	1-1
1.2. Scope	1-2
1.3. Reference Design Description	1-7
2. SUMMARY OF RESULTS	2-1
2.1. Parameter Sensitivity and Optimization	2-1
2.2. Core System Technology-Optimization Relationships	2-4
2.3. Safety Coefficient Parameterization	2-12
2.4. Heat Transport System Technology-Optimization Relationships	2-12
3. PARAMETER SENSITIVITY AND OPTIMIZATION	3-1
3.1. Introduction	3-1
3.2. Fuel Pin Diameter	3-2
3.3. Fuel Pin Pitch	3-4
3.4. Fuel Pin Length	3-5
3.5. Fabrication Cost Effect on Optimum Core Design	3-6
3.6. Reprocessing Cost Effects	3-8
3.7. Plutonium Value Effect on Optimum Core Design	3-8
3.8. Burnup Effect on Optimum Core Design	3-10
4. CORE SYSTEM TECHNOLOGY-OPTIMIZATION RELATIONSHIPS	4-1
4.1. Introduction	4-1
4.2. Fuel Model Parametrics	4-3
4.3. Linear Heat Rating	4-8
4.4. Fuel Pin Cladding Thickness	4-16
4.5. Spacer Type	4-18
4.6. Orifice Effectiveness	4-22
4.7. Fuel Specific Power	4-26
4.8. Reactor Inlet and Outlet Temperature Effects on Core Design	4-28
5. SAFETY COEFFICIENT PARAMETERIZATION	5-1
6. HEAT TRANSPORT SYSTEM TECHNOLOGY-OPTIMIZATION RELATIONSHIPS	6-1
6.1. Core Outlet Temperature and Temperature Rise	6-1
6.2. Steam Generator - Reheater Optimization	6-6

CONTENTS (Cont'd)

	Page
6.3. Heat Exchanger LMTD	6-7
6.4. Steam Generator Hot End Temperature Difference	6-8
7. EFFECT OF ECONOMIC PARAMETERS ON THE REFERENCE DESIGN	7-1
Appendix A. NAPS Computer Code	A-1

List of Tables

Table

1-1. Variables and Parameters Examined for Core Parameter Sensitivity and Optimization Studies	1-3
1-2. Variables and Parameters Examined for Core System Technology-Optimization Relationships	1-4
1-3. Heat Transport System Variables Examined	1-5
1-4. Variables Examined for Effects on the Reference Design - Fuel Cost and Doubling Time	1-7
1-5. Parameter Study Reference Core Design Data	1-10
4-1. Effect of Density and Corresponding Linear Heat Rate Changes on Fuel Cost	4-4

List of Figures

(Figures are placed at end of each section.)

Figure

3-1. Effect of Pin Diameter, Pitch, and Fabrication Cost on Fuel Cost
3-2. Effect of Pin Diameter and Pitch on Power Generation Cost
3-3. Effect of Pin Diameter and Pitch on Core Volume Fractions
3-4. Effect of Pin Diameter and Pitch on Breeding Ratio
3-5. Effect of Pin Diameter and Pitch on Enrichment
3-6. Effect of Pin Diameter on Fuel Cost Components
3-7. Effect of Pin Diameter and Pitch on Doubling Time
3-8. Effect of Pin Diameter and Pitch on Primary Pumping Power and on Fuel Can Thickness
3-9. Effect of Pin Pitch and Diameter on Breeding Ratio
3-10. Effect of Pin Pitch and Diameter on Doubling Time
3-11. Effect of Pin Pitch and Diameter on Fuel Cost
3-12. Effect of Pin Pitch and Diameter on Power Cost
3-13. Effect of Pin Ligament and Pitch on Fuel Cost
3-14. Effect of Pin Ligament and Diameter on Fuel Cost

Figures (Cont'd)

Figure

- 3-15. Effect of Pin Ligament and Pitch on Power Generation Cost
- 3-16. Effect of Pin Ligament and Diameter on Power Generation Cost
- 3-17. Effect of Pin Length and Diameter on Fuel Cost
- 3-18. Effect of Pin Length and Diameter on Power Generation Cost
- 3-19. Effect of Pin Diameter, Pitch, and Length on Fuel Cost
- 3-20. Effect of Pin Diameter, Pitch, and Length on Power Generation Cost
- 3-21. Effect of Pin Length, Diameter, and Pitch on Doubling Time
- 3-22. Effect of Pin Diameter, Pitch, and Length on Doubling Time
- 3-23. Effect of Pin Length and Plutonium Value on Fuel Cost for 0.34-Inch Pitch and 0.28-Inch Pin Diameter
- 3-24. Effect of Pin Length and Unit Fabrication Cost on Fuel Cost for 0.34-Inch Pitch and 0.28-Inch Pin Diameter
- 3-25. Effect of Pin Diameter and Constant Fabrication Cost on Fuel Cost for 0.28-Inch-Diameter Pin
- 3-26. Effect of Pin Diameter, Length, and Unit Fabrication Cost on Fuel Cost
- 3-27. Effect of Pin Diameter and Reprocessing Cost on Fuel Cost
- 3-28. Effect of Pin Diameter and Reprocessing Throughput on Fuel Cost
- 3-29. Effect of Pin Diameter, Pitch, and Plutonium Value on Fuel Cost
- 3-30. Effect of Pin Diameter, Pitch, and Plutonium Value on Plutonium Credit
- 3-31. Effect of Pin Diameter, Pitch, and Plutonium Value on the Difference Between Plutonium Working Capital and Credit
- 3-32. Effect of Pin Diameter, Pitch, and Length and Plutonium Value on Fuel Cost
- 3-33. Effect of Pin Diameter, Burnup, and Plutonium Value on Fuel Cost
- 3-34. Effect of Pin Pitch and Burnup on Minimum Fuel Cost
- 3-35. Effect of Burnup and Pin Diameter on Fuel Cost
- 3-36. Effect of Pin Diameter on Fuel Cost Components at 50,000 MWD/T
- 3-37. Effect of Pin Diameter on Fuel Cost Components at 150,000 MWD/T
- 3-38. Effect of Pin Diameter, Burnup, and Fabrication Cost on Fuel Cost
- 3-39. Effect of Pin Diameter and Burnup on Doubling Time
- 4-1. Fuel Cost Dependence on Linear Power Rating for 80% Fuel Density
- 4-2. Fuel Cost Dependence on Burnup for 80% Fuel Density
- 4-3. Effect of Initial Fuel Density on Allowable Linear Heat Rate
- 4-4. Effect of Fuel-Clad Gap Unit Surface Thermal Conductance on Maximum Allowable Linear Heat Rate
- 4-5. Densification Effects on Fuel Performance at BOL
- 4-6. Densification Effects on Fuel Performance at 140,000 MWD/T
- 4-7. Effects of Uncertainties in Columnar Grain Formation Temperature on Allowable Linear Heat Rate
- 4-8. Effect of Fuel-Clad Gap Heat Transfer Coefficient Uncertainties on Allowable Linear Heat Rate

Figures (Cont'd)

Figure

- 4-9. Effect of Uncertainty in Fuel Conductivity on Linear Heat Rate
- 4-10. Effects of Allowable Maximum Linear Heat Rate and Average Burnup on Power Generation Cost
- 4-11. Power Generation Cost Variation With Pin OD and Pitch at a Maximum Linear Heat Rate of 14 kW/ft
- 4-12. Power Generation Cost Variation With Pin OD and Pitch at a Maximum Linear Heat Rate of 17 kW/ft
- 4-13. Power Generation Cost Variation With Pin OD and Pitch at a Maximum Linear Heat Rate of 20 kW/ft
- 4-14. Fuel Cost Vs Burnup at 14 and 17 kW/ft Linear Heat Rates
- 4-15. Qualitative Effect of Design Limit Imposed by Clad-Fuel Interaction
- 4-16. Effects of Allowable Maximum Linear Heat Rate and Fuel Pin Fabrication Costs on Power Generation Costs
- 4-17. Doubling Time Vs Pin Diameter at Various Linear Heat Rates
- 4-18. Doubling Time Variation With Maximum Linear Heat Rate
- 4-19. Power Generation Cost for Various Fuel Pin Cladding Thicknesses
- 4-20. Effect of Cladding Thickness on Doubling Time
- 4-21a. Effect on Spacer Type, Pitch, and Thickness and Fuel Pin Pitch on Power Generation Cost
- 4-21b. Effect of Spacer Type, Pitch, and Thickness and Fuel Pin Pitch on Doubling Time
- 4-22. Variation of Power Generation Cost With Orifice Effectiveness
- 4-23. Effect of Fuel Specific Power on Power Generation Cost
- 4-24. Effect of Fuel Specific Power on Doubling Time
- 4-25. Effect of Fuel Specific Power on Outpile Fraction and Breeding Ratio at Constant 0.060-Inch Ligament
- 4-26. Effect of Reactor Inlet Temperature on Fuel Cost at Constant 300 F Reactor Coolant Temperature Rise
- 4-27. Effect of Varying Reactor Coolant Temperature Rise on Fuel Cost at Constant Reactor Inlet or Outlet Temperature.
- 4-28. Effects of Reactor Inlet and Outlet Temperatures on Power Generation Cost, Maintaining Optimum Pin OD and Pitch
- 4-29. Effect of Reactor Coolant Temperature Rise on Power Generation Cost for Various Pin Diameters and Pitches
- 4-30. Effect of Reactor Coolant Temperature and Coolant Flow Rate (or Temperature Rise) on Doubling Time
- 6-1. LMFBR Schematic Flow Diagram
- 6-2. Effects of Reactor ΔT on Power Generation Cost for Various Reactor Outlet Temperatures, Reference Plant
- 6-3. Cost of Heat Transport System Components
- 6-4. Effects of Reactor ΔT on Steam Generator Cost for Various Reactor Outlet Temperatures
- 6-5. Effects of Reactor ΔT on Nuclear and Turbine Island Costs
- 6-6. Effect of Reactor ΔT on Power Generation Cost
- 6-7. Effects of Reactor ΔT on Power Generation Cost for Various Reactor Outlet Temperatures
- 6-8. Effect of $\Delta T_{IHX} - \Delta T_{RH}$ on Power Generation Cost ($\Delta T_R = 200$ F)
- 6-9. Effect of $\Delta T_{IHX} - \Delta T_{RH}$ on Power Generation Cost ($\Delta T_R = 300$ F)
- 6-10. Effect of $\Delta T_{IHX} - \Delta T_{RH}$ on Power Generation Cost ($\Delta T_R = 400$ F)
- 6-11. Effect of $\Delta T_{IHX} - \Delta T_{RH}$ on Component Costs ($\Delta T_R = 200$ F)
- 6-12. Effect of $\Delta T_{IHX} - \Delta T_{RH}$ on Component Costs ($\Delta T_R = 300$ F)

Figures (Cont'd)

Figure

- 6-13. Effect of $\Delta T_{IHX} - \Delta T_{RH}$ on Component Costs ($\Delta T_R = 400$ F)
- 6-14. Effects of IHX LMTD on Power Generation Cost for 2400 psi/950 F/950 F Steam Cycle
- 6-15. Effect of Steam Generator Hot End ΔT on Power Generation Cost
- 6-16. Effect of Steam Generator Hot End ΔT on Steam Generator Cost
- 7-1. Effect of Burnup, Fabrication, and Plutonium Costs on Fuel Cost
- 7-2. Effect of Burnup on Fuel Cost Components
- 7-3. Effect of Burnup and Plutonium Value on Fuel Cost
- 7-4. Effect of Burnup on Doubling Time
- 7-5. Cycle Time + Outpile Time Vs Burnup
- 7-6. Effect of Outpile Time on Doubling Time
- 7-7. Effect of Outpile Time on Fuel Cost
- 7-8. Effect of Burnup on the Relative Importance of Fuel Cost Components
- 7-9. Effect of Unit Fabrication Cost on the Relative Importance of Fuel Cost Components
- 7-10. Effect of Plutonium Value on the Relative Importance of Fuel Cost Components
- 7-11. Effect of Pin Diameter on the Relative Importance of Fuel Cost Components

1. INTRODUCTION

1.1. Purpose

The parametric studies described in this report have been undertaken to investigate the quantitative effects of selected parameters on the design and economics of the 1000-MWe liquid metal fast breeder reactor (LMFBR). The parameters represent important areas of technological and economic uncertainties that can influence the direction of future design and development work leading to a competitive LMFBR industry.

In general terms, the objectives of the studies are as follows:

1. To determine the values of the major core and reactor plant design and operating parameters that result in an LMFBR optimized for the minimum net electric generating cost. The optimum parameter values are to be determined on the basis of reference values for specified economic variables, e.g., plutonium value and unit fabrication cost. The studies are intended to show the variation in optimum parameter values over a range of values of the selected economic variables. In addition, the values of the major parameters that result in an LMFBR optimized for fuel conservation, i.e., lowest doubling time, are to be determined. These studies are described principally in section 3.

2. To provide data that will permit "cost-benefit" evaluations in a subsequent task (Task IV) of the Follow-On Program with respect to the research, development, and component testing program required for the design and construction of the reference design LMFBR. The data developed will indicate the penalties in generating cost, fuel cost, and doubling time resulting from the partial, or the non-achievement of the R&D specified as necessary. In addition, the data will show the economic and fuel conservation incentives for improvements in technology beyond the values of the parameters specified in the reference design. Section 4 describes the results of these studies.

3. Inasmuch as there is considerable uncertainty in predicting the values of the economic variables that will exist when the reference LMFBR plant is constructed and becomes part of a viable LMFBR economy, the fuel and power generating costs of the reference design will be determined over a range of values of selected economic parameters; the reference design fuel doubling time will also be determined over a range of fuel burnups and outpile times. These data are presented in section 7.

1.2. Scope

1.2.1. Method of Analysis

The studies were performed with the aid of the NAPS computer code (described in the appendix), which is designed especially for this kind of parametric study. NAPS generates a series of design variants, using as a basis the reference plant as described in section 1.3; perturbations in design and operating characteristics are determined as a function of basic design parameter input data. The code also determines the fuel, capital, and operating cost for each design variant in mills per kWh.

The following example illustrates how the NAPS code interrelates the many core and plant effects that result from the perturbation of a single parameter. To investigate fuel pin diameter effects, the NAPS code is run using a series of fuel pin diameters as the independent input variable while other core geometry features are held constant. For each diameter the code calculates a new fuel unit fabrication cost, the changes in core volume fractions, changes in coolant pressure drop and pumping power, and resultant changes in core diameter and blanket thickness. Also calculated are the required initial and final fissile mass, the initial fertile mass, the breeding ratio, changes in core and reactor vessel dimensions and in the associated structures and shielding, and the changes in the capital costs for these equipment and structural changes. New reactor thermal power and plant net electrical output are determined, as are new sizes and costs for the heat transport system (primary and intermediate circuit pumps, heat exchangers, and the like). Fuel cycle costs, plant capital cost, operation and maintenance cost, and total generating cost (in mills per kilowatt-hour) are then determined

for the specific core and plant design variant resulting from the perturbation of the pin diameter.

1.2.2. Core Parameter Sensitivity and Optimization

Reactor core designs are investigated to determine parameter sensitivity and optimum design values for the fuel pin diameter, pitch, ligament, and length using the reference cost values for fuel fabrication, reprocessing, and plutonium, and the reference average core burnup (see Table 1-1). Optimum design points are also determined over a range of combinations of burnup values and economic parameters, thus reflecting present uncertainties in the values that will exist in the 1980s. Also investigated are the basic reasons for the trends that result from the perturbation of each variable, such as the effect on enrichment, breeding ratio, steel fraction, pressure drop, etc., as well as the interaction of these effects to produce designs of minimum fuel cost and doubling time under various combinations of these parameters.

Table 1-1. Variables and Parameters Examined for Core Parameter Sensitivity and Optimization Studies

<u>Item</u>	<u>Range</u>
Fuel pin diameter, in.	0.21 - 0.31
Fuel pin pitch, in.	0.30 - 0.34
Fuel pin length, in.	28.0 - 40.0
Core unit fabrication cost, \$/kg oxide	135 - 542
Reprocessing cost, \$/day	10,000 - 90,000
Reprocessing plant throughput, kg/day	165.0 - 1480.0
Plutonium value, \$/gm	5.0 - 20.0
Core average burnup, MWD/T	50,000 - 200,000
Doubling time, yr	11 - 18

1.2.3. Core System Technology - Optimization Relationships

These studies are concerned primarily with the reactor core parameters whose allowable design and operating limits depend on future research and development programs. Table 1-2 lists the variables and parameters investigated.

Table 1-2. Variables and Parameters Examined for Core System Technology-Optimization Relationships

Item	Range
Linear heat rate, kW/ft	14 - 20
Coolant inlet/coolant bulk outlet, F	600 - 1000/900 - 1200
Coolant temperature rise, F	200 - 400
Maximum cladding surface temperature, F	1150 - 1300
Fuel density, % of theoretical	75 - 95
Effective fuel thermal conductivity, Btu/hr-ft-°F	1.31 - 1.77
Cladding thickness, in.	0.010 - 0.020
Fuel-to-clad bond conductance, Btu/hr-ft ² -F	1000 - 30,000
Fuel average burnup, MWD/T	25,000 - 200,000
Spacer type	Helical ribbon, grid, wire-wound
Core orificing effectiveness	0.0 - 0.5
Core unit fabrication cost, \$/kg oxide	135 - 542
Pin diameter, in.	0.22 - 0.36
Pin pitch/ligament, in.	0.27 - 0.40/0.04 - 0.07
Fuel specific power, kW/kg fissile	500 - 2000
Steam cycle, psi/F/F	1000/546, 2400/950/950
Doubling time, yr	9 - 24

1.2.4. Safety Coefficient Parameterization

The majority of the parameters that will be examined in other parts of this study are independent variables. For example, the pin diameter can be changed without changing length or pitch. The effects of such changes on power costs can be quite accurately evaluated with the aid of parametric codes such as NAPS. On the other hand, the safety parameters, sodium void and Doppler coefficients are dependent variables and hence can be modified only by changes in such physical parameters as composition or geometry. Furthermore, because of the nature of the safety coefficients, detailed calculations showing exact composition and geometry are required for meaningful results.

A comprehensive study relating power costs and the safety parameters computed for several combinations of compositions and geometries was completed early in Task II; the results are presented in section 2, Volume 4 of this report. Since this study represents the most accurate and detailed calculations performed in this area, the results and conclusions will be abstracted and used here. Although the base case of the trade-off study and the reference core are not identical, enough similarities exist so that the trends and relative changes should be applicable. (The reader is referred to section 2, Volume 4 for complete details.)

1.2.5. Heat Transport System Technology-Optimization Relationships

The heat transport system parameters of reactor outlet temperature, reactor temperature rise, intermediate heat exchanger log mean temperature difference (LMTD), and steam generator hot end temperature difference were investigated to determine the operating conditions at which the lowest plant generating cost resulted. For a list of the variables examined and their ranges, see Table 1-3.

Table 1-3. Heat Transport System Variables Examined

<u>Item</u>	<u>Range</u>
Coolant bulk outlet temp, F	800 - 1200
Coolant temp rise, F	200 - 500
$\Delta T_{IH\bar{X}}'' - \Delta T_{RH}$ (see section 6.2), F	25 - 150
IHX LMTD, F	50 - 150
Steam generator hot end ΔT , F	20 - 230
Steam cycle, psi/F/F	2400/950/950, 1000/546

The studies of reactor outlet temperature determined the optimum temperature at various values of reactor temperature rise. In this study, as in the other heat transport system parameter studies, the reactor core and the steam cycle conditions (with one exception—

discussed below) were held constant. Thus, the optimum temperature depends primarily on the relative costs of equipment in the primary and intermediate systems.

In order to investigate the entire range of reactor coolant outlet temperatures specified in the contract (from 800 to 1200 F) the 1000 psig, dry and saturated steam cycle, as well as that of the reference design (2400 psig/950/950), are examined, with the 1000 psig, dry and saturated cycle covering the entire temperature range. Optimum temperature increases are then determined for a number of reactor outlet temperatures, with the optimum point again a function of the heat transport system component costs. Also determined is the optimum IHX LMTD at a series of reactor outlet temperatures; the reference steam cycle is used for this study.

The original contract requirement for investigation of the steam generator LMTD was found to be unrealistic, since the hot and cold end temperatures are not the main criteria for component design, in that the steam generator actually consists of economizing, evaporating, and superheating sections, each with its own LMTD. As a consequence, the steam generator study took the form of investigating the hot end temperature difference (ΔT), which is a more significant temperature parameter. Optimum hot end ΔT s are studied as a function of a series of reactor outlet temperatures.

1.2.6. Effects of Economic Parameters on the Reference Core

The parameters of core unit fabrication cost, plutonium value, unit reprocessing cost, average burnup, and outpile time are varied over a range of values (see Table 1-4) to determine the effect of each parameter (singly, and in certain cases, two parameters simultaneously) on the fuel cost of the reference design. The relative importance of each, as a fraction of the total fuel cost, is also determined over a range of economic variables.

Table 1-4. Variables Examined for Effects on the Reference Design - Fuel Cost and Doubling Time

Item	Range
Burnup, MWD/T	50,000 - 200,000
Unit fabrication cost, \$/kg Oxide	135 - 542
Plutonium cost, \$/gm	5.00 - 20.00
Outpile time, yr	0.67 - 2.7

1.3. Reference Design Description

The following paragraphs describe the reference design that was used as a basis for the parametric studies:

The reference design incorporates an LMFBR that produces sufficient heat to generate a minimum of 1000 MWe. Heat from the core and blanket regions of the reactor is transferred by the primary sodium coolant to six IHXs. Since all primary equipment components, including the core, core pressure vessel, primary pumps, IHXs, and irradiated fuel storage drums, are housed within the reactor vessel, the reactor system is known as a "pot" or "integral" type of design. A secondary circuit of sodium flows through the IHXs and transfers the reactor heat to three once-through steam generators, where steam at 2400 psig and 950 F is produced; this steam is then sent to a tandem-compound, six-flow, high-pressure turbine. Three sodium reheaters raise the temperature of the exhaust steam from the high-pressure turbine to 950 F before the steam enters the intermediate low-pressure turbine.

Refueling is accomplished by an under-the-plug scheme. The top of the reactor vessel is covered by an annular cover plug 10 feet thick. Three eccentrically-mounted rotating plugs are positioned in the cover structure; each of the plugs is approximately 10 feet thick and is supported by heavy duty bearings to facilitate indexing. Refueling is carried out using a fuel transfer machine mounted on the inner rotating plug; this machine transfers both spent and fresh fuel between the reactor core and the fuel storage drums. Irradiated fuel from the decay storage drums within the containment is transferred through the containment building using a shielded, gas-cooled cask mounted on a gantry.

The reactor system is housed within a cylindrical containment vessel 100 feet in diameter, which is accessible to reactor personnel during normal operation.

The reactor core, along with its axial and radial blankets, is contained within a core vessel, which in turn is contained in a large pool of sodium within the 52-foot-diameter reactor vessel; the core vessel is surrounded by neutron shielding. In the annulus between the outside of the neutron shielding and the inside of the reactor vessel, and submerged in the sodium pool, are the six primary sodium pumps, six IHXs, two rotating fuel decay storage drums, and the cold traps. The primary sodium enters the suction side of the primary pumps and flows from the pumps through the connecting piping into the lower core vessel plenum, up through the core and radial blanket, into the upper core vessel plenum. From that point, the sodium flows through the six IHXs by gravity and discharges to the sodium pool, completing the circuit; the primary pumps take suction from this pool of sodium.

Sodium in the intermediate system circulates through three identical loops, each of which contains two IHXs, one steam generator, one reheater and one pump. A sodium bypass enables easier modes of control by permitting the flow and temperature conditions to be varied in the secondary system.

The steam system comprises three steam generators, three sodium reheaters, a tandem-compound turbine, a turbine-driven pump, and six feedwater heaters.

The active core has 288 fuel assemblies and 25 control rods, which are evenly spaced among the fuel assemblies. Both fuel assemblies and control rods have hexagonal cross sections, since the fuel pins are arranged on a triangular pitch. The stainless-steel-clad fuel pins are of a vented-to-sodium design; each has an active fuel length of 34.7 inches of vibratory compacted $\text{PuO}_2\text{-UO}_2$, and 15.9 inches of depleted UO_2 material above and below the active fuel length form the axial blankets. The pins are held together by top and bottom assembly fixtures and are spaced by twisted-ribbon spacers.

The fuel assemblies are arranged in a cylindrical pattern and are surrounded by 151 radial blanket assemblies. Each radial blanket

contains stainless-steel-clad pins of depleted UO_2 , each of which has an active length of 42.7 inches and is not vented to the sodium.

All fuel and blanket assemblies are located between the top and bottom holddown structures and are preloaded upward to prevent hydraulic lifting during operation. The walls of the fuel and blanket assemblies are solid cans, enabling individual orificing to each fuel assembly as required.

The control rods consist of tantalum metal contained in rods. Each rod has a mechanical drive assembly mounted on the upper surface of the reactor cover structure; an extension rod and a positive coupling connect the drive to the control rods. In the event of a reactor scram, both the control and extension rods are uncoupled from the drive mechanism and are allowed to fall freely. Because the parameter study was initiated before the reference design had been finalized, there are differences between the design data for the parameter study core and those for the final 1000-MWe Follow-On Study reference core. Differences also exist in the blanket design data, since the NAPS code designs a blanket for a given core. That blanket may not be the same as one that more detailed physics calculations would show as best for the particular core. Blanket differences would affect slightly the blanket unit fabrication cost, reprocessing time, and the breeding ratio.

It is clear that the power generation costs quoted in this study are somewhat lower than those given for the reference plant in Volume 1. The major differences are found in the fixed or capital cost and in the operation, maintenance, and insurance costs. The latter is low by approximately 0.08 mill/kWh; this is a result of a low operation and maintenance cost estimate.

Capital costs are low by approximately $\$16.5 \times 10^6$, of which approximately $\$12 \times 10^6$ is direct cost. Of this figure, approximately $\$5 \times 10^6$ and $\$7 \times 10^6$ can be attributed to the turbine island and to the nuclear island, respectively.

Although most of the cost differences are associated with equipment that has relatively little effect on the majority of the parametric and trade-off studies, some of the differences in the heat transport system costs might affect the trends established in the steam cycle selection trade-off study (Volume 4) and the heat transport system technology

optimization relationships (section 2.4). Table 1-5 lists the reference design parameters used in this parameter study.

Table 1-5. Parameter Study Reference Core Design Data

<u>Reactor</u>	
<u>Physics Characteristics</u>	
Avg core burnup, MWD/T	100,000
Radial power peaking factor	1.27
Axial power peaking factor	1.26
Core power fraction at EOL	0.904
Axial and radial blanket power fraction at EOL	0.096
Fuel data	
Type	Mixed oxide, vibratory compacted
Theoretical density, gm/cm ³	11.04
% theoretical density	85.0
Thermal conductivity, Btu/hr-ft-°F	1.54
Initial fissile concentration fraction	0.720
Breeding ratio	1.338
Doubling time, yr	11.92
Fuel specific power, kW/kg fissile	890
Cycle time, yr	3.17
Outpile fuel fraction	0.422
Core configuration	Cylindrical
<u>Thermal and Hydraulic Characteristics</u>	
Bulk reactor inlet temp, F	800
Bulk reactor outlet temp, F	1100
Thermal power, MWt	2450
Primary sodium flow rate, lb/hr × 10 ⁶	92.4
Orifice effectiveness	0.4
Fuel-cladding surface conductance, Btu/hr-ft ² -°F	1500
Fuel melting temp - BOL, F	4950
Fuel melting temp - EOL, F	4730
Maximum linear heat rate, kW/ft	17.0
Core pressure drop, psi	
Friction	20.67
Head	2.05
Acceleration	0.57
Spacers	7.16
	<hr/>
Total	30.45
Hot channel flow rate, lb/hr	1006.4

Table 1-5. (Cont'd)

Temperature, F	
Max cladding surface (103% power)	1209.0
Max fuel central (111% power)	4650.0
<u>Mechanical Design Characteristics</u>	
Nuclear island configuration	Pot type
Fuel pin type	Vented
Fuel pin dimensions, in.	
OD	0.280
Active fuel length	34.7
Gas void length	2.0
Axial blanket length (each)	15.9
Total core plus blanket length	68.5
Cladding thickness	0.010
Cladding material	SS 348
Fuel pin lattice	
Type	Triangular
Pitch, in.	0.337
Blanket pin dimensions, in.	
OD	0.456
Length	42.7
Fuel pin spacer	
Type	Spiral ribbon
Material	SS 304
Thickness, in.	0.020
Width, in.	0.113
Twist pitch, in.	2.00
Fuel can	
Type	Solid-wall
Material	SS 348
Wall thickness, in.	0.132
Pitch, in.	6.504
Number of elements	
Core fuel	288
Blanket	151
Control	25
Pins per element, fuel/blanket	331/127

Table 1-5. (Cont'd)

Intermediate Heat Exchangers

Number	6
Temp differences, F	
Primary	300.0
Secondary	300.0
Log mean (LMTD)	100.0
Flow rates, lb/hr $\times 10^6$	
Primary	92.36
Secondary	92.35
Total heat transfer area, ft ²	79,560

Steam Generators

Number	3
Type	Once-through
Temp differences, F	
Superheater section	
Steam	288.0
Sodium	118.6
Log mean	114.6
Boiler section	
Sodium	139.0
Log mean	139.0
Economizer section	
Sodium	90.0
Feedwater	178.0
Log mean	118.7
Sodium flow rate, lb/hr $\times 10^6$	66.69
Heat transfer areas, ft ²	
Boiler section	12,901.0
Economizer section	10,090.0
Superheater section	14,751.0

Reheaters

Number	3
Temp differences, F	
Sodium	175.0
Steam	340.0
Log mean	113.1
Sodium flow rate, lb/hr $\times 10^6$	25.66

Table 1-5. (Cont'd)

Total heat transfer area, ft ²	60,201.0
Steam cycle, psi/F/F	2400/950/950

Fuel Economic Data

Fissile plutonium value, \$/gm	10.00
Unit fabrication cost, \$/kg	
Core	271.00
Blanket	73.00
Unit reprocessing cost, \$/day	30,000.00
Reprocessing throughput, kg/day	493
Unit reconversion cost, \$/kg U	5.60
Unit shipping cost - core + axial blanket, \$/kg	20.00
Unit shipping cost - radial blanket, \$/kg	10.00
Refueling downtime, days/cycle	10.00
Spent fuel storage time, yr	0.247
Spent fuel shipping time, yr	0.167
Reprocessing time, yr	0.340
Fabrication time, yr	0.500
Fresh fuel on-site storage time, yr	0.083
Total outpile time, yr	1.338

2. SUMMARY OF RESULTS

This summary is necessarily long because of the large number of parameters investigated. Nevertheless, it is only a representative selection of the most significant results and conclusions. Actually, the parametric studies are best summarized in the 96 curve-plot figures in the report. It is from these curves that the optimum parameter values can be determined and the sensitivity of the optimum points to the technological and economic parameters clearly discerned. The curves must also be consulted to determine how economics and doubling time are affected by core and plant performance that is either inferior or superior to that specified in a reference design; these data are necessary to determine the penalties and improvements associated with the research and development accomplishments.

The reference design mentioned above is a parameter study reference or base point, about which perturbations are made. This base-point design varies slightly with respect to the final 1000-MWe LMFBR reference core details reported in Volumes 1, 2, and 3.

2.1. Parameter Sensitivity and Optimization

2.1.1. Fuel Pin Diameter and Pitch

At the reference unit fabrication cost, the fuel pin-diameter/pitch combination yielding the minimum fuel cost is a 0.28-inch diameter on a 0.33-inch pitch. Increasing the unit fabrication cost drives the optimum pin/pitch combination to slightly larger values, and lower unit fabrication costs decrease the optimum values slightly (see Figure 3-1). The shortest doubling time is achieved for the reference core length at a pin diameter of 0.28 inch and a pitch of 0.34 inch. The doubling time is 11.9 years. At smaller pin diameters and pitches, doubling time tends to increase slightly (see Figure 3-7).

There is an optimum pin diameter for a given pitch and length which yields the lowest doubling time, with sharp increases in doubling time at larger and smaller pin diameters. At a constant pin diameter and pitch, however, doubling time decreases with decreasing length. For the reference design, the doubling time would be reduced from 11.9 to about 10.9 years if the core length were shortened to 20 inches and a 0.253-inch-diameter pin on a 0.30-inch pitch were used (see Figure 3-22).

At a given pin diameter there is an optimum pitch. For the reference pin diameter of 0.280 inch, the optimum pitch yielding the minimum fuel cost is at 0.34 inch. Increasing the pitch at a constant diameter has much the same effect as decreasing the diameter at a constant pitch. The flow area increases, pressure drop decreases, and can thickness decreases. The decreasing steel volume causes a drop in fuel costs. However, as the sodium volume increases, softening of the spectrum increases the enrichment and decreases the breeding ratio, thus tending to increase fuel costs. The opposing effects result in an optimum pitch (see Figures 3-9 and 3-11).

The optimum ligament (clearance between pins) with respect to fuel and power generation costs is in the range of 50 to 60 mils for the optimum pin diameter and varies only a small degree with diameter (see Figures 3-12 through 3-16).

Traditionally, LMFBRs have been designed with fuel pin diameters of approximately 0.25 inch, whereas these studies indicate that the optimum diameter is somewhat larger, i.e., 0.27 to 0.28 inch. The two factors that most affect the optimum pin diameter are unit fabrication cost (\$/kg) and the treatment of the outpile fraction in the calculation of the plutonium inventory charge. The unit fabrication costs in NAPS are strongly diameter-dependent. Figure 3-25 demonstrates the result of assuming a unit fabrication cost that is independent of pin diameter. The optimum point is clearly shifted to a smaller diameter. Similarly, if a constant outpile fraction is assumed for a series of cases having different pin diameters, then the optimum point is shifted toward smaller pins. In reality, the outpile time rather than outpile fraction is more nearly constant; the times required for fabrication, fresh fuel storage, spent fuel storage, and shipping should be relatively independent

of pin diameter. Only reprocessing would vary with the mass. Thus, with a larger pin and hence larger mass and greater cycle time for a given burnup, the outpile time is spread over more kWh/cycle. If, on the other hand, a constant outpile fraction is assumed, the smaller pin suffers the same penalty in inventory as the larger pin.

2.1.2. Fuel Pin Length

The active length, pin diameter, and pitch optimized for the minimum fuel costs predicted by NAPS are: length, 40 inches; diameter, between 0.27 and 0.285 inch; pitch, between 0.32 and 0.34 inch. The fuel cost for both combinations is 0.808 mill/kWh, and the doubling time of the latter pin/pitch combination is 12.36 years. If doubling time is the criterion of optimization, the best combination is a length of 20 inches, a 0.25-inch pin diameter, and a 0.30-inch pitch. The resulting doubling time is 10.9 years.

The reference core length of 34.7 inches represents a compromise between the two extremes and factors in other considerations. For this length, NAPS indicates a doubling time of 11.87 years and a fuel cost of 0.822 mill/kWh. Thus, the doubling time for the reference pin length is only 9% higher than the minimum, and the fuel cost is less than 2% higher than the minimum at 40 inches. However, the fuel cost of the minimum doubling time combination is nearly 16% higher than that for the reference core; thus, the reference length represents a good compromise.

Additional factors that affect the choice of the reference core active length are discussed in Volume 2, Appendix 4-E. Other considerations, such as sodium voiding and the scram stroke, indicate the desirability of a shorter core than the economic optimum.

2.1.3. Fabrication and Reprocessing Cost Effect

It is significant to note that the optimum pin diameter varies little with the unit fuel fabrication cost, even though the unit cost is a strong function of diameter. High unit fabrication cost, however, does tend to shift the optimum pin diameter to somewhat larger sizes. Using a unit cost (as a function of diameter) that is twice the cost

calculated by our methods, the optimum pin diameter changes from the reference value of 0.28 to about 0.29 inch (see Figure 3-26).

As in the case of the unit fabrication cost, wide variations in the reprocessing cost affect the optimum pin diameter only slightly. Thus, at a reprocessing plant daily cost of \$90,000, which is three times the nominal value, the optimum diameter is 0.285 inch, while at \$10,000 per day, it is at about 0.28 inch (see Figure 3-27).

2.1.4. Plutonium Cost Effects

Increasing the plutonium value drives the optimum pin diameter and pitch combination to smaller values, since smaller pins result in a smaller fuel inventory. Again, the effect on optimum diameter is small (see Figure 3-29).

2.1.5. Burnup Effects

The optimum pin diameter decreases as burnup increases. Since the unit fabrication cost in mills/kWh decreases as more energy is extracted from the fuel, more expensive (in \$/kg) fuel pins can be used, because the smaller pins result in a smaller fuel inventory with decreased fuel carrying charges. At half the reference burnup, i.e., 50,000 MWD/T, the optimum diameter is at 0.295 inch; at twice the reference burnup (200,000 MWD/T), the optimum diameter decreases to 0.27 inch.

The physics model used in NAPS assumes that the breeding ratio is independent of burnup and, hence, overestimates plutonium credit at long burnups. In reality, the breeding ratio tends to decrease with increasing burnup, so that the calculated fuel costs at high burnups are somewhat low. The effect of plutonium credit is reduced somewhat, because the plutonium inventory component is excessive.

2.2. Core System Technology-Optimization Relationships

2.2.1. Fuel Model Parametrics

The reference design employs a vibratory compacted, mixed-oxide fuel with an as-fabricated fuel of 85% of the theoretical density. With densities less than theoretical, it is expected that fuel swelling in an outward radial direction will be reduced, thus extending

the allowable burnup. Calculations performed with the B&W TAMPA computer code have shown that additional benefits may be gained in the form of increased allowable linear heat ratings over some range of decreasing density (Figure 4-3). This increased heat rating can result from more extensive fuel restructuring, densification, and central void formation with the decreasing as-fabricated density. (A larger central void decreases the thermal resistance seen by the innermost fuel.) Since decreasing as-fabricated fuel density is detrimental to breeding performance, there exists an optimum fuel density which balances the effects of decreased breeding ratio against the effects of increased burnup and linear heat rate. Thus fuel density becomes one of the prime areas of interest for research and development, since it directly influences three prime parameters that have a strong influence on LMFBR economics.

The effects of fuel model parameter variations on the maximum allowable linear heat rate have been ascertained (see Figures 4-4 through 4-9). Slight variations in fuel restructuring, fuel densification, and fuel-clad gap thermal conductance have considerable effect on the allowable linear heat rate. Also, since these variables enter into the general problem area of fuel and clad mechanical interaction, it is quite apparent that these parameters require investigation; such investigations will improve fuel model accuracy considerably.

2.2.2. Linear Heat Rate Effects

At constant burnup and fuel pin diameter, the maximum linear heat rating affects fuel cycle cost, since the heat rating sets the core total active fuel length. High linear heat rates lower power generation costs primarily by lowering the plutonium inventory. However, the effect is tempered somewhat by changes in the breeding ratio or the fuel pin unit fabrication costs. Either a decrease in breeding ratio or an increase in fuel pin unit fabrication cost accompanies an increase in linear heat rate, depending on how the core height-to-diameter ratio is changed (see Figure 4-10). Also, changes in enrichment result in a less-than-proportional decrease in plutonium inventory with an increase in linear heat rating, further tempering the effect.

Increases in linear heat rating can result in appreciable reductions in capital costs of the core vessel, reactor vessel, and biological shielding, depending on the core height-to-diameter ratio.

The linear heat rate will have some effect on the allowable burnup, since the heat rate affects cladding and fuel temperatures. Consequently, the combined effects of linear heat rate and burnup on the power generation cost are shown (Figure 4-10), although the absence of a functional relationship between linear heat rate and allowable burnup precludes any quantitative results at this time. In a qualitative sense, increasing the linear heat rate at a constant coolant bulk temperature degrades cladding performance by raising cladding temperatures and decreasing the creep strength. On the other hand, increasing the linear heat rating raises fuel temperatures, and, discounting fuel melting or slumping, this is desirable in that increased average fuel temperatures increase the proportion of fuel in the plastic state, with a possible reduction of mechanical forces (fuel swelling) between the fuel and cladding. Also, high fuel temperatures promote fission gas release, thus partially alleviating fuel swelling. Depending on the extent to which the linear heat rate affects the allowable burnup, the linear heat rate may have more effects on power generation costs than was heretofore believed. This points up the necessity of investigating the fuel-clad interaction.

As previously mentioned, fuel pin unit fabrication cost can increase with increasing linear heat rating, depending on the change in the height-to-diameter ratio of the core. At very high unit fabrication costs, e.g., twice the reference core value, this effect becomes pronounced, further reducing the benefits that result from increased heat rating (Figure 4-16). This points out additional incentives for an accurate definition of unit fabrication costs.

Fuel thermal conductivity and fuel-clad gap thermal conductance variations may be translated into changes in allowable maximum linear heat rating while maintaining constant maximum central fuel temperature (Figures 4-8 and 4-9). Better definition of both fuel thermal conductivity and gap conductance will have an appreciable effect on the allowable maximum linear heat rate. The role of these two parameters in the burnup and linear heat rate functional relationship also requires investigation. It has been found that oxide fuels behave plastically

at temperatures above 900 C.¹ It is conceivable, then, at a constant fuel central temperature, that a high fuel thermal conductivity and a very low gap thermal conductance would raise the average fuel temperature sufficiently to reduce the fuel-to-clad mechanical forces and extend the allowable burnup. Therefore, the use of fuel-to-clad bonding materials that give high thermal conductance would be undesirable. These considerations reinforce the necessity of investigating the fuel-clad interaction.

Increasing the maximum linear heat rate has a favorable effect on doubling time (Figure 4-17). The degree to which doubling time is reduced depends on the accompanying change in core height-to-diameter ratio. This favorable effect on doubling time indicates an additional incentive for defining the maximum allowable linear heat rate.

Increasing the maximum linear heat rate increases the optimum pin diameter for the minimum power generation cost appreciably (Figures 4-11 through 4-13). The optimum ligament remains approximately constant. The optimum pin diameter for the minimum doubling time increases slightly with increasing linear heat rate, while the ligament is again essentially unchanged.

2.2.3. Fuel Pin Cladding Thickness

The reference core fuel pin cladding thickness has been set at 0.010 inch; cost and doubling-time penalties will be incurred if this objective is not attained. Increased cladding thickness strongly affects the core steel volume fraction and, consequently, the breeding ratio. This decreases the plutonium credit component of the fuel cost and also drastically increases the doubling time.

Cladding thickness may affect the allowable fuel burnup. An increase in thickness might reduce the clad stresses (caused by fuel-clad mechanical forces) enough to extend the burnup and actually reduce the fuel cost. This area points out an additional incentive for investigating the burnup, linear heat rating, and fuel-clad mechanical interaction relationships.

Increasing the cladding thickness shifts the optimum pin diameter for the minimum power generation cost slightly upward (Figure 4-19). The optimum ligament remains essentially constant.

Increasing thickness also shifts the optimum pin diameter appreciably upward for the minimum doubling time (Figure 4-20). The optimum ligament in this case also remains essentially constant.

2.2.4. Spacer Type

The sodium coolant pressure drop through the core determines the fuel can wall thickness in the reference design; increasing the spacer component of pressure drop increases the core steel volume fraction and thereby adversely affects the breeding performance. An additional consideration is the amount of steel in the spacers themselves, which can have a considerable effect on economics and doubling time (see Figure 4-21). It is very important to LMFBR economics and fuel conservation to maintain a low spacer component of pressure drop, and, although the ribbon spacer employed in the reference design does indeed give a low pressure drop; other considerations (such as assembly fabricability, spacer tolerance buildup, fuel pin bow, fuel pin vibration and corrosion fretting, spacer structural integrity, and fuel pin swelling accommodation) are very important. The graphical results included in the text are useful for comparing spacers on the premise that all spacer types allow fulfillment of the target burnup. Since no guarantee can now be made of spacer type equivalence in this respect, only qualitative conclusions can be drawn from the results in Figure 4-21; the main conclusion is that both spacer pressure drop and spacer steel volume are important considerations, as mentioned above.

The optimum ligament for minimum power generation cost is determined by a "balance" between pumping power and the plutonium credit component of the fuel cost on one hand, and the plutonium carrying charge component and the reactor vessel capital cost on the other hand; the two latter effects tend to drive the optimum ligament down for the cases examined. The effect of reactor vessel capital cost is independent of spacer type or geometry; however, the pumping power, plutonium credit, and plutonium carrying charges may be affected to different degrees by the spacer type and geometry. The effects of spacer pressure drop and steel volume on the pumping power, plutonium credit, and plutonium carrying charges are dictated by the geometry and functional characteristics of each spacer type. Therefore, each spacer

type, as well as variable dimensions for each type, will result in a different optimum ligament.

2.2.5. Orifice Effectiveness

Orifice effectiveness is a measure of the degree to which the core gross flow profile matches the radial power profile. Orificing a core while maintaining a constant core flow rate and inlet temperature reduces the hot channel maximum clad surface temperature at the expense of increased core pressure drop (Figure 4-22) and lower breeding ratio. Orificing a core while maintaining a constant maximum clad surface temperature permits lowering the coolant flow rate and increasing the bulk outlet temperature, thereby enhancing the performance of the system external to the reactor.

A plot of power generation cost versus orifice effectiveness shows incentives for investigating two areas of interest: (1) the maximum clad surface temperature and burnup relationship, and (2) temperature effects on reactor internals (at the outlet) and IHXs. The first area of interest arises when the bulk reactor outlet temperature is limited by equipment other than the reactor itself, and the cladding temperature limit corresponding to the design burnup is excessive for the design burnup value. In this case, orificing of the core can possibly bring the maximum clad temperature down to a value consistent with the design burnup. This orificing is detrimental to breeding ratio, as explained above, so that it is important to know very accurately just how much the maximum clad temperature must be reduced.

The second area of interest arises when the maximum clad temperature limits the reactor bulk outlet temperature in the un-orificed condition. In this case, orificing of the core at a constant maximum clad surface temperature can allow a decrease in flow rate, bringing the bulk outlet temperature upward. If the bulk outlet temperature increases to the point where the IHX hot leg ΔT limit is exceeded, then no further orificing is allowable. Since heat transport equipment sizes and costs decrease with increasing LMTDs, this points out the need for developing equipment that can operate under higher ΔT s.

The reference core condition is neither of the two discussed above. The bulk reactor outlet temperature was fixed at 1100 F

because of steam generator and IHX limitations, but at this outlet temperature the design value of the maximum clad surface temperature is not met, even at the unorificed condition. The orificing was assumed to be advantageous (in the reference design) to the attainment of the target average removal burnup of 100,000 MWD/T.

2.2.6. Fuel Specific Power

Fuel specific power has been included in the parametric study, even though it is not a significant indication of either economics or fuel conservation if changes are accomplished at a constant maximum linear heat rate. Fuel specific power can be increased by reducing pin diameter, but at the expense of breeding ratio. This is because it is felt that the 0.010-inch-thick cladding is the thinnest that can be practically fuel-loaded by vibratory compacting, and thus, the steel volume fraction increases with decreasing pin diameter and lowers the breeding ratio. The decrease in breeding ratio that accompanies a decrease in pin diameter from the reference core value of 0.28 inch contributes to increasing both the power generation cost and the doubling time (Figures 4-23 and 4-24).

Fuel specific power may also be increased slightly by decreasing the core steel volume fraction, which can be accomplished by increasing the number of fuel pins per can. The reference design number of pins per can, however, is at the practical maximum from the standpoint of sodium voiding and criticality. Consequently, this area was not investigated for effects on fuel specific power.

Changes in the linear heat rate also change specific power. High linear heat rates result in small cores and low fissile loadings. Figures 4-11 through 4-13 show the changes in fuel specific power associated with variations in linear heat rating for cores with the same number of fuel pins. The trend of increasing fuel specific power with increasing linear heat rating is tempered by the increased enrichments required for smaller cores.

2.2.7. Core Inlet and Outlet Temperature

Core bulk inlet and outlet temperatures affect core design in three distinct ways: Inlet temperature alone, outlet temperature alone, and the inlet-outlet ΔT (or coolant flow rate) each have separate

effects on core design. Since inlet, outlet, and temperature rise cannot be varied independently, the temperature studies have arbitrarily been separated into (1) the variation of reactor inlet at constant temperature difference and (2) the variation of ΔT at constant inlet or outlet temperature.

Variation of the inlet temperature at a constant flow rate dictates an identical variation in the reactor bulk outlet temperature. The prime effect on core design, then, is the increase in clad temperature associated with increasing the bulk outlet temperature. Increasing clad temperature limits the allowable burnup, either by clad mechanical property degradations due to sodium-clad mass transfer phenomena, or temperature effects on fatigue strength and creep rate. A definite need has been shown for investigation of the functional relationship between allowable burnup and maximum clad surface temperature.

Consideration of the effects of inlet temperature alone results in relatively minor effects on core design, except where steam cycle inconsistencies are brought about; this requires a change in steam cycle and, consequently, a change in cycle efficiency and the amount of core thermal power (Figure 4-26). For a given steam cycle, a reduced bulk core inlet temperature results in a reduced can thickness, a reduced steel volume fraction, and an increased breeding ratio—the can thickness is reduced by the increased allowable stress accompanying the decrease in temperature. Decreasing the reactor inlet temperature has a slight effect on reducing the optimum pin diameter for the minimum power generation cost.

The effects of an increase in the reactor coolant temperature rise (or more appropriately, flow rate decrease) are as follows: (1) the coolant pressure drop is lowered, thereby decreasing can thickness and steel volume fraction and increasing breeding ratio; (2) the optimum pin size for the minimum power generation cost is decreased; and (3) the doubling time is decreased (see Figures 4-28 and 4-30). Lowering the flow rate at a constant reactor inlet temperature raises the maximum clad surface temperature, thereby reducing the allowable burnup. Lowering the flow rate at a constant outlet bulk temperature (decrease in inlet temperature) increases the maximum clad surface temperatures slightly, but more importantly, it reduces the heat

transport system LMTD, thereby increasing heat transport equipment sizes. Since a lower flow rate greatly improves fuel cost and doubling time, further emphasis is put on the importance of more detailed knowledge of the clad temperature and burnup relationship.

2.3. Safety Coefficient Parameterization

The safety coefficients are not amenable to parameterization in that both are dependent variables and require more detailed calculations than are possible in a parameter study. Trends were established in the Spoiled Vs Unspoiled Core Geometry Trade-Off Study, which indicated that any improvement in the sodium void coefficient carried with it a penalty in increased power cost. Halving the void coefficient increased the power costs by more than 0.25 mill/kWh, and reducing it to zero increased power costs by more than 0.6 mill/kWh. The Doppler coefficient is also changed if the core is spoiled to improve the void coefficient. With one method of spoiling the Doppler coefficient decreases, while with another it nearly doubles.

2.4. Heat Transport System Technology-Optimization Relationships

2.4.1. Reactor Outlet Temperature and Temperature Rise

Penalties in power generation cost due to non-achievement of the reference design bulk outlet temperature are appreciable. The attainable bulk outlet temperature may be limited either by maximum clad surface temperatures or the IHX hot end temperature difference (for a given maximum sodium inlet temperature to the steam generator). Increasing the reactor outlet temperature over 1100 F gains very little from a heat transport and steam generating system standpoint (at constant steam cycle conditions and IHX hot leg temperature differences), since increased steam generator costs are incurred with the addition of a stainless steel superheater.

The choice of reactor bulk inlet temperature at constant reactor outlet temperature is an optimization problem. Attainment of this optimum inlet temperature is not limited in any way by the heat transport system or the steam generating equipment requirements. The

optimum reactor inlet temperature "balances" the effects of pumping power against the effects of IHX, steam generator, and reheater sizes.

2.4.2. IHX LMTD

For the reference steam cycle and a reactor bulk inlet temperature of 800 F, the optimum IHX LMTD ranges from 70 to 115 F for a range of reactor bulk outlet temperatures from 1050 to 1200 F (see Figure 6-14). These optimum values may be limited somewhat by IHX hot and cold leg temperature differences since a given practical configuration of tubes and/or tube sheets may not withstand large temperature differences. Design values of the IHX hot and cold leg differences resulting in LMTDs that are not the optimum, however, will not ordinarily result in severe power generation cost penalties. Optimum IHX hot and cold leg values balance the effects of IHX size and cost against the effects of the combined steam generator and reheater size and cost. Also, these hot and cold leg difference values affect the balance between the secondary sodium system pumping power and the sizes of the IHXs, steam generators, and reheaters.

2.4.3. Steam Generator Hot End ΔT

An optimum steam generator hot end temperature difference is determined for each bulk reactor outlet temperature investigated (see Figure 6-15). The optimum values range from 50 to 160 F for the reference plant as the reactor outlet temperature is varied from 1050 to 1200 F. As in the case of IHX hot and cold leg differences, the attainable temperature differences may be limited. Again, the power generation cost penalties of non-attainment are ordinarily not severe. At constant reactor bulk outlet temperature and constant design steam inlet temperature to the turbine, the IHX hot leg temperature difference and the steam generator hot end temperature difference cannot be varied independently, so it is sufficient to discuss only IHX hot leg temperature difference with regard to system optimization.

2.4.4. Steam Generator-Reheater Optimization

The secondary sodium flow from the IHX is split between the steam generator and the reheater (see Figure 6-1). The proportion of flow going to the steam generator and reheater determine the relative

sizes of these two pieces of equipment. A flow split exists that will give a minimum cost for the steam generator and reheater combination. One measure of the flow split is the difference between the secondary sodium temperature rise through the IHX and the sodium temperature drop through the reheater. The optimum value of this difference has been found to range from 100 to 175 F over a normal range of reactor inlet and outlet temperatures. The power generation cost penalties for non-optimum values of this difference are small. Limitations on the amount of flow split may arise with design difficulties in the piping connections, where the high-temperature sodium exiting from the reheater must mix with the relatively low-temperature sodium from the steam generator.

3. PARAMETER SENSITIVITY AND OPTIMIZATION

3.1. Introduction

A number of key reactor core system parameters were studied to determine the value of each that is required to produce a design optimized for minimum generating costs and minimum fuel doubling time. Fuel doubling time is taken as the most significant criterion of fuel conservation. The effects of a particular parameter were studied by perturbing the reference design to produce a design variant reflecting the effects of a change in the value of that parameter. The effects on the design that resulted from the simultaneous perturbation of two or more selected parameters were also examined.

The studies also covered the effects of changes in selected economic variables on the optimum parameter values. In most of the cases, however, the reference values of the economic parameters were used as a basis for the work. These values, specified by the contract, are representative of those expected to exist when the LMFBR industry is a viable one. The ranges of values account for the uncertainties that now exist in predicting those values.

The following design variables were studied:

1. Fuel pin diameter.
2. Fuel pin pitch.
3. Fuel pin length.
4. Fuel pin ligament (distance between adjacent pins).

The economic variables considered are as follows:

1. Core fabrication cost.
2. Axial and radial blanket cost.
3. Fuel reprocessing cost.
4. Plutonium value.
5. Burnup.

Although core burnup is not an economic parameter, it is included here because it has a particularly important impact on the fuel cost; therefore, it is conventionally considered along with the economic parameters.

3.2. Fuel Pin Diameter

Figure 3-1 shows the fuel cycle cost as a function of pin diameter for three pin pitches and at three unit fabrication costs (the reference cost, twice the reference cost, and half of the reference cost). Considering the design at reference fabrication costs, with all other economic conditions at reference values and all other core and plant parameters constant, the lowest fuel cycle costs result from a pin diameter of 0.27 to 0.29 inches, both having a pitch equivalent to a 0.050 to 0.060 inch pin ligament or clearance.

The total power generation cost variation of pin diameter with pitch, at reference fabrication costs (corresponding to the center set of curves on Figure 3-1) is shown in Figure 3-2. Again, the lowest cost is found at the same diameter-pitch combination.

The relationship between pin diameter and fuel cost can be explained by Figures 3-3 through 3-5. As the fuel pin diameter increases, there is an increase in the fuel inventory, a corresponding increase in the fuel and steel volume fractions, and a decrease in the sodium volume fraction (see Figure 3-3). The core is here assumed to be designed at a constant (reference) pin rating of 17 kW/ft. The decreasing sodium volume fraction causes a hardening of the spectrum. This effect, coupled with the larger fuel volume, allows the enrichment to decrease and the breeding ratio to increase. With the hardening of the spectrum, the capture-to-fission ratio for ^{239}Pu decreases, and the average number of neutrons emitted per fission increases. In addition, the fast fission rates of ^{238}U and ^{240}Pu are increased; these effects also reduce the fissile enrichment. The breeding ratio increases because, although the capture cross sections for both ^{238}U and ^{239}Pu decrease, the capture cross section of ^{239}Pu decreases much more rapidly than that of ^{238}U . With the reduced enrichment, the ^{238}U is now able to compete more favorably for neutrons.

The effects of pin diameter and pitch on enrichment and breeding ratio are shown in Figures 3-5 and 3-4, respectively. These figures show that there is an optimum pin diameter for each pitch, which increases as the pitch increases. The effects of breeding ratio and enrichment on economics are felt in both the plutonium credit and the plutonium inventory or carrying charge. These two components of fuel cycle cost (for reference economic conditions), as a function of pin diameter, are shown in Figure 3-6 for the 0.34-inch pitch; this pitch is chosen because it yields the lowest enrichment and the highest breeding ratio in both Figure 3-4 and 3-5. Returning to Figure 3-6, we see that while the inventory cost continues to increase with enrichment, there is a maximum plutonium credit at about a 0.295-inch-diameter pin—in the same diameter range as the optima of Figures 3-4 and 3-5.

The plutonium credit, which increases with increasing breeding ratio and decreasing enrichment, reaches a maximum at about 0.295-inch diameter. At this point, a further increase in pin diameter causes a rapid increase in the steel volume fraction, which causes a decrease in breeding ratio.

The plutonium carrying charge in Figure 3-6 increases with pin diameter, since the total fuel volume increases faster than the enrichment decreases.

The pin diameter that yields the lowest fuel cost is shown (in Figure 3-6) to be between 0.28 and 0.295 inch for the 0.34-inch pitch. It is interesting to note that the lowest doubling time also results at this diameter and pitch combination (see Figure 3-7).

Doubling time, as used in this report, refers to the geometric or compound interest definition, as follows:⁵

$$\text{Doubling time} = \frac{0.693 t_c}{\ln(M_2/M_1)}$$

where

t_c = fuel cycle time (inpile and outpile)
 M_2, M_1 = final and initial fissile core loadings less reprocessing and fabrication losses.

Returning to Figure 3-3, the rapidly increasing steel volume fraction with increased pin diameter at constant pitch is due to the increase in the fuel element can wall thickness. This can wall increase results from an increase in coolant pressure drop as the space between adjacent fuel pins decreases (note that in these cases, the coolant flow rate is constant). As the coolant pressure drop increases, the coolant pressure at the core inlet increases, and the pressure across the can wall at that location also increases, since the coolant pressure in the space between adjacent fuel assembly cans remains small.

The increase in can thickness with pin diameter at constant pitch is shown in Figure 3-8. Also shown in this figure is the increase in pumping power, which is reflected in net electric power generation and higher unit power costs.

3.3. Fuel Pin Pitch

Increasing the pin pitch at constant pin diameter (see section 3.2, Fuel Pin Diameter) has much the same effect as decreasing the diameter at constant pitch. The flow area is increased, the core pressure drop decreases, and the can thickness decreases. The decreasing steel volume fraction (due to the decreasing can thickness) initially causes a decrease in the fuel cost. As the sodium volume fraction increases, however, the resultant softening of the spectrum increases the enrichment and decreases the breeding ratio. Therefore, the fuel cost increases.

Figures 3-9 through 3-12 show the effects of pin pitch and diameter on the breeding ratio, doubling time, fuel cost, and power cost, respectively. As the ligament is decreased, the fuel and power costs decrease, reaching a minimum at about a 50- to 60-mil ligament, and then increase. Figures 3-13 and 3-14 show the decreasing cost with decreasing ligament for several pin pitches and diameters. At a constant ligament, the larger diameter has the lower cost, because it has a smaller sodium volume fraction and a harder spectrum. This is obviously not true for very small ligaments, because of the small flow area and correspondingly high pressure drop across the core. Beyond the minimum, the cost increases, since the can thickness (and hence the steel fraction) increases as the pressure drop increases; this effect

counteracts the effect of the hardened spectrum with decreased sodium fraction. Figures 3-15 and 3-16 show the effect of ligament on power cost and show the same trend as the fuel cost curves of Figures 3-13 and 3-14.

3.4. Fuel Pin Length

The performance of the reactor is affected not only by the pin diameter and pitch, but by its length. Making the fuel pins longer would tend to decrease the leakage, thus lowering the enrichments. Competing with this is the increase in the core pressure drop as the core is lengthened, which increases the fuel can thickness and increases the steel fraction. Increasing the fuel pin length while holding total length of pins constant also decreases the unit fabrication cost (\$/kg).

Figures 3-17 and 3-18 show the effect on fuel and power costs with increasing pin length. Note the change in slope from negative to positive due to the rapid increase in can thickness with increasing pin length. The differences in the curves for the total power generation cost and the fuel cost in Figures 3-17 and 3-18 are due to the changes in core size with increasing pin diameter and length. The minima, however, occur at approximately the same point for all the figures.

Figures 3-19 and 3-20 show the effects on the fuel cost and power generation cost, respectively, of the pin diameter, length, and pitch. The cost decreases with increasing length at constant pitch and diameter because of decreasing leakage and unit fabrication cost. The rate of the decrease slows because of the greater sensitivity of larger areas to increased pressure drop and increasing steel fraction. The minima (with respect to length) shift to slightly smaller pins, because the increase in the pressure drop is more rapid for large pins (small ligament) than for small pins. Using Figures 3-17 through 3-20 together, it can be seen that the minimum fuel and power cost is achieved with a 40-inch-long pin at either of two combinations of diameter and pitch (the 0.28-inch diameter/0.34-inch pitch reference design or the 0.27-inch diameter/0.32-inch pitch design). This length is somewhat more than the reference design length of 34.7 inches, which represents a compromise between fuel cost, doubling time, and sodium voiding. The latter are improved by shortening the core.

Increasing the pin diameter also causes the pressure drop to increase, so that increasing the diameter shifts the fuel cost minimum to shorter pins.

Figures 3-21 and 3-22 show the effect of the pin length and the pin diameter and pitch, respectively, on doubling time. Decreasing the pin length decreases the doubling time and shifts the minima to a smaller pin pitch combination. The decrease in doubling time with decreasing pin length is caused by the increased breeding in the axial blanket due to the increased leakage in the axial direction. Decreasing the pin length causes the core enrichment to increase because of increasing leakage; since this tends to reduce the total breeding ratio, the doubling time increases for very small pin lengths, as shown in Figure 3-21. The reprocessing time, and hence the outpile time also, is increased as the pin length decreases, due to the increased axial blanket mass.

Figures 3-23 and 3-24 demonstrate the relationship between plutonium value and unit fabrication cost, respectively, on the optimum pin length from the minimum fuel cost standpoint. Referring to Figure 3-23, the optimum length increases from 40 inches at a plutonium value of \$20/gm to about 44 inches at a \$5/gm value; the trend here is fairly obvious. As discussed above, increasing length decreases the breeding ratio due to increased pressure drop and, hence, increased can wall thickness and steel fraction. Since increased plutonium value tends to increase fuel costs (the plutonium carrying charge is almost twice the plutonium credit), the optimum core would tend toward a higher breeding ratio at the higher plutonium value and, hence, a shorter core.

Figure 3-24 describes the relationship between unit fabrication cost and pin length in order to determine the optimum length. Here the optimum length decreases with decreasing fabrication cost. The influence of unit fabrication cost is the determining factor; lower unit fabrication costs result from longer pin lengths, and thus, if fabrication costs are basically high, then a longer length is required to compensate.

3.5. Fabrication Cost Effect on Optimum Core Design

The effect of a varying unit fabrication cost on the optimum pin diameter/pitch combination was also investigated and is shown in Figure 3-1. The fabrication cost was varied by multiples of the unit cost

as determined by the reference method of calculation; the multiples were one-half and twice the reference cost. The reference cost, of course, is not a single unit cost but is a function of pin design variables, such as diameter, length, and the fabrication plant throughput equivalent to a 15,000-MWe capacity.

From Figure 3-1 it is seen that, for the reference costing method, the lowest fuel cost results from a pin diameter of about 0.28 inch and a pitch between 0.32 and 0.34 inch. At half the reference fabrication cost, the optimum diameter is only very slightly less, or about 0.268 inch at a pitch of 0.32 inch.

Another analysis was made of the effect of unit fabrication cost on the optimum pin/pitch combination of using a constant unit fabrication cost, i.e., independent of pin diameter. In Figure 3-25 the center set of curves uses the fabrication cost (on a \$/kg basis) of a 0.28-inch pin (the reference design) for all diameters; also shown are curves for twice and half that unit cost.

Without the unit fabrication cost penalty for the smaller pin diameters, the smaller pitch and pin diameter combination (0.30-inch pitch/0.245-inch diameter) is clearly better. Compare the curve for the reference unit fabrication cost and that using a constant unit fabrication cost equal to that of the 0.28-inch-diameter pin at a 0.34-inch pitch (Figure 3-25). For pins less than 0.28 inch in diameter, the reference unit fabrication cost is higher, since the smaller pins cost more to fabricate than do the 0.28-inch-diameter pins. For larger pins the opposite is true. For the 0.30-inch pitch, the difference in the slope between the constant unit fabrication cost curve and the reference unit fabrication cost curve is due to the increasing difference between the cost of a 0.28-inch pin and pins of smaller diameter.

Figure 3-25 also shows that there is no noticeable change in the position of the minima when the unit fabrication cost is increased from half to twice the cost of the 0.28-inch pin. This is to be expected, since in this case, the perturbation is of the following form:

$$\text{fuel cost} = C + x (\text{fabrication cost})$$

where $C = \text{fuel cost} - \text{fabrication cost}$

Figure 3-26 shows the effect on the fuel cost of varying the fuel pin diameter and length and the unit fabrication costs. Increasing the unit fabrication costs drives the geometry for minimum fuel cost to both larger-diameter and longer-length pins. As discussed previously, with the large unit fabrication costs, the reduction in the unit fabrication costs from going to the larger and longer pins overshadows the increased plutonium carrying charge and recovery costs that come with the increased mass of the larger pins. For the small unit fabrication costs, just the opposite is true. The unit fabrication costs exert less influence, so that the decrease in the carrying charges and recovery costs that come with the small pins is the determining factor.

3.6. Reprocessing Cost Effects

Figure 3-27 shows the effect of the unit reprocessing cost on the fuel cost at various pin diameters. The reference reprocessing throughput for LMFBR fuel (in kg/day) is specified by the ground rules as 67% of that of the hypothetical AEC enriched uranium reprocessing plant described in TID-7025; it is based on the total plutonium plus ^{235}U content, rather than on the fissile content. Because of the lower critical mass of plutonium fuels, the plutonium reprocessing plant has a smaller throughput than a uranium plant would have.

Figure 3-28 shows the effect of changing the throughput on the fuel cost. Halving the reference throughput has an effect similar to doubling the unit reprocessing cost. However, the reprocessing carrying charge and the plutonium inventory charge during reprocessing increase because of the increased reprocessing time. As the throughput is decreased, the reprocessing time increases; this, while it increases the reprocessing cost component, also increases the reprocessing and reconversion carrying charge, which is a credit. Offsetting the increasing carrying charge credit is the increasing plutonium inventory charge during reprocessing, which keeps the fuel cost minimum from moving toward the larger pins as fast as if the unit reprocessing cost were being increased.

3.7. Plutonium Value Effect on Optimum Core Design

The value of plutonium is an important but uncertain parameter, with estimates ranging from \$5 to \$20/gm fissile. The value of plutonium

will ultimately be determined by the relative economics of both thermal and breeder reactors. In these studies the reference value is \$10/gm fissile, and, except where noted, all cases are at the reference pin length (34.7 inches).

Figure 3-29 shows how the fuel cost is affected by varying the plutonium value. For a constant pitch, a higher plutonium value moves the minimum cost toward smaller pin diameters, thus tending to offset the fabrication cost penalty associated with small pins. Varying the pitch at the same time the plutonium value is increased shifts the fuel cost minimum toward both a smaller pin pitch and diameter. At a given pitch, increasing the plutonium value penalizes the large pins in the form of increased carrying charges because of the larger mass involved. Although enrichment decreases, the larger total mass still results in a larger fissile plutonium mass. (Please refer to the discussion on the effects of pin pitch and diameter. The enrichment does decrease, and then it increases with increasing pin diameter, giving a minimum for each curve, but in general, enrichment decreases over the span of each curve.)

The change in plutonium credit is shown in Figure 3-30. For the greater unit plutonium value, there is a greater decrease in plutonium credit with decreasing pin diameter and pitch than with the lower price. Figure 3-31 shows the difference in the sum of the plutonium working capital (or carrying charge) and the plutonium credit. Note the large penalty paid for the large pin and pitch combination for the high unit plutonium value.

Figure 3-32 shows the effect of the pin diameter, pitch, and length, and plutonium values on the fuel cost. Increasing the plutonium value drives the fuel cost toward smaller and shorter pins and smaller pitches, since these changes tend to reduce the fissile inventory.

Figure 3-33 shows how varying the unit plutonium value and burnup at reference fabrication costs affects the fuel cost. Increasing both the burnup and plutonium price drives the fuel cost minimum rapidly toward smaller pins. Both the increasing unit plutonium value and increasing burnup contribute to moving the fuel cost minimum to the smaller pins. This curve clearly demonstrates the fuel cost penalties associated with

failure to achieve the desired burnup and shows the advantages to be gained from increasing burnup.

3.8. Burnup Effect on Optimum Core Design

The burnup that can be achieved by plutonium oxide fuels is at present very uncertain. Although estimates do not run much above 100,000 MWD/T average, the burnup in these studies is varied from 50,000 to 200,000 MWD/T in order to get a clear idea of the effects of burnup on the fuel cost.

Figure 3-34 shows the effect of pin pitch and burnup variations on the minimum fuel cost. Increasing the burnup drives the fuel cost minimum not only toward smaller pins (as mentioned below) but also toward a smaller pitch. Although for low burnup the small pitch (0.30 inch) costs the most, at the high burnup it is the cheapest. This is due to the slower rate at which the plutonium carrying charge increases with pin diameter at the smaller pitch than at the larger pitch.

Figures 3-35 through 3-37 show the effect of the burnup on the fuel cost for increasing pin diameter at constant pitch. Figure 3-34 indicates that increasing the burnup drives the fuel cost minimum to smaller pin diameters. Figures 3-36 and 3-37 give the fuel cost components at 50,000 and 150,000 MWD/T and can be used to explain the decrease in optimum pin diameter with increasing burnup. The corresponding cost components for 100,000 MWD/T are presented in Figure 3-6. The figures show the decrease in the fabrication cost component of fuel cost with increasing burnup. The fabrication cost decrease allows the plutonium carrying charge to exert more leverage on the fuel cost, thus forcing the optimum pin diameter downward. The lower fabrication costs result from the increased cycle times (decreased number of pins over the plant lifetime).

Figure 3-38 shows the effect on the fuel cost of varying both the burnup and unit fabrication cost at constant unit plutonium value. Increasing both the burnup and fabrication cost drives the fuel cost minima toward smaller pins, but not as fast as increasing the burnup alone. This is because increasing the unit fabrication cost drives the fuel cost minimum toward larger pins (see Figure 3-1).

Figure 3-33 shows the effect on the fuel cost of varying the unit plutonium value and burnup at reference fabrication cost. Both increases contribute to driving the fuel cost minimum to the smaller pins (see Figures 3-29 and 3-34, respectively).

Figure 3-39 shows the effect of the burnup on doubling time for increasing pin diameter. Increasing the burnup decreases the doubling time and drives the minimum to smaller pins. The doubling time decreases with the increasing final fissile mass. The minima shift to smaller pins, because the outpile time and cycle time do not increase as rapidly for small pins as for large pins.

Figure 3-1. Effect of Pin Diameter, Pitch, and Fabrication Cost on Fuel Cost

Figure 3-2. Effect of Pin Diameter and Pitch on Power Generation Cost

Figure 3-3. Effect of Pin Diameter and Pitch on Core Volume Fractions

Figure 3-4. Effect of Pin Diameter and Pitch on Breeding Ratio

Figure 3-5. Effect of Pin Diameter and Pitch on Enrichment

Figure 3-6. Effect of Pin Diameter on Fuel Cost Components

Figure 3-7. Effect of Pin Diameter and Pitch on Doubling Time

Figure 3-8. Effect of Pin Diameter and Pitch on Primary Pumping Power and on Fuel Can Thickness

Figure 3-9. Effect of Pin Pitch and Diameter on Breeding Ratio

Figure 3-10: Effect of Pin Pitch and Diameter on Doubling Time

Figure 3-11. Effect of Pin Pitch and Diameter on Fuel Cost

Figure 3-12. Effect of Pin Pitch and Diameter on Power Cost

Figure 3-13. Effect of Pin Ligament and Pitch on Fuel Cost

Figure 3-14. Effect of Pin Ligament and Diameter on Fuel Cost

Figure 3-15. Effect of Pin Ligament and Pitch on Power Generation Cost

Figure 3-16. Effect of Pin Ligament and Diameter on Power Generation Cost

Figure 3-17. Effect of Pin Length and Diameter on Fuel Cost

Figure 3-18. Effect of Pin Length and Diameter on Power Generation Cost

Figure 3-19. Effect of Pin Diameter, Pitch, and Length on Fuel Cost

Figure 3-20. Effect of Pin Diameter, Pitch, and Length on Power Generation Cost

Figure 3-21. Effect of Pin Length, Diameter, and Pitch on Doubling Time

Figure 3-22. Effect of Pin Diameter, Pitch, and Length on Doubling Time

Figure 3-23. Effect of Pin Length and Plutonium Value on Fuel Cost for 0.34-Inch Pitch and 0.28-Inch Pin Diameter

Figure 3-24. Effect of Pin Length and Unit Fabrication Cost on Fuel Cost for 0.34-Inch Pitch and 0.28-Inch Pin Diameter

Figure 3-25. Effect of Pin Diameter and Constant Fabrication Cost on Fuel Cost for 0.28-Inch-Diameter Pin

Figure 3-26. Effect of Pin Diameter, Length, and Unit Fabrication Cost on Fuel Cost

Figure 3-27. Effect of Pin Diameter and Reprocessing Cost on Fuel Cost

Figure 3-28. Effect of Pin Diameter and Reprocessing Throughput on Fuel Cost

Figure 3-29. Effect of Pin Diameter, Pitch, and Plutonium Value on Fuel Cost

Figure 3-30. Effect of Pin Diameter, Pitch, and Plutonium Value on Plutonium Credit

Figure 3-31. Effect of Pin Diameter, Pitch, and Plutonium Value on the Difference Between Plutonium Working Capital and Credit

Figure 3-32. Effect of Pin Diameter, Pitch, and Length and Plutonium Value on Fuel Cost

Figure 3-33. Effect of Pin Diameter, Burnup, and Plutonium Value on Fuel Cost

Figure 3-34. Effect of Pin Pitch and Burnup on Minimum Fuel Cost

Figure 3-35. Effect of Burnup and Pin Diameter on Fuel Cost

Figure 3-36. Effect of Pin Diameter on Fuel Cost Components at 50,000 MWD/T

Figure 3-37. Effect of Pin Diameter on Fuel Cost Components at 150,000 MWD/T

Figure 3-38. Effect of Pin Diameter, Burnup, and Fabrication Cost on Fuel Cost

Figure 3-39. Effect of Pin Diameter and Burnup on Doubling Time

4. CORE SYSTEM TECHNOLOGY-OPTIMIZATION RELATIONSHIPS

4.1. Introduction

The studies described in this section provided data that are useful in evaluating the economic, i.e., electric generating cost, penalties that would be incurred in the reference LMFBR plant as a result of only partial achievement or non-achievement of the research and development work required in key areas of LMFBR technology. These results are intended for use in "cost-benefit" studies to be made in a subsequent task of the LMFBR Follow-On Study, wherein the required research and development program will be set forth.

The economic effects of a particular parameter are determined by perturbing the reference design to produce a series of design variants, together with their electric generating costs, that reflect a range of values for the particular variable. Thus, incremental power generation costs (the difference in cost from that of the reference design) can be determined for a range of parametric values reflecting degrees of success in the research and development program. In this manner, the value to an entire LMFBR industry can be determined and compared with the cost of the corresponding research and development needed to demonstrate or ensure the use of a particular value of a parameter in the design or operation of the LMFBR.

The following parameters were considered in these studies:

1. Linear heat rate.
2. Coolant inlet and outlet temperatures.
3. Coolant temperature rise.
4. Maximum fuel central temperature.
5. Maximum cladding surface temperature.
6. Fuel density.
7. Fuel thermal conductivity.
8. Cladding thickness.

9. Fuel-to-cladding bond thermal conductance.
10. Fuel average burnup.
11. Spacer pressure loss.
12. Core orifice effectiveness.
13. Porosity in equiaxed grain region of fuel.
14. Fuel specific power.
15. Core unit fabrication cost.
16. Pin diameter.
17. Pin pitch and ligament.
18. Steam conditions.
19. Doubling time.

Parameters 1 through 14 are important because the values used in the reference design entail considerable uncertainty at this time, and therefore, research and development work will be required to establish and demonstrate their allowable design and operating limits. Although item 15, fuel fabrication cost, is not a design variable, it has a significant effect on fuel costs and also entails considerable uncertainty; work will be required to stake the costs that will pertain in a viable commercial LMFBR industry.

Items 16 through 18 are design variables that are not technology-dependent to the degree of items 1 through 14; it is the purpose of the study to determine the relationship between these reactor and plant features (with which the designer has considerable design freedom) and the technology-dependent variables cited above. These relationships can be used to determine the reactor and plant design points that result in the minimum power generation cost. Item 19, doubling time, is a measure of the degree to which a particular reactor and fuel cycle contribute to the conservation of uranium resources; the sensitivity of this parameter to certain technology-dependent variables is also included in the study.

As in the other sections of this report, the studies are concerned with perturbations of the reference design. Thus, in all the discussions and figures included herein, the reference design values are the basis for investigation or analysis, except for those specific values of the parameters noted in a particular figure or discussion.

4.2. Fuel Model Parametrics

4.2.1. Linear Heat Rate, Density, and Burnup

One of the most important parameters relating linear heat rate to allowable burnup is initial (as-fabricated) fuel density, since variations in initial fuel density affect the thermal, mechanical, and physics performance of the fuel.³ The highest realizable initial fuel density is desirable from a breeding performance standpoint, since a decrease in density primarily involves the removal of ^{238}U from the fuel pin. It is apparent, however, that degradation of breeding performance with a decrease in initial density can be more than offset by improvements in allowable burnup and restructured fuel geometry. Thus the as-fabricated fuel density becomes an optimization problem "balancing" the detrimental effects on breeding ratio and thermal conductivity with decreasing density against the favorable effects on allowable burnup and restructuring.

Results included here show the extent to which fuel costs increase with an as-fabricated fuel density decrease from 85 to 80% of theoretical (TD). B&W's GAM-SIZLE code package was used to determine the physics performance by one-dimensional diffusion-theory calculations. The calculations were performed for the reference core configuration, except that a batch cycle achieving 77,500 MWD/T average burnup was considered. The methods used are identical to those described in section 4, Core System Description.

Table 4-1 shows the results of that study; a fuel density decrease from 85 to 80% TD at constant maximum linear heat rate and at constant burnup causes a 0.045 mill/kWh increase in fuel cost. This increase was found to result primarily from the decreased plutonium credit. Figures 4-1 and 4-2 show the fuel cost trends with increasing linear heat rate and burnup, respectively, for the case of 80% dense, as-fabricated fuel. Figure 4-1 shows that the maximum allowable linear heat rating at 80% TD must increase from the reference value of 17 to approximately 18.9 kW/ft in order to attain the reference design fuel cost. Alternatively, Figure 4-2 shows that an increase in burnup from 77,500 to about 93,500 MWD/T is required to offset the effects of a density change from 85 to 80%.

Table 4-1. Effect of Density and Corresponding Linear Heat Rate Changes on Fuel Cost

	Fuel density, % TD		
	85	80	80
Max linear heat rate, kW/ft	17	17	18.7
Burnup, MWD/T	77,500	77,500	77,500
Cycle time, days	821	771	696
Thermal power, MWt	2413	2413	2413
Core volume, liters	6516	6516	5865
Fuel loading, T	23.8	22.4	20.3
Initial fissile loading, kg	2770	2770	2493
Final fissile loading, kg	3550	3448	3131
Initial enrichment, %	0.116	0.125	0.124
Breeding ratio	1.35	1.32	1.32
Fuel cost, mills/kWh	0.908	0.953	0.913

The as-fabricated fuel density affects the thermal and mechanical fuel behavior in the following manner: Low as-fabricated densities result in initially low thermal conductivity. Since fuel restructuring and densification occur at established threshold temperatures, a lower as-fabricated density results in more extensive restructuring at a given heat rate (the radial temperature gradient increases). Thus, a larger proportion of the fuel is restructured, and a smaller width of the circumferential, as-fabricated band of fuel results. The increased portion of densified fuel combined with the lowered as-fabricated density results in a larger center void (conservation of mass).

The end effects of a reduction in as-fabricated fuel density on the mechanical characteristics are as follows: Primarily, the increased porosity allows increased accommodation of fuel swelling in this mode; the four modes of swelling accommodation are (1) porosity, (2) axial, (3) inward radial (where a center void exists) and (4) outward radial. The temperature profile is changed so that the average temperature is increased, thus increasing the proportion of fuel in a plastic

state and necessarily promoting fuel creep and a reduction of fuel-to-clad mechanical forces. Also, the average temperature increase promotes fission gas release, thereby diminishing one of the driving forces for fuel swelling. The fuel restructuring results in a center void (progressing radially outward) an annular columnar grain region, then an annular equiaxed grain region, and finally, the outside annular, as-fabricated region. The columnar grain region in a fuel pin is generally extensively cracked (radial cracks) and will probably contribute only small mechanical forces due to swelling. This leaves the equiaxed and the as-fabricated, annular region as the prime source of mechanical forces on the fuel pin cladding. Since reduced as-fabricated density can reduce the mechanically active annular ring width, as well as the mechanical strength of the as-fabricated portion, we can expect a reduction in mechanical forces and induced cladding stress resulting from fuel swelling.

From a thermal standpoint, a decreasing as-fabricated density can result in a higher maximum allowable linear heat rate. The restructuring and fuel densification can result in a final increase in effective or apparent fuel conductivity. This is a result of fuel densification accompanied by increased local thermal conductivity and also increased central void, which decreases the thermal resistance "seen" by the centrally located fuel. Results of calculations performed with B&W's TAMPA computer code exhibit this trend of increasing allowable linear heat rate with decreasing as-fabricated fuel density.⁴ Figure 4-3 shows this effect. Table 4-1 shows the change in fuel cost expected by operation at 80% fuel density and the corresponding maximum allowable linear heat rate of 18.7 kW/ft as determined using the TAMPA code.

4.2.2. Fuel-to-Clad Bonding

Figure 4-4 may be used to evaluate the effects on allowable linear heat rate of employing bonding agents to increase the fuel-clad gap thermal conductance (neglecting effects of the bonding agent on fuel restructuring, mass transfer, fuel swelling, etc.). The reference design employs no bonding material, and a design value for the gap thermal conductance of 1500 Btu/hr-ft²-°F is used. This conductance gives a temperature drop across the gap of 570 F at a linear heat rate

of 17 kW/ft at the reference fuel pin diameter. A bonding material, such as sodium would increase the gap thermal conductance to approximately 30,000 Btu/hr-ft²-°F and allow a maximum linear heat rate of approximately 20.0 kW/ft. The use of such a bonding agent brings about other considerations, such as problems in transient power performance, chemical fuel attack, changes in fuel restructuring and densification, and complications in the fuel-cladding interaction. It has been found that fuels behave plastically at temperatures above 900 C.¹ Consequently, maintenance of a constant maximum fuel central temperature, while decreasing the gap temperature drop (the linear heat rate must be increased) can lower the average fuel temperature and lower that proportion of fuel that behaves plastically. This can conceivably alter the modes of fuel swelling and decrease the allowable burnup. Therefore, an investigation of fuel and cladding mechanical interaction is a necessary adjunct to the use of a thermal bond agent.

4.2.3. Fuel Restructuring

An important factor in fuel performance is restructuring. When pins are fabricated, the fuel is in the form of a uniformly compacted powder. Grain growth will occur at elevated temperatures, densifying the fuel and forming a central void. Experimental data show that above about 3200 F, columnar grains form and densify, apparently independently of initial density, to a 96 to 100% TD.² Above about 2700 F, an equiaxed grain region forms; data show considerable scatter regarding the resulting density in this zone. Some experimenters show virtually no densification, and others report final densities as high as 96 to 98% TD. For the reference core design, a value of 94% has been selected. An uncertainty of ±6% in the final density of the equiaxed region could vary the maximum linear heat rate by ±1 kW/ft, as indicated in Figures 4-5 and 4-6. A more important parameter appears to be the density in the columnar grain region. A difference of 1% in the final fuel density in this region (columnar) would vary the allowable heat rate by as much as 0.5 kW/ft.

The resulting densities in the columnar and equiaxed regions contain additional uncertainties in the temperature range at which they occur. Inpile data yield varying results with different batches of

fuel. Apparently, slight differences in the content, test conditions, and type of retained impurities are sufficient to produce these variations. Consequently, calculations performed for the high temperature range contain these uncertainties, and the resulting fuel performance limitations should be judged accordingly. The effects of grain formation temperatures are shown graphically in Figure 4-7. Results indicate that an uncertainty of ± 100 F in the equiaxed grain formation temperature could, accordingly, vary the maximum linear heat rate by ± 0.25 kW/ft.

4.2.4. Fuel-Clad Gap Heat Transfer Coefficient

The available data for the fuel-clad gap heat transfer coefficient have been obtained primarily for pellet fuels. It might be expected that thermal resistance would be reduced with particulate fuel because of the improved fuel-clad contact. Figure 4-8 shows graphically the relationship between allowable linear heat rate and gap coefficient from which the importance of the gap coefficient can be assessed. Beginning-of-life (BOL) gap coefficients appear reasonably certain; but the values at high burnups will be dependent on a number of obscure parameters, including thermal cycling.

4.2.5. Fuel Thermal Conductivity

Numerous inpile tests have been run to accumulate data on fuel thermal conductivity as a function of fuel burnup. A major problem exists in collecting any such data, in that much of the temperature range of interest is above the allowable operating levels for available thermocouples. Consequently, researchers have been forced to rely on integral conductivity data and on extrapolation of conductivity functions based on grain formation and fuel melting as indications of fuel temperature. Unfortunately, this method requires that the thermal conductivity be discerned from other effects, such as gap conductance and fuel restructuring, which affect the fuel temperature distribution. These effects, together with other fuel changes, may tend to lead to erroneous interpretations of available data, and consequently, widely different thermal conductivities have been reported. As indicated in Figure 4-9, an uncertainty of 15% in the conductivity function may change

the allowable heat rate by as much as 2.5 kW/ft. A change of this magnitude could certainly have major repercussions throughout the reactor design.

4.3. Linear Heat Rating

4.3.1. General

Perturbations to the reference design to accommodate variations in linear heat rate are simply the increase or decrease in total fuel pin length. Trends were determined, both for changes in active fuel length keeping the number of pins constant, and for changes in the number of pins keeping the active fuel length constant.

Where effects of variations in maximum allowable heat rating are examined, the radial and axial peaking factors and the over-power and uncertainty factor values used in the reference core design are held constant at the values used in the reference design. Therefore, the reference core ratio of maximum-to-average linear heat rating was applied to these studies.

Increased maximum linear heat rate results in extensive repercussions in core design and performance. The resulting decrease in core size decreases the capital costs for the core vessel, reactor vessel, and biological shielding. Changes in linear heat rate affect the optimum fuel pin diameter and ligament for the minimum power generation cost and also strongly affect the plutonium inventory and fuel specific power. The fuel inpile time variations with linear heat rate (at constant burnup) affect the required cladding thickness, since the corrosion allowance is 0.5 mil per year. The cladding thickness, however, was held constant at 10 mils for this linear heat rate study. With respect to performance, changes in linear heat rate affect the attainable burnup, the breeding performance, and doubling time, as well as fuel pin fabrication costs. Increasing the linear heat rate decreases the influence of plutonium cost on the design; however, combined linear heat rate and plutonium cost perturbations are not considered in this report. For perturbation effects of plutonium cost (at 17 kW/ft linear power rating) see section 3.7.

4.3.2. Burnup Effects

Figure 4-10 shows the power generation cost versus fuel pin maximum linear heat rate with average burnup parameterized over a range from 25,000 to 200,000 MWD/T. The figure pertains to core geometries having the reference core pin pitch and diameter. The NAPS code does not determine the breeding ratio as a function of burnup, so that fuel costs for the high-burnup curves are optimistic (breeding performance and, hence, the plutonium credit component of the fuel cost decrease with increasing burnup).

Curves for both constant core diameter and constant core height are shown in Figure 4-10. The reduction in power generation cost that results from extensions of the allowable burnup become less significant at the higher burnups. This is a result of increases in unit fabrication costs, since the fabrication plant throughput is reduced, and because higher inpile plutonium carrying charges are incurred at the higher burnups.

Figure 4-10 exhibits discontinuities as a result of the procedure used in the NAPS computer code to determine the core vessel diameter. As the number of required fuel and blanket assemblies is increased, the core vessel size is increased only when the number of rows of assemblies is equal to or greater than $N + 0.5$ (where N is some integral value, i.e., 1, 2, 3, 4 . . .). Thus, step changes occur in the core, core vessel, and shielding diameters.

The changes in the relative slopes for lines of constant core diameter and height at different burnups are primarily a result of changes in fabrication costs. The fabrication component of fuel cost affects the power generation cost trend of the constant diameter core much more than the constant height, since the active length is a variable.

Power generation costs become more sensitive to variations in maximum linear heat rate at the higher burnups, regardless of how the change in linear heat rate is accommodated in the core design, i.e., changes in pin active fuel length or number of pins. The larger cores (corresponding to lower heat rates) are penalized more at high burnups than are the smaller cores, primarily because of proportionately higher plutonium carrying charges. It may be seen in Figure 4-14 that

a core having the reference core height and designed for 14 kW/ft actually displays a minimum plutonium carrying charge at approximately 130,000 MWD/T. An explanation of this trend lies in the fact that regardless of the fuel inventory (14, 17, or 20 kW/ft linear heat rate), the inpile carrying charges increase with increasing burnup. Outpile plutonium carrying charges decrease with increasing burnup but decrease less rapidly at the higher burnups. Some point is reached, then, when the rate of increase of inpile plutonium carrying charges with increasing burnup exceeds the rate of decrease of outpile carrying charges. The burnup at which this point is reached increases with increasing linear heat rate, since at any given burnup, the outpile fraction increases with increasing linear heat rate, resulting in more outpile plutonium carrying charge leverage on fuel cost.

Figure 4-14 also shows that smaller cores produce a smaller reprocessing component of fuel costs at high burnups. Since Figure 4-14 pertains to a core that is equal in height to the reference core, an operating point is reached, with increasing burnup, where the reprocessing component of fuel cost is independent of the core linear heat rating. For 14 and 17 kW/ft core designs, this burnup occurs at approximately 110,000 MWD/T. The curves for the reprocessing component of the fuel cost intersect because unit reprocessing costs are strongly dependent on the final fuel enrichment, and the final enrichment for the 14 kW/ft case increases faster with burnup than does the final enrichment of the 17 kW/ft case (i.e., the low linear heat rate core has the better breeding performance).

Returning to Figure 4-10, the increasingly lower relative power generation costs of the smaller cores (compared with larger cores) can be partially attributed to greater burnup effects on plant capacity factor, i.e., small cores experience proportionally larger gains in the energy generated per cycle.

In order for Figure 4-10 to be useful in evaluating returns in cost reduction for the increasing burnups, the relationship between allowable maximum linear heat rate (for the type of cladding material employed) and burnup must be determined. Line A-A has been arbitrarily positioned in Figure 4-15 to indicate qualitatively what the relation between heat rate and burnup might be. This line would represent a

design limit in that a core design plotted as a point to the left of the line would result in safe operation over the cycle time. A design represented by a point to the right of this line would result in cladding failure.

The expected trend of this design limit curve is as shown, i.e., as the linear heat rating is increased at a constant outside cladding temperature, the allowable burnup decreases. For a constant cladding outside temperature, increasing linear heat rate increases the average cladding temperature, which decreases the cladding material's fatigue strength (cycles to failure), increases creep rate, and possibly increases the cladding embrittlement (due to the increased neutron flux levels). The cladding stresses vary, also, with linear heat rate and burnup, since the higher heat rates result in higher fuel temperatures, changes in fuel swelling, and changes in thermal and mechanical fuel properties.

4.3.3. Fabrication Cost Effects

Figure 4-16 shows the power generation costs versus fuel pin maximum linear heat rate with the parameter of fuel pin unit fabrication cost. This plot indicates the sensitivity of power generation costs to changes in fuel fabrication costs of 50, 100, 150, and 200% of estimated costs (\$271/kg for reference core fuel pins). At a heat rate of 17 kW/ft an increase from 100% to 150% of the estimated unit fabrication costs will increase the power generation cost by 2.72%.

As discussed previously, accommodating decreased allowable linear heat rate by adding more fuel pins to the reference core design does not appreciably affect the fabrication component of the fuel cost. The unit fabrication cost decreases slightly, since fabrication plant throughput increases slightly (the fractional mass increase exceeds the fractional cycle time increase). If, for decreased linear heat rating, the alternative of adding total fuel length by increasing core height is selected, the fabrication component of the fuel cost decreases rapidly. This is a result of the lower unit fabrication costs incurred with an increased pin length.

The sensitivity of fabrication costs to changes in linear heat rate for the alternative of maintaining constant core diameter (constant number of pins) is exemplified by the changes in slope for the 50, 100, 150, and 200% fabrication cost curves. Very little change in the

slope of the constant core height curves are observed for 50, 100, and 150% of the estimated fabrication costs.

The change in the slope of the constant core diameter curve for 50% of estimated fabrication costs indicates that, if fabrication costs are low enough, a reversal of the most economical alternative takes place over a range of linear heat rates. In this event, a reduction of allowable heat rating from 17 to 15 kW/ft should be accommodated by adding more fuel pins to the reference design. This definitely is not the case in the event that fabrication costs prove to be equal to or higher than those estimated.

For the curve pertaining to 150% of fabrication costs, the trends are essentially unchanged from those observed in the case of 100% fabrication costs. One exception is the minimum point exhibited in the power generation cost at approximately 18 kW/ft heat rate for the constant core diameter curve. This apparently optimum heat rate arises as a result of the very high unit fabrication costs associated with high linear heat rates. It does not indicate an optimum reactor heat rate, since the high fabrication costs drive the optimum pin size upward.

4.3.4. Pin Pitch and Diameter Effects

Figures 4-11 through 4-13 show the effects of fuel pin pitch and diameter on the power generation cost at maximum linear heat rates of 14, 17, and 20 kW/ft, respectively. The change in linear feet of fuel corresponding to the three heat rates studied was accomplished by changing the active pin length and retaining the number of pins in the reference design. These curves illustrate the fact that the optimum fuel pin pitch and diameter both increase with increasing linear heat rate. This effect applies to both the alternative of reducing the number of fuel pins and for that of reducing the pin active fuel length, since the optimum pin size shift results from decreased leverage of plutonium carrying charges on the fuel cost. In the case of constant core height, the pin diameter shift will be somewhat less, since the fabrication component of the fuel cost is essentially constant and does not assist in the shift to a larger diameter. Figures 4-11 through 4-13, however, pertain explicitly to the alternative of decreasing fuel pin active fuel length to accommodate increased maximum linear heat rate while maintaining the reference core number of pins.

It should be pointed out here that lines of constant ligament plotted on Figure 4-13 will exhibit discontinuities. At constant ligament, the core diameter increases with increasing pin diameter; however, the radial blanket thickness (as calculated by the NAPS computer code) may actually decrease. If the sum of core and blanket rows falls below $N + 0.5$ (where $N = 1, 2, 3, 4 \dots$, etc.), the computer code will set the core vessel diameter corresponding to a hexagonal array of N rows.

Examination of Figure 4-10 along with Figures 4-11 through 4-13 shows that for linear heat rates above that of the reference core, the power generation costs are somewhat more sensitive to the linear heat rate design value if an optimum pin diameter is maintained. At heat rates below the reference core value, the costs are somewhat less sensitive to heat rate than what was previously indicated. In other words, the re-optimization of pin pitch and diameter affect the curves in Figures 4-10 and 4-11 to some extent. The re-optimization, however, does not alter the general trends as discussed above.

Fuel specific power (kW/kg fissile) is also parameterized in Figures 4-11 through 4-13. Since higher linear heat rates result in lower total oxide and plutonium inventories, the fuel specific power increases with increasing linear heat rate. Two other effects are present, however, resulting in a relatively small net increase in specific power. The reduced core height causes less coolant pressure drop, less can thickness, and less steel volume fraction going from 14 to 17 kW/ft, which tends to lower the required enrichment. The core size effect on neutron leakage tends to raise the enrichment. The net enrichment increase is proportionally less than the total oxide decrease, so that the fuel specific power increases by 9% from 850 to 925 kW/kg-fissile for a corresponding 21% increase in linear heat rate from 14 to 17 kW/ft. Some small effects on enrichment are also felt from sodium volume fraction decrease with the increase in optimum pin diameter. The plots at 14 and 17 kW/ft show the optimum pin diameter to be 0.260 and 0.270 inch, respectively, and the pin pitch to be approximately 0.320 and 0.330 inch. This shows that the optimum pin diameter increases at constant ligament over this range of heat rating. Increasing pin diameter at constant ligament results in a slightly smaller sodium volume fraction, which

tends to harden the neutron energy spectrum and decrease the plutonium enrichment.

The trend of optimum fuel specific power for minimum fuel cost is a continual increase with increasing linear heat rate except where step changes in the core vessel diameter force the optimum pin diameter upward. For a linear heat rating of 20 kW/ft, the fuel specific power resulting from a change in optimum pin size is reduced to approximately 900 kW/kg fissile. The drop to 900 kW/kg fissile from the value of 925 for 17 kW/ft heat rating is a result of the step change in core vessel diameter, as discussed previously. In this case, the core vessel diameter decreases by steps when the number of blanket elements in the outer row falls below half of the number required for a full row.

4.3.5. Doubling Time

Figure 4-17 shows the effects of varying linear heat rate on doubling time. The abscissa is fuel pin diameter with pin pitch parameterized. Sets of pin pitch curves are shown for 14, 17, and 20 kW/ft. These curves pertain to the case in which changes in linear heat rate are accommodated by changing the pin active fuel length. The total number of core pins is identical to that for the reference core (95,328). Three points are shown, however, which pertain to the case of changing the number of pins to accommodate changes in linear heat rate, leaving pin active fuel length constant. The points correspond to pin diameters and pitches of 0.280 and 0.337 inch, respectively. The effect of pin pitch and diameter on doubling time is shown in Figure 3-7.

The sets of curves in Figure 4-17 for 14, 17, and 20 kW/ft show that some shift in the optimum size occurs with increasing heat rate. The pin size for minimum doubling time at the 14 kW/ft heat rate is approximately 0.277 inch. At 20 kW/ft, the pin diameter for minimum doubling time is approximately 0.282 inch. This shift in pin diameter is a result of the decrease in cycle time with increasing linear heat rate, allowing outpile fraction to exert more influence on doubling time, which drives the pin diameter for minimum doubling time upward.

Figure 4-17 shows that, for a given pin pitch and diameter, increasing linear heat rate decreases the doubling time. This is primarily a result of changes in breeding ratio and cycle time. With

increasing linear heat rate, core height, pressure drop, and steel volume fraction decrease, and breeding ratio increases. At constant burnup, increasing linear heat rate lowers the fuel cycle time, which in turn lowers the doubling time. Increasing the linear heat rate above 20 kW/ft will decrease the doubling time, but at a smaller rate than indicated in going from 17 to 20 kW/ft. This is a result of a tendency toward increased enrichment for smaller cores (higher leakage) and increased outpile fraction.

Points are shown in Figure 4-17 which pertain to the case of changing the number of fuel pins to accommodate a change in linear heat rate. It is apparent that changing the number of fuel pins has less effect on doubling time than does changing fuel pin active fuel length. This result is a consequence of the flow area, pressure drop, steel fraction, and breeding ratio changes. An increase in linear heat rate, while maintaining core height constant, results in less flow area, higher pressure drop and steel volume fraction, and lower breeding ratio. The decrease in cycle time, however, is still sufficient to produce a net decrease in doubling time. Decreasing the linear heat rate and adding pins to the core is less deleterious to doubling time than adding to the pin active fuel length. This is due to the increase in breeding ratio with the increasing flow area associated with the addition of fuel pins, which reduces the core pressure drop and steel volume fraction. Conversely, increasing linear heat rate and deleting pins from the core will be less beneficial than decreasing the pin active fuel length (core height). This is shown in Figure 4-18. It is shown that no further gains in doubling time would be expected for linear heat rates above 24.0 kW/ft for the case of constant core diameter and pin size.

Increasing the linear heat rate shifts the optimum pin diameter (for minimum power generation cost) upward considerably, as discussed in section 4.3.4, Pin Pitch and Diameter Effects. Consequently, the improvement in doubling time shown in Figure 4-18 cannot be fully realized. Some compromise in an actual design would be made between doubling time and power generation cost.

4.4. Fuel Pin Cladding Thickness

4.4.1. Effect on Generating Cost

Figure 4-19 shows the effect of the fuel pin cladding thickness on power generation cost, which is very sensitive to cladding thickness and increases at a rate of approximately 0.4% per mil of cladding thickness at the 10-mil thickness. The 0.4% per mil change accounts for effects of pin re-optimization with additional cladding.

Figure 4-19 is a plot of power generation cost versus pin diameter, with pin pitch and cladding thickness parameterized. A plot of power generation cost versus pin diameter and pin pitch in a three-axis cartesian coordinate system would result in surfaces for each cladding thickness illustrated.

Required increases in cladding thickness may come about through definition of the limit imposed by cladding corrosion. The reference design allows 2.0 mils of the cladding to provide for corrosion over the life of the pin. The development of a cladding failure criteria and a fuel-cladding interaction model may also dictate additional thickness.

A change in the required cladding thickness necessitates a change in pin diameter and pitch for minimum power generation costs. The optimum pin pitch and diameter are increased with increased cladding thickness; the reasons for this are discussed below. The increased pin pitch and diameter bring about larger capital costs because of increased core vessel, reactor vessel, and biological shielding diameters. The capital cost contribution to the increased power generation costs with increased cladding thickness is approximately 15% of the total change, the remainder being attributed to increased fuel costs.

The effect of increased cladding thickness on the fuel cost is primarily the effect on breeding ratio and plutonium credit resulting from the increased steel volume fraction. The decreased plutonium credit allows the fabrication component of the fuel cost to exert more leverage on the fuel cost, forcing the optimum pin diameter upward. An increase in pin pitch accompanies the increased pin diameter, and, as can be determined from Figure 4-19, the optimum pin ligament remains very nearly constant at 0.060 inch, regardless of the cladding

thickness. The pin diameter increase at constant ligament tends to reduce the steel and sodium volume fractions, partially compensating for the increased steel due to cladding thickness increases. (Refer to sections 3.2 and 3.3 for a discussion of pin pitch and diameter optimization.)

The increases in power generation cost for increasing cladding thickness (as shown in Figure 4-19) do not take into account the change in burnup. For constant core flow, constant inlet and outlet temperatures, and pin diameter, the mean cladding and fuel temperatures go upward with increasing thickness (while maintaining a constant linear heat rate). Consequently, the allowable burnup must decrease, which would in turn increase fuel costs and power generation costs even more than is indicated in Figure 4-19 (this conclusion assumes that the increased cladding thickness and the resulting lower stresses have a negligible effect on allowable burnup).

4.4.2. Effect on Doubling Time

Figure 4-20 shows the effect of increased cladding thickness on doubling time for a range of pin diameters and pitches. Cladding thickness is parameterized and ranges from 0.010 to 0.020 inch (see Figure 3-7 for a plot showing pin diameter and pitch effects on doubling time).

Increased cladding thickness has a marked effect on doubling time. The increased steel volume fraction (for a given pin size) increases the enrichment and decreases the breeding ratio, both of which contribute to increased doubling time. Since a cladding thickness of 0.010 inch represents a large proportion of the total pin volume for small pins (0.240-inch diameter), doubling the cladding thickness has a more pronounced effect here than on the larger pins. Consequently, the optimum pin diameter for minimum doubling time is shifted upward for increased cladding thickness. The optimum pin diameter for a cladding thickness of 0.020 inch is shifted to diameters considerably larger than that which gives the minimum power generation cost. This is evidenced by comparing Figures 4-19 and 4-20.

The increased pin diameter and pitch at greater cladding thicknesses helps to maintain the breeding ratio; however, there is still

an appreciable drop in breeding ratio. The re-optimization of pin diameter and pitch, however, have little effect on holding down the doubling time. The decrease in breeding ratio is minimized by increasing pin diameter, but this increases fuel inventory and cycle time. Consequently, the doubling time will still increase rapidly with increased cladding thickness.

4.5. Spacer Type

4.5.1. General

Figure 4-21 shows the effects of spacer type, pitch, and thickness and fuel pin pitch on (a) power generation cost and (b) fuel doubling time. The spacer types considered are the helical spiral ribbon (the reference spacer), wire-wrapped (or wire-wound), and the grid type (or honeycomb or hexagonal egg-crate). The spacer pitch in the case of the helical spiral ribbon is the axial distance within which the ribbon makes a complete 360° twist; for the grid type it is the axial distance between leading edges; for the wire-wrapped spacer it is the axial distance within which the wire makes one complete wrap around the fuel pin. The spacer thickness for the helical ribbon is the small dimension of a cross section of the ribbon; for the grid, it is the total thickness of the web between adjacent fuel pins. The wire diameter of the wire spacer is equal to the pin-to-pin ligament (pin pitch less pin diameter) so that the wire on one pin contacts the cladding of an adjacent pin.

The following limitations apply to Figure 4-21:

1. Fuel pin diameter is equal to 0.280 inch, and pins are spaced on a triangular pitch.
2. Differences in spacer fabrication costs and other fabrication considerations, such as the minimum sizes that can be fabricated and spacer utilization feasibility (as determined by the effects of tolerance buildup on locating fuel pins) are not included.
3. The curves do not include the functional relationship between the diameter and pitch of the fuel pin and the spacer geometry (thickness and axial pitch) to result in guaranteed acceptable levels of performance with respect to fuel pin vibration (flow-induced), corrosion fretting, bow, spacing, swelling accommodation, and spacer structural integrity.

4. Because of the fact stated in item 3, certain fuel pin diameter-pitch and spacer geometry combinations shown in the figure may be invalid for the cladding thickness or fuel burnup (MWD/T) quoted; test results are required in order to demonstrate the validity of any type or geometry shown.

The discontinuities in the curves shown in Figure 4-21 are a result of step changes in the radial blanket pin diameter and fabrication component of the fuel cost as calculated by the NAPS computer code. With increasing fuel pin diameter, the fuel assembly can pitch and the blanket assembly can pitch both increase (they are always equal). Consequently, the blanket pin diameter increases (the blanket pin ligament is maintained at a constant value) until it reaches a given limit; increasing the can pitch further results in a step change decrease in pin diameter and a step change increase in the number of radial blanket pins.

The shaded areas shown in the figure represent the areas into which the grid spacer design may fall. The areas are bounded above by a pessimistic (as of the present time) design, i.e., a tight spacer pitch and thick web, and below by an optimistic design, i.e., a loose spacer pitch and thin web. The vertical bars connected to the wire-wound and helical ribbon curves indicate the range of power generation cost and doubling time incurred by changing the spacer pitch as noted; the range is shown at the pin pitch of 0.337 inch.

4.5.2. Power Generation Cost and Spacer Type

The purpose of a spacer is to maintain the proper fuel pin spacing in the array that makes up one fuel assembly and to eliminate or minimize fuel pin flow-induced vibration and subsequent corrosion fretting and cladding cyclic stresses. The presence of a spacer adversely affects core performance in three ways:

1. The spacer steel volume increases the core steel volume, thereby decreasing breeding performance owing to parasitic neutron absorption.

2. The spacer hydrodynamic drag increases the coolant pressure drop through the core, thereby further increasing the core

steel volume fraction, since the can wall thickness increases with the square root of the core pressure drop (less the elevation head).

3. The additional pressure drop increases the pumping power requirement, thereby increasing the required reactor thermal power output and increasing the core size and fuel cost.

An examination of Figure 4-21a shows that at a pin diameter of 0.280 inch, the helical spiral ribbon can reasonably be expected to produce relatively low power generation costs, as can some grid geometries. This is true, providing that these grids will result in acceptable fuel pin vibration levels and will withstand the hydraulic forces, high temperatures, and high fluences expected in the LMFBR core milieu. The figure leads the LMFBR designer to favor the helical ribbon or grid spacer; however, in light of the limitations of the figure (as mentioned previously), this result must be supported by test data. Uncertainties must be resolved concerning the mechanical and fretting corrosion performance aspects of each spacer type and geometry.

We may draw some definite conclusions, however, one of which is the effect of spacer type on the optimum ligament for minimum power generation cost. The optimum ligament is set primarily by the effects of fuel, steel, and sodium volume fractions and fuel enrichment on the core breeding performance and the plutonium credit component of the fuel cost. Additional effects include the plutonium carrying charge component of the fuel cost, the reactor vessel capital cost, and the primary system pumping power. For the cases examined, the plutonium carrying charge increases with increasing pin ligament, since the enrichment increases and results in a net increase in fissile loading; this effect tends to drive the optimum ligament downward. The reactor vessel capital cost also drives the optimum ligament down, since increasing ligament increases the reactor size and the capital cost. Pumping power decreases with increasing ligament; as a consequence, increasing pressure drop drives the optimum ligament upward.

For a pin diameter of 0.280 inch, Figure 4-21a shows that the use of a helical ribbon spacer (with a 2-inch pitch and 18-mil thickness) results in an optimum ligament of approximately 57 mils. The grid-type spacer (11.4-inch pitch and 15-mil thickness) results in

an optimum ligament of approximately 67 mils. A wire-wound spacer with a 9-inch pitch would result in an optimum ligament of 45 mils for a 0.280-inch pin diameter. The optimum ligament for each spacer type is dependent on the particular spacer pressure drop and spacer steel volume characteristics.

As mentioned previously, Figure 4-21 applies to the case of constant fuel pin diameter. The high core steel volume fraction caused by the spacer and can steel would result in a larger optimum fuel pin diameter and a somewhat lower power generation cost than that indicated for the wire-wrapped case. The change resulting from pin re-optimization, however, would be rather small—a reduction of less than 0.01 mill/kWh. The figure, then, can be considered fairly indicative of the power generation cost obtained for optimum pin pitch and diameter at the optimum ligament shown for each spacer configuration.

4.5.3. Doubling Time and Spacer Type

Figure 4-21b shows how fuel pin pitch and spacer type affect doubling time. The limitations of this figure, which should be kept in mind, are discussed in section 4.5.1; the main limitation is that certain spacer types or configurations may be invalid for the pin pitch, cladding thickness, and/or burnup (MWD/T) quoted. Thus, the wire-wound spacer should not be ruled out on the basis of poor doubling time, since the performance of the helical ribbon or grid is not guaranteed to be as shown.

The helical ribbon and the optimistic grid design (the lower boundary on the shaded area) result in low doubling times because of the relatively low spacer steel volumes and low spacer component of coolant pressure drop (and relatively low can thickness). The wire-wrapped type, as well as the pessimistic grid design (shaded area upper boundary), incur high doubling times because of the high spacer steel volumes in combination with the high pressure drop.

4.6. Orifice Effectiveness

4.6.1. General

Orifice effectiveness is defined as:

$$F_e = \frac{(W_{NHO}/W_{NHU}) - 1}{(P_{\max}/\bar{P})_R - 1}$$

where

W_{NHO} = nominal hot channel flow rate under orificed core conditions, lb/hr

W_{NHU} = nominal hot channel flow rate under unorificed core condition, lb/hr

$(P_{\max}/\bar{P})_R$ = core maximum radial power peaking factor (dimensionless)

The orificing effectiveness is a measure of the extent to which the coolant flow profile matches the power profile to give a more uniform temperature distribution across the core. A value of F_e equal to 0.0 indicates no orificing, whereas a value of 1.0 indicates perfect orificing, wherein each fuel pin receives a flow proportional to the pin power.

The numerator in the equation above may be termed the flow factor or extent of orificing. With no core orificing, this term will be zero. Increasing amounts of orificing (degree of orificing) will increase this term until it reaches some value (say, for example, the limiting flow factor) corresponding to that orificed condition wherein each hot channel in each assembly receives sufficient flow to limit the pin cladding to the same maximum surface temperature. This value of the limiting flow factor depends on the radial power profile and the number of pins per assembly, since assembly, rather than individual pin, orificing is the only practical scheme.

The dependence of the limiting flow factor on the radial power profile is exemplified by increasing the radial power gradient for an assembly in a previously properly orificed core (with flow factor equal to the limiting flow factor). The change in one assembly radial power gradient (maintaining the average assembly power constant) requires a complete core flow redistribution to provide for equal assembly hot

channel maximum cladding temperatures. Likewise, the limiting flow factor dependence on the number of pins per can is seen by examining the case of one can per core, where the limiting flow factor is zero, and the case of one can per pin, where the limiting flow factor is identical to the core radial power peaking factor minus one.

The limiting flow factor is also dependent on the degree to which the power profile changes during the core lifetime. With a fixed orificing arrangement, the flow must be distributed to protect the beginning- and end-of-life (BOL and EOL) hot channels, which may be located at different radial positions. Thus, the BOL hot channel flow will necessarily be low, since the EOL hot channel is overcooled at BOL conditions (BOL radial power profile). Conversely, the EOL hot channel flow at EOL power profile conditions will be low, since at that time the BOL hot channel is overcooled.

Figure 4-22 shows the effect of orificing on the power generation cost. Lines representing constant reactor outlet temperature with varying orifice efficiency are shown, as are lines representing constant maximum cladding temperature (at 103% power). Burnup is parameterized and ranges from 80,000 to 120,000 MWD/T. Linear heat rate is maintained constant at 17 kW/ft (maximum).

The curves of Figure 4-22 correspond to a core having 331 fuel assemblies. Consequently, a definite limit to the orificing efficiency (at constant radial power distribution) exists and is approximately 0.4. This efficiency corresponds to the orificing scheme that results in the same cladding surface temperature for the hot pin in each fuel assembly. A further increase in orifice efficiency is attainable only by improving the radial power profile over that of the reference core. Figure 4-22, however, is valid only for a radial peaking factor of 1.27.

The effect of improvement in the radial peaking factor would be to shift each constant core outlet temperature curve and each constant cladding surface temperature curve downward.

Point "A" in Figure 4-22 corresponds to the reference core at 1209 F maximum cladding surface temperature, 1100 F core outlet temperature, and 100,000 MWD/T burnup. It is immediately apparent that increased orifice effectiveness at constant cladding

temperature will result in decreased power generation cost. It is not possible, however, to increase the orifice effectiveness at constant radial power distribution without decreasing the number of fuel pins per fuel assembly and, consequently, increasing the steel volume fraction. The increased steel volume fraction would invalidate the cost trend shown.

In varying the core outlet temperature from 1050 to 1200 F for Figure 4-22, the system IHX hot leg temperature difference is varied from 50 to 200 F, so as to maintain the secondary sodium outlet temperature at a constant 1000 F. Consequently, the steam cycle is maintained identical to that for the reference core. All changes in the reactor outlet temperature are accommodated in the IHX design. No changes are made to the steam generator and reheater to re-optimize the system, nor is the core geometry re-optimized for the change in flow rate accompanying the change in outlet temperature (for effects of reactor temperature on optimum pin diameter and pitch, see sections 4.8.6 through 4.8.8).

The curves of Figure 4-22 illustrate the two separate and distinct results of core orificing under conditions of constant reactor flow or constant maximum cladding surface temperature. Orificing may be increased while (1) maintaining constant reactor flow, which results in lowered maximum cladding surface temperatures (lines of positive slope in Figure 4-22); or (2) maintaining constant maximum cladding surface temperature, which requires a decreased reactor coolant flow rate and an increased reactor outlet temperature at constant inlet temperature (lines of negative slope in Figure 4-22).

4.6.2. Orificing at Constant Reactor ΔT

Examining the curves for 100,000 MWD/T, it is seen that the reactor outlet temperature is varied from 1050 to 1200 F. These curves are for constant coolant flow rate through the reactor. An increase in orifice effectiveness (or extent of orificing) at constant core flow rate will decrease the maximum cladding surface temperature, but it will increase the power generation cost (at constant burnup). The increased power generation costs are caused by the increased core pressure drop, increased can wall thickness, increased steel volume fraction, increased enrichment, decreased breeding ratio, and resultant

decreased plutonium credit component of fuel cost. Pumping power increases with increased orificing at constant flow rate, adding to increased power generation costs.

Decreasing the reference core orificing effectiveness from a value of 0.4 to 0.0, while maintaining the core outlet temperature of 1100 F, will reduce the power generation cost by approximately 0.39% at a constant burnup of 100,000 MWD/T; however, the 44 F increase in cladding temperature may reduce the allowable burnup, so as to give a net increase in power generation cost.

Figure 4-22 points out the necessity of determining the functional relationship between burnup and cladding temperature. Meaningful results from this figure in evaluating the effects of orifice effectiveness and operation at higher cladding temperatures cannot be obtained without the aforementioned functional relationship.

4.6.3. Orificing at Constant Cladding Temperature

As indicated in Figure 4-22, increased orificing may lower power generation costs if the maximum cladding temperature is held constant while the reactor outlet temperature is increased (corresponding to decreased flow rate). The lines of constant maximum cladding surface temperature correspond to constant core pressure drop, since the pressure drop is set by the hot channel required flow rate. This is true, even though total core flow rate decreases with increasing orifice efficiency. Consequently, the fuel cost is essentially constant (no change in core pressure drop, can thickness, steel volume fraction, and breeding ratio). The power generation cost is reduced with increasing orifice efficiency, because pumping power decreases and the IHX size decreases, corresponding to the increased core outlet temperature. Increased core outlet temperature increases the IHX log mean temperature difference, and the heat exchanger size (heat transfer area) is inversely proportional to the log mean temperature difference.

Incentives for orificing while maintaining constant maximum clad surface temperature are shown in Figure 4-22. The maximum cladding surface temperature at a value of F_e equal to 0.0 and a reactor mixed mean outlet temperature of 1100 F is 1253 F. Maintaining this temperature and increasing F_e to 0.4 requires a net reactor outlet

temperature increase to 1140 F and reduces the power generation cost by 0.33%. This results primarily from the accompanying IHX size reduction, but some savings are effected through a reduction in flow and pumping power in the primary loops.

4.7. Fuel Specific Power

Fuel specific power may be improved by reducing the core total oxide loading and/or the enrichment. The primary means of reducing the core loading are increasing the maximum linear power rating or decreasing the fuel pin diameter. The improvements in fuel specific power that accompany increased linear power rating are discussed in section 4.3.4. In section 4.3.4, as well as in this section, enrichment changes with changes in pin diameter and pitch and core leakage are taken into account; however, enrichment changes with the number of fuel pins per assembly were not investigated. This is a result of the existing limit on the number of pins per assembly set by sodium voiding and criticality.

Figure 4-23 shows the variation of power generation cost in mills/kWh with fuel specific power in kW/kg-fissile. Pin outside diameter and pin pitch are parameterized. The minimum power generation cost of 3.309 mills/kWh occurs at a pin diameter of approximately 0.270 inch and a ligament of approximately 0.060 inch, corresponding to a specific power of 940 kW/kg.

Although fuel specific power is important with respect to the plutonium carrying charge and to fuel doubling time, the final choice of fuel specific power is dictated by the combination of core linear heat rate, pin active fuel length, core coolant flow rate, and pin diameter and pitch that result in the minimum power generation cost; Figure 4-23 illustrates this. At small diameters (at the optimum pitch), which result in relatively high fuel specific power, the plutonium carrying charge is low; however, the fabrication component of fuel cost is high, resulting in non-minimal power generation cost. Also, the breeding ratio is low at the small pin diameters, resulting in a low plutonium credit component of fuel cost. The low breeding ratios occur at small pin diameters, because the steel cladding represents a very significant portion of the pin volume. The cladding thickness of 0.010 inch is held constant and is at

a minimum value due to fabrication, oxide interaction, corrosion, and structural stability considerations. Conversely, low fuel specific power (large-diameter fuel pins) results in high breeding ratio but high plutonium carrying charges. Increased burnup will partially or totally alleviate the detrimental effect of high fuel specific power on power generation cost. It is shown in section 3.8 that increasing burnup forces the optimum pin size toward the smaller diameters and, therefore, higher fuel specific power.

The cost relationship of specific power to heat rating at various pin diameters and pitches is shown in Figures 4-11 through 4-13. Figure 4-24 shows the relationship between doubling time and fuel specific power. Results of the parametric study indicate virtually no interdependence between the two parameters over the normal range of fuel pin pitches and diameters. However, both above and below this range, doubling time tends to increase.

It should be noted that fuel specific power is not a measure of the total fissile mass associated with a particular reactor design. Fresh fuel and spent fuel in storage at the reactor site, together with other outpile fuel, is also an important economic factor. Given a maximum allowable fuel burnup, low fuel specific power designs will have longer cycle times. Since most outpile times are relatively independent of cycle time (e.g., spent fuel storage time), the variation of the ratio of inpile to outpile times will tend to moderate the effects of fuel specific power with regard to the total fissile inventory, as shown in Figure 4-25.

Two important parameters in determining doubling time are the integrated breeding ratio and the reactor fissile inventory. At extremely low fuel specific powers, the fuel inventory will be sufficiently high to produce relatively long doubling times. At extremely high fuel specific powers, the fuel volume fraction will be low, and hence, the integrated breeding ratio will be low and doubling time will again suffer. Between these two extremes lies an optimum range for fuel specific power where the doubling time remains virtually constant.

4.8. Reactor Inlet and Outlet Temperature Effects on Core Design

4.8.1. General

The reactor inlet and outlet temperatures affect core design and performance in the following ways: (1) in the reference design, the fuel assembly can thickness is determined as a function of core inlet temperature and coolant temperature rise through the core (more appropriately, coolant flow or pressure drop); (2) at a given linear heat rate, the inlet and outlet temperatures directly influence the maximum fuel central temperature, average fuel and cladding temperatures, and consequently the allowable burnup; and (3) at a given maximum fuel central temperature, the inlet and outlet temperatures affect the allowable linear heat rate and the required total length of fuel pins.

High reactor inlet and outlet temperatures are desirable in the heat transport loops for minimum power generation costs. For a given steam cycle, increasing reactor inlet and outlet temperatures increases the log mean temperature differences for the IHX and for the steam generator-reheater combination, consequently reducing the required heat transfer areas and equipment costs. Higher reactor inlet and outlet temperatures are conducive to high-temperature, high-efficiency steam cycles which reduce power generation costs, unless the temperature limits are exceeded for economical heat exchanger materials.

4.8.2. Can Thickness Effects

The reference core fuel assembly can thickness is set by the inlet fluid pressure and temperature (however, if the outlet temperature were increased sufficiently, it would determine the can wall thickness). The fluid pressure is set by the coolant flow rate and fuel assembly flow resistance. The fuel assembly can wall at the reactor inlet is subjected to an internal pressure equal to the pressure drop (not including hydrostatic head) from the fuel assembly inlet plenum to the reactor outlet plenum. This is because the bypass or leakage flow around the outside of the bundles is restricted at the lower support grid, thereby giving an external can pressure equal to the reactor outlet plenum pressure plus hydrostatic (elevation) head. It is desirable, then, to minimize the core pressure drop and flow rate, so that the can thickness,

which is proportional to the square root of the pressure difference across the wall, is as small as practicable. A small can thickness, giving low core steel volume fraction, is desirable in that decreased steel reduces parasitic captures, decreasing the required plutonium enrichment and increasing the breeding ratio. The lower can thickness effect on power cost at low flow rates and pressure drops, however, is countered by one of two effects: (1) at constant reactor inlet temperature, the reactor outlet temperature increases, as do the maximum fuel central temperature and maximum cladding temperature, possibly reducing the allowable burnup; and (2) at constant reactor outlet temperature, the inlet temperature must be decreased, which is detrimental to the IHX and/or steam generator performance.

Can thickness varies with reactor inlet temperature at constant inlet pressure or reactor flowrate, since the can material allowable stress decreases with increasing temperature. Thus, can thickness increases with increasing temperature, although this is a relatively minor effect below about 800 F. Again, this increase in can thickness will cause breeding ratio to suffer. However, lowering reactor inlet temperature (at constant reactor flow and temperature rise) is detrimental to plant efficiency.

4.8.3. Cladding Temperature Effects

The inlet and outlet temperatures of the reactor affect the maximum cladding temperature and the maximum fuel central temperature. The maximum cladding temperature occurring in the reactor may limit the allowable burnup due to material creep. On the other hand, it is more likely to expect the limit to come from fuel swelling, or more appropriately, fuel swelling and cladding temperature. It is expected that the cladding will limit radial fuel swelling to some extent. Thus low cladding temperatures are desirable to maintain cladding strength. However, high fuel temperatures may allow some plastic flow of the fuel into the center void, thus reducing the radial swelling and the radial load on the pin cladding. Since knowledge of the fuel and cladding interaction is meager and not sufficient to evaluate effects of reactor inlet and outlet temperatures on allowable burnup and fuel cost, only qualitative results may be obtained from the accompanying plots.

4.8.4. Linear Heat Rate Effects

At constant maximum fuel central temperature, higher maximum linear heat rates result from reductions in reactor inlet and/or outlet temperatures, since cladding temperature (the temperature that the fuel "sees") is reduced. Since the maximum fuel radial temperature drop from centerline to cladding surface is approximately 3500 F, a 100 F reduction of inlet and outlet temperatures will allow an increase of approximately 3% in linear heat rate. This increased heat rate decreases the total fuel pin length required and decreases power generation costs in other respects, depending on the design changes made (see section 4.3, Linear Heat Rate). The change in allowable linear heat rate is small and is not accounted for in the figures pertaining to this section.

4.8.5. Steam Cycle Considerations

The range of temperature variations is limited, since some reactor inlet and outlet temperatures are incompatible with a particular steam cycle. For instance, a reactor outlet temperature of 950 F results in an infinite required heat transfer area for each IHX, steam generator, and reheater in the case of the 2400/950/950 steam cycle. The reference design steam cycle (2400/950/950) was used for reactor inlet temperatures ranging from 700 to 1000 F and reactor outlet temperatures ranging from 1100 to 1200 F. The steam cycle of 1000/546 was used to investigate the effects of reactor inlet temperatures varying from 500 to 800 F and reactor outlet varying from 800 to 1000 F. The power generation cost curves in this section are plotted for approximately optimum heat transport system conditions. These optimum conditions vary with reactor inlet and outlet temperatures.

4.8.6. Reactor Inlet Temperature

The effects of core inlet temperature on reactor design and fuel cost are seen in Figure 4-26. This figure is a plot of fuel cost versus fuel pin diameter with pin pitch and reactor inlet temperature parameterized. Reactor coolant temperature rise is held constant at the reference value of 300 F, resulting in constant coolant flow per fuel pin.

As previously mentioned, a reduction in reactor inlet temperature has three primary effects: (1) the can material creep strength is improved, resulting in lower can thickness for a constant coolant pressure drop; (2) maximum fuel temperatures are reduced, allowing slightly higher linear heat rates and correspondingly lower power generation costs (Figure 4-26, however, is for a constant maximum linear heat rate of 17 kW/ft); (3) the average and maximum cladding surface temperatures are reduced, affecting the allowable burnup. Allowable burnup may increase or decrease with decreasing inlet temperature, depending on whether or not cladding creep strength improvement overrides the decrease in fuel plasticity. Figure 4-26 pertains to the case of a constant 100,000 MWD/T burnup. This figure can be used in combination with Figure 3-33 to evaluate changes in fuel cost with changes in burnup due to reactor inlet temperature variations, so long as inlet temperature and burnup are close to the reference core values.

Figure 4-26 shows that inlet temperature at constant coolant temperature rise, linear heat rate, and burnup has a minor effect on fuel cost, except where the inlet temperature is reduced so low that it requires a different steam cycle. A drop of reactor inlet temperature from 800 to 700 F requires a change to a lower temperature steam cycle, since the reactor outlet temperature falls to 1000 F. A change in steam cycle from 2400/950/950 to 1000/546 involves a net plant efficiency drop from 42 to 33%, which increases fuel cost considerably. The increased core thermal requirement increases the total length of fuel pins. The fuel cost curves of Figure 4-26 pertain to a constant fuel pin active fuel length of 34.7 inches, so that total fuel length is increased by adding more fuel assemblies to the core periphery. The increased plutonium carrying charges decrease the optimum pin size and pitch for minimum fuel cost with the change in steam cycle. Decreasing inlet temperature while maintaining the same steam cycle has a negligible effect on optimum pin pitch and diameter.

4.8.7. Reactor Coolant Temperature Rise

Effects of varying reactor coolant temperature rise are dependent upon whether the inlet or the mixed mean outlet temperature is held constant. In either case, fuel costs are reduced with increased

coolant temperature rise because of the decreased core pressure drop. These effects will be discussed later. For constant reactor inlet temperature, increasing coolant temperature rise will increase the maximum fuel and maximum cladding surface temperatures. The fuel-cladding interaction is dependent upon temperature, and consequently, so is the allowable burnup. Figure 4-27, which shows the effects of coolant temperature rise on fuel cost, does not account for these changes in allowable burnup.

Figure 4-27 shows the effects of varying reactor coolant temperature rise at constant inlet or outlet temperatures. Two sets of curves are shown: One set is for varying coolant temperature rise at high average core temperatures (corresponding to the 2400/950/950 steam cycle), and one set is for low average core temperatures (corresponding to the 1000/546 steam cycle). These curves show that, from a fuel cost standpoint, there is little difference between maintaining constant inlet or maintaining constant outlet temperature while varying reactor temperature rise. Some small differences arise from varying inlet temperature due to effects on can wall thickness (see section 4.8.6, Effects of Reactor Inlet Temperature).

From a capital cost standpoint, increasing the coolant temperature rise at constant reactor outlet is undesirable. For a given steam cycle, decreasing reactor inlet temperature decreases the log mean temperature differences for the heat transfer equipment, thereby increasing required heat transfer areas, equipment sizes, and, consequently, the capital cost component of power generation cost. Thus, capital costs increase but fuel costs decrease with decreasing core inlet temperature at constant bulk outlet temperature. Therefore, some optimum inlet temperature exists which "balances" these two opposing trends and results in a minimum power generation cost; Figure 4-28 shows this effect.

Decreasing reactor inlet temperature at constant mixed mean outlet is not entirely favorable to fuel cost. Lower reactor flow rate results in decreased reactor inlet temperature, while holding the mixed mean outlet at a constant value (of course, the coolant temperature rise is inversely proportional to flow rate), and of itself results in increased hot channel maximum cladding temperatures. This is

because the hot channel temperature rise is proportional to the reactor coolant average temperature rise. The increasing cladding temperature, then, with decreasing inlet temperature, will limit the allowable burnup to some extent. The change in burnup, as mentioned previously, is not accounted for in the figures accompanying this discussion. Another detrimental effect of decreasing reactor flow and increasing reactor temperature rise is the thermal stress generated in the core assembly. It is felt, however, that proper mechanical design will minimize any resulting penalty from this effect.

The discussion above points out the desirability of employing a custom-fitted steam cycle with the breeder reactor. A steam cycle supplying a high steam temperature but relatively low steam pressure to the turbine inlet results in low feedwater and low boiler water temperatures, which are conducive to low reactor inlet temperatures.

Figure 4-27 shows the effects of varying reactor coolant temperature rise at constant inlet or outlet temperatures. The effect on optimum pin pitch and diameter for minimum fuel cost is much the same, regardless of maintaining constant inlet or outlet temperatures. The effect of increasing coolant temperature rise on pin pitch and diameter is primarily a decrease in the pin-to-pin ligament with some attendant decrease in pin diameter. A simplified explanation of this trend of decreasing ligament with increasing coolant temperature rise is obtained by considering that the optimum ligament (termed " ℓ " for convenience) for a given pin diameter gives a balance between plutonium carrying charge and the plutonium credit component of fuel cost. Increasing the coolant temperature rise by reducing the flow results in less pressure drop, less can thickness, less steel volume fraction, and a higher breeding ratio. The ligament rate change of steel fraction is decreased over the entire range of ligaments, which "pulls" the optimum ligament downward and, consequently, decreases the ligament rate change of sodium fraction to partially restore the balance. This new ligament (termed " ℓ' " for convenience) results in a higher breeding ratio. The fuel fraction for ligament " ℓ' ", however, is excessive, since the pin diameter (d) has remained constant. A new and smaller optimum pin diameter (d') reduces the plutonium carrying charge more than enough to offset the detrimental effects of fabrication cost increase and plutonium credit decrease

to form the new combination of pin pitch ($\ell' + d'$) and diameter (d'). Figure 4-29 best exemplifies this trend and includes effects from capital cost changes.

4.8.8. Reactor Inlet and Outlet Temperatures

Figure 4-28 shows the power generation cost variation with reactor inlet and outlet temperature for two steam cycles, i.e., the reference steam cycle of 2400/950/950 and the low steam pressure and temperature cycle of 1000/546. Each point on these curves is for optimum pin pitch and diameter for minimum power generation cost at the particular reactor inlet and outlet temperature. The capital cost component of the power generation cost is approximately optimum for each point.

Figure 4-30 shows the effect of reactor inlet and mixed mean outlet temperatures on doubling time and shows the optimum pin pitch and diameter for minimum doubling time. Curves for reactor coolant temperature rises of 200, 300, and 400 F are shown. An appreciable decrease in doubling time occurs for the reference design if the inlet temperature is reduced to 700 F (with mixed mean outlet temperature at 1100 F). The power costs are not appreciably affected, as evidenced by Figure 4-28; however, the hot channel maximum cladding temperature at 103% power (shown as T_c) increases from 1210 to 1242 F. Again, the importance of the definition of allowable maximum cladding surface temperature is apparent. This inlet temperature decrease will decrease doubling time by more than 7%. The decrease in doubling time is a result of the lower coolant flow (higher coolant temperature rise), lower accompanying pressure drop, can wall thickness, and steel volume fraction. This decrease in steel volume fraction decreases the required plutonium enrichment and increases the breeding ratio. The increased breeding ratio and decreased enrichment both contribute to lower doubling times.

Figure 4-1. Fuel Cost Dependence on Linear Power Rating
for 80% Fuel Density

Figure 4-2. Fuel Cost Dependence on Burnup for 80% Fuel Density

Figure 4-3. Effect of Initial Fuel Density on Allowable Linear Heat Rate

Figure 4-4. Effect of Fuel-Clad Gap Unit Surface Thermal Conductance on Maximum Allowable Linear Heat Rate

Figure 4-5. Densification Effects on Fuel Performance at BOL

Figure 4-6. Densification Effects on Fuel Performance at 140,000 MWD/T

Figure 4-7. Effects of Uncertainties in Columnar Grain Formation Temperature on Allowable Linear Heat Rate

Figure 4-8. Effect of Fuel-Clad Gap Heat Transfer Coefficient Uncertainties on Allowable Linear Heat Rate

Figure 4-9. Effect of Uncertainty in Fuel Conductivity on Linear Heat Rate

Figure 4-10. Effects of Allowable Maximum Linear Heat Rate and Average Burnup on Power Generation Cost

Figure 4-11. Power Generation Cost Variation With Pin OD and Pitch at a Maximum Linear Heat Rate of 14 kW/ft

Figure 4-12. Power Generation Cost Variation With Pin-OD and Pitch at a Maximum Linear Heat Rate of 17 kW/ft

Figure 4-13. Power Generation Cost Variation With Pin OD and Pitch at a Maximum Linear Heat Rate of 20 kW/ft

Figure 4-14. Fuel Cost Vs Burnup at 14 and 17 kW/ft Linear Heat Rates

Figure 4-15. Qualitative Effect of Design Limit Imposed by Clad-Fuel Interaction

Figure 4-16. Effects of Allowable Maximum Linear Heat Rate and Fuel Pin Fabrication Costs on Power Generation Costs

Figure 4-17. Doubling Time Vs Pin Diameter at Various Linear Heat Rates

Figure 4-18. Doubling Time Variation With Maximum Linear Heat Rate

Figure 4-19. Power Generation Cost for Various Fuel Pin Cladding Thicknesses

Figure 4-20. Effect of Cladding Thickness on Doubling Time

Figure 4-21a. Effect of Spacer Type, Pitch, and Thickness and Fuel Pin Pitch on Power Generation Cost

Figure 4-21b. Effect of Spacer Type, Pitch, and Thickness and Fuel Pin Pitch on Doubling Time

Figure 4-22. Variation of Power Generation Cost With Orifice Effectiveness

--- Max Cladding Surface Temp, F
 — Reactor Outlet Temp, F

Active fuel length, in. 34.7
 Linear heat rate, kW/ft 17
 Bulk T_R inlet, F 800
 Fuel pin OD, in. 0.280
 Fuel pin pitch, in. 0.337
 IHX cold leg ΔT , F 100
 Na inlet T to SG & RH, F 1000

Figure 4-23. Effect of Fuel Specific Power on Power Generation Cost

Figure 4-24. Effect of Fuel Specific Power on Doubling Time

Figure 4-25. Effect of Fuel Specific Power on Outpile Fraction and Breeding Ratio at Constant 0.060-Inch Ligament

Figure 4-26. Effect of Reactor Inlet Temperature on Fuel Cost at Constant 300 F Reactor Coolant Temperature Rise

Figure 4-27. Effect of Varying Reactor Coolant Temperature Rise on Fuel Cost at Constant Reactor Inlet or Outlet Temperature

Figure 4-28. Effects of Reactor Inlet and Outlet Temperatures on Power Generation Cost, Maintaining Optimum Pin OD and Pitch

Figure 4-29. Effect of Reactor Coolant Temperature Rise on Power Generation Cost for Various Pin Diameters and Pitches

Figure 4-30. Effect of Reactor Coolant Temperature and Coolant Flow Rate (or Temperature Rise) on Doubling Time

5. SAFETY COEFFICIENT PARAMETERIZATION

The Spoiled Vs Unspoiled Geometry trade-off study clearly indicates that the changes in composition and/or geometry that are required to significantly improve the sodium void coefficient will also increase power generation costs. The severity of the penalty depends on the degree and type of modification, i. e. , spoiling required.

If, for example, the void coefficient is halved using the most favorable means of spoiling, the power cost penalty is greater than 0.25 mill/kWh. The degree of spoiling required to reduce the sodium void coefficient to zero will increase power costs between 0.6 and 0.7 mill/kWh. This particular type of spoiling involves reducing the core height to increase leakage. Other means of spoiling can also be utilized to achieve the desired void coefficient. However, power cost penalties may be as much as 50% greater.

The behavior of the doubling time as the sodium void coefficient is varied is also strongly dependent upon the type of spoiling used. Reducing core height to improve the void coefficient results in little change in the doubling time. Other types of spoiling, such as increasing the coolant fraction and adding a moderating material such as BeO, result in a sharp increase in doubling time.

The Doppler coefficient is even less amenable to parameterization than the sodium void coefficient. In addition to being a dependent variable, the behavior of the Doppler coefficient is strongly dependent upon the type of spoiling used to improve the void coefficient. Decreasing the core height, which is the most economic means of spoiling, decreases the Doppler coefficient. Adding BeO significantly increases the Doppler coefficient. Thus, we have two cores with the same void coefficient, yet widely differing Doppler coefficients and power generation costs.

6. HEAT TRANSPORT SYSTEM TECHNOLOGY- OPTIMIZATION RELATIONSHIPS

6. 1. Core Outlet Temperature and Temperature Rise

6. 1. 1. General

In this section and the several that follow, a number of heat transport system parameters are investigated to determine the conditions under which lowest power generating cost results. Heat transport system parameters studied are the core outlet temperature and temperature rise, the intermediate heat exchanger (IHX) log mean temperature difference (LMTD), and the steam generator (SG) hot end temperature difference. Two steam cycles were also included; one—the reference cycle, forms the basis for most of the work; a second cycle was also studied (as discussed below) to permit the study of the desired range of reactor coolant temperatures.

To understand these analyses more easily, the heat transport system arrangement is shown schematically in Figure 6-1. There are six reactor coolant pumps and six gravity flow IHXs. There are three intermediate coolant loops; included in each loop is one intermediate pump, one once-through steam generator, and one sodium-heated reheater. Each intermediate loop supplies coolant to two IHXs.

6. 1. 2. Outlet Temperature

The reference steam cycle (2400 psi/950 F/950 F) places a lower limit on the core outlet temperature; the full range of reactor outlet temperatures to be investigated (from 800 to 1200 F) could, therefore, only be studied by including another steam cycle—the 1000 psig dry and saturated cycle. The investigations concerning the core outlet temperature were coupled with the effects of varying the reactor temperature rise through the range of 200 to 500 F.

The first portion of the study consisted of varying the reactor outlet temperature from 1060 to 1200 F (for a series of reactor ΔT s) while maintaining the hot and cold end temperature differences across the IHX at 100 F and a steam temperature of 950 F (i.e., the reference steam cycle conditions). The value of 1060 F was obtained by allowing the steam generator sodium inlet temperature to approach the steam temperature to within 10 F; this was considered to be lowest practical value. The investigation was performed holding the core geometry and, hence, the fuel costs, constant to permit the effects of the heat transport system alone to be determined.

The capital cost of the plant is calculated by the NAPS computer program as the summation of the costs of the individual components of the nuclear steam supply system and the turbine island. The costs of the individual components are calculated after their physical size is computed from the operating requirements. With a change in reactor outlet temperature, the items that are most influential in changing the plant capital cost are the steam generators, reheaters, reactor and intermediate coolant pumps, and the turbine island.

The IHX cost does not vary significantly, since the LMTD and the duty are essentially constant for all combinations of reactor outlet temperatures and reactor ΔT s for a given steam cycle of 100% load. To clarify this statement, the following explanation is offered: The IHX LMTD is constant because the hot and cold end ΔT s are independent variables and are set at 100 F. The Q_{IHX} is a dependent variable and is a function of the steam cycle demand; therefore, it is the sum of the reactor power and the fluid energy supplied by the reactor coolant pumps. Now, as the ΔT across the reactor is varied, the reactor coolant flow will also vary. This, in turn, changes the reactor coolant system pressure drop and the energy supplied by the pumps. Hence, as the reactor ΔT is increased, the flow decreases, the power input by pumps decreases, and the reactor power must increase to satisfy the demand by the steam cycle. The slight variation in the cost of the heat exchangers is due to the changes in configuration that are calculated to satisfy the pressure drop limitations set for the intermediate coolant flowing through the tubes.

The effects of reactor ΔT on power generation costs for the reference plant are shown in Figure 6-2. For a given reactor outlet

temperature, the power generation costs drop as the reactor ΔT is increased until a minimum cost is reached. A further increase in reactor ΔT increases the power generation cost. Figure 6-3 can help to explain the reasons for the minima points. The figure shows the costs of the major components, as well as a summation of these costs, as a function of reactor ΔT . From previous work performed in the selection of plant functional parameters for the 1000-MWe LMFBR, it was determined that the reheater sodium outlet temperature ($T_{\text{Na RH out}}$) yielding the minimum combined cost of reheater and steam generator (all else being held constant) approximated the following relationship:

$$T_{\text{Na RH out}} = T_{\text{Na RH in}} - \Delta T''_{\text{IHX}} + 125$$

where $T_{\text{Na RH in}}$ = temperature of sodium into the reheater
 $\Delta T''_{\text{IHX}}$ = IHX temperature drop on intermediate side

This relationship was used as an input to NAPS for all cases involving the 2400/950/950 steam cycle. Therefore, it can be assumed that the cost values for the reheater (RH) and steam generator (SG) in Figure 6-3 are reasonably optimized for all values of ΔT_R . (See section 6.2 for a more detailed discussion on the RH-SG optimization techniques.) The drop in cost of the SG as the reactor ΔT decreases at constant reactor outlet temperature is due to the increase in the LMTD for the boiling and economizer sections. The RHs also drop in cost, although not as dramatically as the SGs.

The IHXs show a slight increase in cost as the reactor ΔT is decreased because of the calculated configuration required to limit the intermediate coolant pressure drop through the IHX, i.e., an increased number of tubes of shorter length resulting in a heavier heat exchanger but one having a relatively constant heat transfer surface. It should be noted that the Q_{IHX} and the LMTD remain essentially constant.

The cost of the pumps increases with a decrease in ΔT_R , because the cost is a direct function of horsepower. The increased flow and increased pressure drop result in higher-horsepower pumps. The

summation curve, then, combines the cost factors and results in a minimum dollar value.

It will be noted in Figure 6-2 that as the reactor outlet temperature increases, the minimum occurs at a higher value of ΔT_R . This is because the factor most influential on the total cost is due to the SGs. For the reference steam conditions, the saturation temperature is approximately 662 F (at 2400 psig). Therefore, low reactor outlet temperatures and their associated low intermediate sodium temperatures decrease the pinch point in the SG rapidly as the ΔT of the reactor and the associated ΔT of the intermediate side of the IHX is increased. Figure 6-4 shows how the cost of the SG varies with reactor outlet temperature and reactor ΔT . Another factor that causes a shift of the optimum cost to higher ΔT s for higher reactor outlet temperature is that the reactor ΔT sets the flow, regardless of the reactor outlet temperature. Thus, going to a higher ΔT reduces the flow and, therefore, the pressure drop, resulting in lower capital costs for the pumps. The shift in optimum ΔT is possible if the LMTDs for the boiling and economizer sections are not penalized. Decreased costs due to a higher sodium temperature in the steam generators are countered by the cost penalty for stainless steel superheater sections for sodium above 1025 F.

In addition to selecting temperatures that minimize power generation costs, consideration must be given to fuel pin cladding temperatures. Figure 6-2 shows the cladding temperatures accompanying the T_{RO} and the associated reactor ΔT . As expected, for all cases, the cladding temperature drops with a decrease in reactor ΔT due to the increased flow.

Figures 6-5 and 6-6 are plots indicating how the capital cost and power generation cost vary as a function of the reactor ΔT . They show that the nuclear steam supply system is the portion of the plant that significantly affects the total cost.

6.1.3. Temperature Rise

To investigate the effect of varying the reactor outlet temperature from 800 to 1200 F in conjunction with reactor ΔT s ranging from 200 to 500 F, a series of runs was made with the 1000 psig, 546 F dry and saturated cycle. The LMTD of the IHX was set at 50 F, with the

hot and cold ends equal; this value was chosen to cover the temperature ranges above. For this portion of the study, the can thickness was also held constant at 132 mils to minimize the changes in fuel cost. The IHX log mean temperature was held constant at 50 F by setting both the hot and cold leg temperature differences at 50 F. By holding all the mechanical aspects of the reactor constant, the total power generation cost varies as a function of the heat transport and steam generating components required. The cycle does not include sodium reheaters; therefore, the power generation cost varies as a function of the costs for the IHXs, reactor and intermediate coolant pumps, the turbine island, and the steam generator. The SGs associated with this cycle do not require superheaters, since the outlet steam conditions are in the dry and saturated region.

The sodium transfers heat to the steam side of the steam generator with Croloy 2-1/4 economizer and boiler sections. The SG is sized as a function of the heat transfer area required for a specific LMTD in each section; this temperature difference is set by the reactor sodium inlet and outlet conditions and the IHX temperature differences. Since the heat transfer area is inversely proportional to the LMTD, a larger LMTD requires less heat transfer area, resulting in a smaller SG and associated cost. The IHX, as stated previously, has a constant LMTD of 50 F. Therefore, the changes in the cost of this unit are associated with the accommodation of the limits set by the intermediate coolant pressure drop.

Figure 6-7 shows the total power generation cost as a function of ΔT_R for the 1000 psig, dry and saturated steam cycle. Since the saturation temperature is only 546 F for this cycle, the effect of high sodium inlet temperatures on the SG is to create very high LMTDs, which in turn reduce the cost of the steam generators, even though they must transfer approximately 20% more heat than the SGs for the 2400/950/950 cycle. Thus, for the higher reactor outlet temperature, i.e., 1000 to 1200 F, and for ΔT_R from 300 to 500 F, the low power generation cost is not determined by decreased steam generator costs (due, of course, to the decreasing reactor ΔT). Under these conditions, the cost of the sodium pumps becomes the influencing factor because of the increased flow and the attendant increased ΔP as the ΔT_R decreases. However,

as the reactor outlet temperature drops (as can be seen by the T_{RO} curve labeled 900 F, for example), the trends are starting to reverse and the SG cost becomes more dominant.

6.2. Steam Generator - Reheater Optimization

The total intermediate flow rate is established by the energy demand of the steam raising equipment and the IHX hot and cold end temperatures. In transferring the heat from the reactor to the steam generators and reheaters, the intermediate coolant system flow is proportioned between these two units. To design these units, the variables that must be considered are sodium flow and sodium outlet temperatures. The constants to be used in the design are the sodium inlet temperature to the units, the feedwater and steam inlet temperatures, and the steam outlet temperatures. As the variables are manipulated, holding all other plant parameters constant, the size and consequently the cost of the individual units change. Hence, we may arrive at a combination SG-RH that exhibits a minimum cost. By utilizing the relationship $\Delta T''_{IHX} - \Delta T_{RH}$, it is possible to program the calculations to arrive at the aforementioned optimum, where $\Delta T''_{IHX}$ is the intermediate sodium temperature difference across the IHX.

The NAPS code has the ability to input a series of values for $\Delta T''_{IHX} - \Delta T_{RH}$ and produce total power generation costs for each value. Figures 6-8, 6-9, and 6-10 show the results of the RH-SG optimization; for the combinations of T_{RO} and ΔT_R examined, minimum power generation cost points are determined. The curves in Figures 6-11 through 6-13 are complementary to those in Figures 6-8 through 6-10; they show the cost variation of the SG and RH.

As an illustration let us examine the curves labeled $T_{RO} = 1100$ in Figure 6-13. The abscissa labeled $T''_{IHX} - T_{RH}$ increases from left to right. Since T''_{IHX} is a constant (at the constant ΔT_R of 400 and the $T_{RO} = 1100$), the entire expression can increase only if the ΔT_{RH} decreases. The ΔT_{RH} can decrease only if the sodium flow rate is increased at the expense of the SG flow rate, which must decrease, since the total intermediate flow rate is a constant. The decreased in ΔT_{RH} , then, increases the LMTD in the RH and thus decreases the heat transfer area. The heat transfer area is a linear function of the capital cost

of the unit. As shown on the curve labeled RH $T_{RO} = 1100$, the cost decreases as the ΔT_{RH} decreases.

By the same token, the curve labeled SG $T_{RO} = 1100$ shows an increase in capital cost, because the sodium temperature out of the SG is dropping as more flow goes to the RH. The summation of these two curves would yield a minimum capital cost. Referring again to Figure 6-10, curve $T_{RO} = 1100$ F indicates the optimum point.

6.3. Heat Exchanger LMTD

The LMTD for the IHX was varied through a range of 50 to 150 F to determine the resulting changes in the total power generation cost. The range of log mean temperatures was obtained by setting the hot and cold end temperature differences as indicated in Figure 6-14. The reactor core configuration was maintained constant. The reactor coolant inlet temperature was held constant at 800 F, and the outlet temperatures were varied. These conditions established a constant fuel cost. The power generating cost variations resulted from the capital cost changes in the rest of the plant, including those of the IHX.

For constant reactor sodium inlet and outlet temperatures, a change in the IHX LMTD will be reflected throughout the plant as increased or decreased fixed charges. The IHX cost is a function of the heat transfer area, which is inversely proportional to the LMTD. Therefore, an increasing LMTD reduces the heat transfer area and the cost. For the 1100 to 1200 F reactor outlet temperature range, the IHX cost is reduced by approximately 40% as the LMTD is increased from 50 to 150 F. Decreasing the cost of the IHX by increasing the LMTD does not always result in lower power generation costs, as can be seen in Figure 6-14.

The hot and cold end temperature differences investigated were chosen to cover an LMTD range of 50 to 150 F and still limit the hot end temperature differences on the steam-raising equipment to a reasonable value. In addition, this range allows observations to be made on the effect of the hot end temperature difference of the steam generator on the total power generation costs, as shown in Figure 6-15.

Figure 6-14 shows the effects of IHX LMTD on total power generation cost for a number of reactor outlet temperatures. The curve

demonstrates that the higher outlet temperatures are more economical. The minimum power generation cost for the curves exists where the cost trend characteristics of the components in the heat transport and steam generating system are such that the cost sum is at a minimum. A change in IHX LMTD from this region results in an increase in power generation cost due to the cost trend effects of the components.

6.4. Steam Generator Hot End Temperature Difference

The investigation of the hot end temperature difference for the reference plant was performed in conjunction with the investigation of the IHX LMTD. Figure 6-15 shows how the total power generation costs vary as a function of the hot end temperature difference for the SG. The optimum points for each curve on Figure 6-15 are identical to the optimum points on the curves shown on Figure 6-14. The optimum power generation costs for the curves shown on either Figure 6-14 or 6-15 are linked together because of the dependency of temperatures in the IHX and SG. The change in the location of the minimum power costs for different reactor outlet temperature is explained in the discussion of bulk core outlet temperatures. Figure 6-16 shows the capital cost of the SGs contributing to the total power generation cost shown in Figure 6-15.

Figure 6-1. LMFBR Schematic Flow Diagram

Figure 6-2. Effects of Reactor ΔT on Power Generation Cost for Various Reactor Outlet Temperatures, Reference Plant

Figure 6-3. Cost of Heat Transport System Components

Figure 6-4. Effects of Reactor ΔT on Steam Generator Cost for Various Reactor Outlet Temperatures

Figure 6-5. Effects of Reactor ΔT on Nuclear and Turbine Island Costs

Figure 6-6. Effect of Reactor ΔT on Power Generation Cost

Figure 6-7. Effects of Reactor ΔT on Power Generation Cost for Various Reactor Outlet Temperatures

Figure 6-8. Effect of $\Delta T_{IHX} - \Delta T_{RH}$ on Power Generation Cost
 ($\Delta T_R = 200$ F)

Figure 6-9. Effect of $\Delta T_{IH\bar{X}} - \Delta T_{RH}$ on Power Generation Cost
 ($\Delta T_R = 300$ F)

Figure 6-10. Effect of $\Delta T_{\text{IHX}} - \Delta T_{\text{RH}}$ on Power Generation Cost
 ($\Delta T_{\text{R}} = 400 \text{ F}$)

Figure 6-11. Effect of $\Delta T_{IHX} - \Delta T_{RH}$ on Component Costs
 ($\Delta T_R = 200$ F)

Figure 6-12. Effect of $\Delta T_{IHX} - \Delta T_{RH}$ on Component Costs
 ($\Delta T_R = 300$ F)

Figure 6-13. Effect of $\Delta T_{IHX} - \Delta T_{RH}$ on Component Costs
 ($\Delta T_R = 400$ F)

Figure 6-14. Effects of IHX LMTD on Power Generation Cost for 2400 psi/950 F/950 F Steam Cycle

Figure 6-15. Effect of Steam Generator Hot End ΔT on Power Generation Cost

Figure 6-16. Effect of Steam Generator Hot End ΔT on Steam Generator Cost

7. EFFECT OF ECONOMIC PARAMETERS ON THE REFERENCE DESIGN

This section of the report describes how the fuel cost is affected by variations in the economic parameters specified in the contract: unit fabrication cost, plutonium value, unit reprocessing cost, reprocessing plant throughput, and core average burnup. The effect of burnup on doubling time is also included. Fuel outpile time has been added to this list as being significant to both economics and doubling time. Although burnup is not an economic parameter, it is included here, since it is conventionally classed as such because of its particularly heavy impact on fuel cost.

In performing this study, all the reference economic parameters are held constant, while the particular parameter being investigated is varied. The reference values of the economic parameters are as follows:

Unit core fabrication cost, \$/kg	271
Unit blanket fabrication cost, \$/kg	73
Plutonium value, \$/gm fissile	10
Unit reprocessing cost, \$/day at 493 kg/day throughput	30,000
Average core burnup, MWD/T	100,000
Outpile time, yr	1.337

Figure 7-1 shows how the fuel cost of the reference design is affected by varying the burnup, unit fabrication cost, and plutonium value separately. Notice that the fuel cost is less sensitive to changes in the plutonium value than to changes in the other parameters. A factor of 4 increase in the unit plutonium value increases the fuel cost by 50%, while a factor of 4 increase in the unit fabrication cost more than doubles the

fuel cost. The effects of the latter two parameters on the fuel cost are nearly linear. The unit plutonium value affects a portion of the fuel costs which is the difference between two large numbers (the plutonium working capital, which is positive, and the plutonium credit, which is negative). At the reference burnup, this component is approximately 30% of the total, whereas the fabrication component is nearly half of the total. These components are compared in Figure 7-2.

Increasing burnup does not reduce fuel costs linearly; Figure 7-2, which shows the variation of the individual fuel cost components, illustrates the reasons. At low burnups, all of the components decrease rapidly with burnup. However, as the burnup increases, the plutonium working capital changes very little, since the outpile costs, which are nearly constant, are spread over a greater number of kilowatt-hours per cycle. The plutonium credit levels out as the fission product inventory increases and the breeding ratio decreases. The reprocessing component, although small, also has a rate of decrease which is less rapid.

If unit fabrication costs were constant, then the fabrication cost component would vary linearly with burnup. However, increasing the burnup for a fixed reactor economy (in this case, 15,000 MWe) decreases the fabrication plant throughput and, hence, raises the unit costs. This causes the decreasing rate of change of the net fabrication cost component curve. Shipping, although small, does vary linearly with burnup. The behavior of the individual components with burnup is consistent with the variation of the total cost.

Figure 7-3 shows the effect of burnup on the reference core fuel cost with the unit fabrication cost and plutonium value as parameters. The curves show the same decreasing rate of change with increasing burnup as is shown in Figure 7-1. As noted earlier, the rate at which the fuel cost decreases with increasing burnup is determined primarily by the interplay of the nuclear component and the fabrication component of the fuel cost (Figure 7-2). With a small unit plutonium value, the nuclear component is small and, hence, has relatively less effect on the fuel cost; the fabrication component, which decreases rapidly with increasing burnup, becomes the dominant effect. At large unit plutonium values, just the opposite is true.

Similarly, the fabrication fuel cost component, which is very strongly dependent on burnup, has more leverage on the total fuel cost when the fabrication cost is a larger part of the total cost. For large unit fabrication costs, the unit plutonium value has much less leverage on the fuel cost than it has for small unit fabrication costs. Note in Figure 7-3 that the fuel costs level out more rapidly at low unit fabrication costs than they do at high unit costs.

Figure 7-4 shows the effect of the burnup on doubling time. The decreasing rate of change in doubling time is caused by the decreasing rate of change of the plutonium mass, which does not increase as rapidly at high burnup because of the increasing fission products and decreasing breeding ratio. Figure 7-5 shows the effect of burnup on the outpile time plus the cycle time. Since their variation is linear with burnup, they do not affect the rate of change of doubling time with burnup. The effect of outpile time on doubling time is shown in Figure 7-6. Changing outpile time causes a linear change in the doubling time. Figure 7-7 shows that changing the outpile time also causes a linear change in the fuel cost; this effect is demonstrated at several plutonium values. Predictably, the greater the plutonium value, the greater the penalty for increased outpile time. The outpile time is made up of the shipping time, reprocessing time, fabrication time, and on-site and spent fuel storage times.

It is also of interest to view the breakdown of fuel cost from a relative standpoint; that is, to determine the fraction of the fuel cost contributed by each component (such as fabrication, plutonium credit, plutonium carrying charge, etc.) as a function of the most significant economic variables. Accordingly, we have prepared Figures 7-8 through 7-11.

In Figure 7-8 it is seen that, with increased burnup, the plutonium credit and plutonium carrying charge assume increasing importance. This curve is derived from Figure 7-2, where it is seen that these elements of cost decrease rapidly (as mills/kWh) with burnup. Figure 7-8, which shows the fractional costs as a function of unit fabrication cost, shows the converse of Figure 7-9; as fabrication costs increase (which has the same effect as decreased burnup), the plutonium credit and carrying charge decrease in importance, since the fabrication cost is

an increasing fraction of the total. The fractional importance of plutonium credit and carrying charge when plutonium value is the variable, is shown again in Figure 7-10.

In Figure 7-11 we have plotted the fractional cost components as a function of the fuel pin diameter; although this parameter is not an economic variable, it is one of the most important design parameters in the core. The fabrication cost fraction decreases as unit fabrication cost decreases with increasing pin diameter. The plutonium carrying charge fraction increases with diameter as the core loading increases. The plutonium credit reaches a maximum at about 0.29 inch diameter, due principally to the fact that the breeding ratio is highest at that point (see Figure 3-4).

Figure 7-1. Effect of Burnup, Fabrication, and Plutonium Costs on Fuel Cost

Figure 7-2. Effect of Burnup on Fuel Cost Components

Figure 7-3. Effect of Burnup and Plutonium Value on Fuel Cost

Figure 7-4. Effect of Burnup on Doubling Time

Figure 7-5. Cycle Time + Outpile Time Vs Burnup

Figure 7-6. Effect of Outpile Time on Doubling Time

Figure 7-7. Effect of Outpile Time on Fuel Cost

Figure 7-8. Effect of Burnup on the Relative Importance of Fuel Cost Components

71

Figure 7-9. Effect of Unit Fabrication Cost on the Relative Importance of Fuel Cost Components

Figure 7-10. Effect of Plutonium Value on the Relative Importance of Fuel Cost Components

Figure 7-11. Effect of Pin Diameter on the Relative Importance of Fuel Cost Components

APPENDIX A
NAPS Computer Code

1. General Description

The work described in this report was performed using the NAPS computer code, which was written specifically to perform parametric studies for LMFBR plants of the size and type developed in Babcock & Wilcox's LMFBR Follow-On Program.

Using basic independent design parameters, the code generates variants in the plant design by determining core thermal and hydraulic characteristics, core structural requirements and nuclear performance, heat transport system characteristics and requirements, and overall plant equipment and construction requirements. The code also computes the overall station net generating cost in mills per kilowatt-hour for each design variant by determining the fuel cycle cost, the operation and maintenance cost, and the capital cost. The fuel and plant economics determined by NAPS should be considered reasonable estimates, rather than accurate figures based on detailed design work and cost estimating procedures.

The NAPS code produces meaningful results that satisfy the purposes and objectives of these studies because of the comprehensive integration of core and plant design considerations. The systems, components, and structures are individually costed as a function of design variables, and individual parameters may be varied continuously to produce a series of design variants that are amenable to comparison, analysis, and optimization.

Following is a short description of the flow of events in the NAPS code; report BAW-1326 is a detailed description of the code.⁵

2. Core Dimensions

The independent core design parameters were selected as coolant inlet-outlet temperatures, steam cycle thermodynamic quantities, fuel pin dimensions, core geometry (cylindrical or annular), and fuel thermal limitations. These variables set the core dimensions. The establishment of optimum axial and radial blanket dimensions requires a knowledge of core physics and geometry. However, these dimensions may be satisfactorily estimated by the core designer without benefit of a detailed analysis of the blanket nuclear performance. Most plutonium will be bred in the portion of the blankets adjacent to the core. Therefore,

moderate variations from the optimum blanket dimensions will not alter nuclear performance significantly. For this reason, it has been possible to estimate the required blanket dimensions on the basis of core geometry.

3. Reactor Hydraulics

Coolant flow distribution through the reactor is not only a function of core and power profiles, but also of control rod, thermal shield, and fuel assembly support structure arrangement and design. In addition, the designer may alter the core orificing scheme. The code will establish the primary coolant flow distribution on the basis of these individual factors.

Having found the primary coolant flow distribution, the code can solve for hot channel conditions. The core pressure drop is then determined on the basis of the fuel pin pitch, diameter, overall length, spacer type, and coolant hot channel flow rate. Provisions are included to consider either honeycomb, wire-wrapped, or twisted-ribbon spacers. The required fuel assembly can thickness is then established on the basis of material properties, temperature, dimensions, and core pressure drop.

4. Plant Heat Balance

Primary pumping power requirements are determined as a function of core pressure drop and coolant flow rates. At this point, the system energy balance may not be satisfied, since, initially, the plant efficiency was assumed in sizing the core. The steam turbine heat loads were set by the selection of the steam cycle, but coolant pumping requirements were initially unknown. Therefore, a series of iterations are required to determine the core size that satisfies the plant heat balance.

5. Design of Major Components

The code performs a thermal and mechanical design analysis of a Fermi-type intermediate heat exchanger compatible with the thermodynamic requirements of the selected steam cycle. This program determines the physical dimensions and weights of the tube arrays, including the related structural components and the containment shell.

Design information is included for a once-through steam generator constructed with a bimetallic tube array.⁶ Croloy 2-1/4 tubes, limited to a maximum temperature of 1000 F, are contained in the economizer, the boiler, and the primary superheater sections. A secondary superheat section constructed of SS 316 tubes is included in the steam generator design only if the sodium inlet temperature exceeds 1000 F.

If the selected steam cycle includes reheaters, then the program can determine a total reheat cost based on the thermodynamic requirements. Total turbine island costs are included from detailed studies of applicable steam cycles.⁷

Reactor vessel structural and shielding costs are determined from core dimensional and thermal variations of a typical reactor design. It is recognized that a large degree of freedom is available to the reactor plant designer. New concepts and ideas are continually altering the design approach and plant economics. Consequently, any code that attempts to optimize reactor design based on plant layout is continually being outdated. Recognizing this problem and yet considering the importance of including the full economic perturbations of core design, this approach to component sizing and costing appears to offer the best compromise.

6. Fuel Cycle Costs

The calculational methods used for fuel costs follow those generally used by the utility industry in estimating and evaluation work. The utility is assumed to own the fuel throughout the fuel cycle, both inpile and outpile, crediting the fuel cycle with the value of excess plutonium after reprocessing is completed. The utility is assumed to make progress payments on fuel fabrication and reprocessing on a straight-line basis over the duration of these operations, since it is assumed that these operations are performed by commercial vendors. The utility is also assumed to finance the fuel as working capital throughout the fuel cycle. Fabrication costs are financed by the manufacturer during the fabrication period, while the utility is assumed to pay a carrying charge for the remainder of the fuel cycle.

The code includes a series of multi-dimensional fits of data obtained from other costing studies for estimating fuel fabrication costs. Fuel

pin diameter, active fuel length, axial blanket length, radial blanket pin dimensions, and fabrication plant capacity are used as independent variables to calculate the fuel fabrication cost. Beginning- and end-of-life core and blanket mass balances, together with core lifetime, core thermal power, and net station sendout for each design variant, are used in computing the fuel cycle cost.

REFERENCES

- ¹ Cornfield, G. C., et al., Irradiation Creep of Annular Pelleted Oxide Fuel, United Kingdom Atomic Energy Authority, TRG Memorandum 3394, March 1966.
- ² Gibson, W. R., personal communication, B&W Nuclear Development Center, Lynchburg, Virginia.
- ³ Rabin, S. A., et al., Short-Term Fast Flux EBR-II Irradiation of PuO_2 - UO_2 Fuel Pins, AEC Research & Development Report, GEAP-5570, October 1967.
- ⁴ Trost, R. J., TAMPA — A Computer Program for the Analysis of Reactor Fuel and Clad, Babcock & Wilcox, TP-349, Lynchburg, Virginia, April 1968.
- ⁵ Crane, R. A., et al., Sodium Parameter Study Code NAPS, A Computer Program for Parametric Studies of Sodium-Cooled Fast Breeder Reactor Plants, Babcock & Wilcox, BAW-1326, Lynchburg, Virginia, April 1968.
- ⁶ Sodium-Heated Steam Generator Development, Babcock & Wilcox, BW-67-2, July 1964.
- ⁷ Engineering Study for Large Steam-Electric Generating Plants, United Engineers & Contractors, Inc., ANL-31-109-38-1717, November 1964.