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.

WARD-2000-96

REACTOR TECHNOLOGY (TID-4500)

COST OPTIMIZATION AND PARAMETRIC STUDIES

WESTINGHOUSE 1000-MWe LMFBR

A. H. Redding
M. Dyos
J. D. Mangus

Approved by:

E. F. Beckett
Project Manager

A. H. Redding
Manager, Advanced Planning

Prepared for Argonne National Laboratory
Under Contract No. 31-109-38-2000

WESTINGHOUSE ELECTRIC CORPORATION
Advanced Reactors Division
P. O. Box 158
Madison, Pennsylvania 15663

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

CONTENTS

SUMMARY	1
INTRODUCTION	2
THE OPTIMIZATION PROGRAMS	3
Introduction	3
FABROC and FITFAB Codes.....	4
SFBROPT Optimization Code.....	6
Accuracy.....	6
Shortcomings of the Program.....	8
PLANT OPTIMIZATION.....	9
Summary.....	9
Introduction.....	9
Constraints.....	9
Optimization.....	12
Conclusions.....	16
PARAMETRIC STUDIES.....	18
Introduction.....	18
Results.....	20
Discussion.....	20
Economic Parameters.....	20
Plutonium Costs.....	20
Fabrication Costs.....	20
Technical Parameters.....	21
Sodium Velocity.....	21
Burnup.....	21
Swelling Rate.....	21
Centerline Temperature.....	21
Thermal Conductivity.....	22
Cladding Temperature.....	22
Secondary Parameters.....	22
Steam Pressure and Temperature.....	22
Reactor Bulk Outlet Temperature.....	22
Blanket Thickness.....	24
Dwell Time.....	24
Steam Generator Hot-End Temperature Difference.....	25
IHX Hot-End Temperature Difference.....	25

CONTENTS (CONTINUED)

PLANT COST STUDIES.....	26
Summary.....	26
Introduction.....	26
Results.....	26
Relationship of Plant Cost Studies to Optimization Studies.....	29
Conclusions.....	29
APPENDIX I FABROC AND FITFAB REACTOR CODES.....	36
Introduction.....	36
Algebraic Representation of the Reactor.....	37
The FITFAB Code.....	38
Optimization Studies.....	40
Parametric Analysis.....	40
General Approach.....	40
Comparison of the Parameters Considered with those Requested...	43
Single-Module Reference Design.....	43
Criteria for the Alternate Design.....	43
Physical Description.....	44
Fuel Cycle Costs.....	45
Summary.....	46
Nuclear Characteristics.....	47
APPENDIX II THE SFBROPT OPTIMIZATION CODE.....	48
Summary.....	48
Introduction.....	48
Overall Optimization Code.....	48
Optimization Technique.....	48
Algorithm for Minimizing an Unconstrained Function.....	49
Constraint Problems.....	49
SFBROPT Input.....	51
Independent Variables.....	51
Component Subprograms.....	52
Calculation of Turbine Plant Heat Rate.....	52
Plant Design.....	52
Calculation.....	52
Analysis of Sodium Pumps.....	53
Pump Selection.....	54
Hydraulic Parameter Curves.....	55
Calculation of Pump Power.....	55
Calculation of NPSH.....	55
Calculation of Cover Gas Pressure.....	56
Costing.....	57

CONTENTS (CONTINUED)

Steam Generator	58
Input.....	58
Output.....	58
Packaging.....	58
Heat Transfer.....	60
Subcritical.....	60
Supercritical.....	61
Crossover	62
Costing.....	62
Intermediate Heat Exchanger.....	62
Input.....	62
Output.....	63
Packaging	63
Heat Transfer.....	64
Costing.....	64
Piping	64
Input.....	65
Output.....	65
Analysis.....	65
Costing	66
APPENDIX III DETAILED RESULTS OF PARAMETRIC ANALYSIS (PRINTOUT).....	67
REFERENCES	164

TABLES

Table	Page
1. Independent Variables.....	7
2. Reactor Design Parameters.....	11
3. 1000-MWe Optimization Study.....	13
4. Effects of Reference Plant Constraints on Steam Generator Parameters.....	14
5. Further Reduction in One-Module Core Plant.....	17
6. Parametric Study Variables.....	19
7. 1000-MWe Plant Cost Summary.....	27
8. Accuracy of Plant Cost Results.....	28
9. Estimace of Construction Cost 1000-MWe LMFBR Nuclear Power Plant.....	30-35
10. FITFAB Listing.....	39
11. Parametric Study for Four-Module Design.....	42
12. Parametric Study for Single-Module Design.....	44
13. Reactor Parameters.....	45
14. Physical Description.....	45
15. Components of the Fuel Cycle Cost.....	46
16. Volume Fractions of the Reactor Constituents.....	46

FIGURES

Figure	Title	Page
1	Optimized Reference Plant Design Parameters with Moisture Separation Only	85
2	Reactor Bulk Temperature Rise as a Function of Reactor Bulk Outlet Temperature.....	86
3	Effect of Plutonium Cost on Power Cost for One- and Four-Module Core Plant.....	87
4	Effect of Fabrication Cost on Power Cost for One- and Four-Module Reactor Plant.....	88
5	Effect of Maximum Sodium Velocity on Power Cost for One- and Four-Module Reactor Plant	89
6	Effect of Average Burnup on Power Cost for One- and Four-Module Reactor Plant.....	90
7	Effect of Fuel Swelling Rate on Power Cost for One- and Four-Module Reactor Plant.....	91
8	Effect of Maximum Fuel Centerline Temperature on Power Cost for One- and Four-Module Reactor Plant	92
9	Effect of Fuel Thermal Conductivity on Power Cost for One- and Four-Module Reactor Plant.....	93
10	Effect of Maximum Cladding Temperature on Power Cost for One- and Four-Module Reactor Plant.....	94
11	Effect of Steam Pressure and Temperature on Power Cost for Four-Module Reactor Plant	95
12	Effect of Reactor Bulk Sodium Outlet Temperature on Power Cost, Plant Capital Cost, and Fuel Cycle Cost for One- and Four-Module Reactors with and without Variable Feedwater Temperature	96
13	Steam Generator Temperature vEnthalpy Relations for Various Reactor Bulk Sodium Outlet Temperatures. Four-Module Core, Constant Feedwater Temperature.....	97

FIGURES (CONTINUED)

Figure	Title	Page
14	Steam Generator Temperature ~Enthalpy Relations for Various Reactor Bulk Sodium Outlet Temperature, Single-Module Core, Constant Feedwater Temperature.....	98
15	Steam Generator Temperature ~Enthalpy Relations for Various Reactor Bulk Sodium Outlet Temperatures, Four-Module Core, Variable Feedwater Temperature.....	99
16	Steam Generator Temperature Enthalpy Relations for Various Reactor Bulk Sodium Outlet Temperatures, Single-Module Core, Variable Feedwater Temperature	100
17	System Temperatures vs. Bulk Sodium Outlet Temperature Constant Feedwater Temperature, Single-and Four-Module Cores.....	101
18	System Temperatures vs. Bulk Sodium Outlet Temperature, Vari- able Feedwater Temperature, Four-Module Core.....	102
19	System Temperatures vs. Bulk Sodium Outlet Temperature, Vari- able Feedwater Temperature, Single-Module Core	103
20	Effect of Bulk Reactor Outlet Temperature on Steam Pressure, Four-Module Core Plant	104
21	Effect of Bulk Reactor Outlet Temperature on Component Costs, Four-Module Reactor Plant.....	105
22	Effect of Bulk Reactor Outlet Temperature on Component Costs, One-Module Reactor Plant.....	106
23	Effect of Blanket Thickness on Power Cost, Single-Module Reactor Plant.....	107
24	Effect of Doubling Time Associated with Blanket Thickness on Power Cost for One-Module Reactor Plant.....	108
25	Effect of Fuel Dwell Time on Power Cost for One-and Four- Module Reactor Plant.....	109
26	Effect of Steam Generator Hot-End Temperature Difference Constraint on Power Cost for Four-Module Core Plant.....	110
27	Effect of Intermediate Heat Exchanger Hot End Temperature Difference Constraint on Power Cost for Four-Module Core Plant.....	111

FIGURES (CONTINUED)

Figure	Title	Page
28	Fuel Cycle Cost as a Function of Fuel Rod Diameter.....	112
29	Fuel Rod Diameter as a Function of Fuel Residence Time.....	113
30a	Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Four-Module Core - Reference Case.....	114
30b	Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Four-Module Core - Reference Case.....	115
30c	Sodium Coolant Velocity vs. Bulk Sodium Outlet Tempera- ture with Minimum Fuel Rod Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Four-Module Core - Reference Case.....	116
30d	Reactor Inlet Temperature vs. Bulk Sodium Outlet Tempera- ture at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet- Four-Module Core - Reference Case.....	117
31a	Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Reference Case...	118
31b	Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Reference Case.....	119
31c	Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Reference Case.....	120
31d	Reactor Inlet Temperature vs. Bulk Sodium Outlet Temperature at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Reference Case.....	121

FIGURES (CONTINUED)

Figure	Title	Page
32a	Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - \$5000/Kg Fissile Plutonium.....	122
32b	Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - \$5000/Kg Fissile Plutonium.....	123
32c	Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - \$5000/Kg Fissile Plutonium.....	124
32d	Reactor Inlet Temperature vs. Bulk Sodium Outlet Temperature at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - \$5000/Kg Fissile Plutonium.....	125
33a	Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - \$20,000/Kg Fissile Plutonium.....	126
33b	Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - \$20,000/Kg Fissile Plutonium.....	127
33c	Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module - \$20,000/Kg Fissile Plutonium.....	128
33d	Reactor Inlet Temperature vs. Bulk Sodium Outlet Temperature at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - \$20,000/Kg Fissile Plutonium...	129

FIGURES (CONTINUED)

Figure	Title	Page
34a	Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Thermal Conductivity = 7 Btu/ft-°F-hr.....	130
34b	Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Thermal Conductivity = 7 Btu/ft-°F-hr.....	131
34c	Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Minimum Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Thermal Conductivity = 7 Btu/ft-°F-hr.....	132
34d	Reactor Inlet Temperature vs. Bulk Sodium Outlet Temperature at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Thermal Conductivity = 7 Btu/ft-°F-hr	133
35a	Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with a Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Thermal Conductivity = 12 Btu/ft-°F-hr.....	134
35b	Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Thermal Conductivity = 12 Btu/ft-°F-hr.....	135
35c	Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core Thermal Conductivity = 12 Btu/ft-°F-hr	136
35d	Reactor Inlet Temperature vs. Bulk Sodium Outlet Temperature at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Thermal Conductivity = 12 Btu/ft-°F-hr.....	137

FIGURES (CONTINUED)

Figure	Title	Page
36a	Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module - Fuel Centerline Temperature = 2163°F	138
36b	Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module - Fuel Centerline Temperature = 2163°F	139
36c	Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module - Fuel Centerline Temperature = 2163°F	140
36d	Reactor Inlet Temperature vs. Bulk Sodium Outlet Temperature at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module - Fuel Centerline Temperature = 2163°F	141
37a	Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Fuel Centerline Temperature = 2545°F	142
37b	Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Fuel Centerline Temperature = 2545°F	143
37c	Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Fuel Centerline Temperature = 2545°F	144
37d	Reactor Inlet Temperature vs. Bulk Sodium Outlet Temperature at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Fuel Centerline Temperature = 2545°F	145

FIGURES (CONTINUED)

Figure	Title	Page
38a	Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Cladding Surface Temperature = 1189°F.....	146
38b	Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Cladding Surface Temperature = 1189°F	147
38c	Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Cladding Surface Temperature = 1189°F	148
38d	Reactor Inlet Temperature vs. Bulk Sodium Outlet Temperature at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Cladding Surface Temperature = 1189°F	149
39a	Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Cladding Surface Temperature = 1284°F	150
39b	Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Cladding Surface Temperature = 1284°F	151
39c	Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Cladding Surface Temperature = 1284°F	152
39d	Reactor Inlet Temperature vs. Bulk Sodium Outlet Temperature at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Cladding Surface Temperature = 1284°F	153

FIGURES (CONTINUED)

Figure	Title	Page
40a	Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Burnup = 50,000 MWD/Tonne	154
40b	Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 Ft/Sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Burnup = 50,000 MWD/Tonne	155
40c	Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet - Single-Module Core - Burnup = 50,000 MWD/Tonne	156
41	Cross-Sectional View of Alternate Reactor Concept	157
42	Radial Power Distribution	158
43	Simplified Flow Diagram of Executive Program OPT	159
44	Schematic Showing Components of Plant Model	160
45	Simplified Flow Diagram of Subroutine CALC	161
46	Rankine Cycle	162
47	Triangular Pitch Tube Geometry	163

SUMMARY

LMFBR plants utilizing four-module core and single-module core reactors were optimized with the Westinghouse FABROC code and the SFBROPT optimization code developed under this contract. The results of this optimization coupled with parametric studies indicate a 0.41 mill/kWh lower power cost with the single module (unspoiled positive sodium voiding geometry) as contrasted with a four-module core. The optimization code was found to have considerable flexibility, i.e. it was possible to come up with a single plant using standard temperatures and pressures at marginal penalty to satisfy both single- and four-module core reactors.

Parametric studies were performed subsequent to the optimization studies. They indicated the following (all for a four-module plant, although results were similar for the one-module plant):

1. a 50 % reduction in fabrication cost results in a power cost reduction of 0.32 mill/kWh;
2. a reduction in average burnup from 100 to 50 MWD/kg results in a power cost increase of 0.33 mill/kWh;
3. a 100°F increase in cladding temperature reduces power cost by 0.14 mill/kWh;
4. a steam pressure increase from 1000 to 2400 psia reduces power cost by 0.16 mill/kWh;
5. 850 and 1000°F steam temperatures give power costs only 0.02 mill/kWh above the optimum (between 900 and 950°F); and
6. with a given reactor, a reactor bulk outlet temperature of 972 or 1022°F will give a power cost 0.02 mill/kWh above the optimum.

A detailed account-by-account calculation of plant cost was made. The calculation was for the reference conceptual design described in WARD-97 and was based on later, more complete data than the optimization study. It showed a plant cost of \$173.03 $\pm$ 18%, and with an operating and maintenance cost of 0.40 mill/kWh, it gave a single-module power cost of 4.1 $\pm$ 0.7 mills/kWh.

This study indicates great potential for power cost gain or loss in plant cost (especially in auxiliary systems and reactor heat transport loops) and in fuel cycle cost (particularly fabrication costs and dwell time).

*Designed for substantially zero sodium voiding coefficient of reactivity.

INTRODUCTION

Three subtasks under Task III of the 1000-MWe Follow-on Study are reported here:

1. The Optimization Study--leading to the selection and specification of the reference conceptual design. This subtask also compares four-module cores designed for substantially zero sodium voiding coefficient of reactivity with the much more economical, unspoiled, single-module core. This study is described on Page 3.
2. The Parametric Study--in which a large number of sensitivity studies were made with the optimizing code. This study is described on Page 18.
3. The Plant Cost Study--in which detailed account-by-account-cost estimates were made of the reference conceptual plant described in WARD-97. This study represents a joint United Engineers and Constructors - Westinghouse effort on the reference plant. In this study an assessment was made of how the reference plant was affected by the cost changes which occurred from the time of the inputs, to the optimization code, to the time of the plant cost study. In addition, an effort was made to establish tolerances to the plant cost and power cost results. The plant cost study is described on Page 26.

The optimization code, developed in part to perform Subtasks 1 and 2 above, has developed into a powerful tool for optimizing, performing sensitivity studies, and developing an insight into plant costs and relative development emphasis. It is described on Page 6 and Appendices I and II.

THE OPTIMIZATION PROGRAMS

INTRODUCTION

The optimization program developed as a part of Task III of the 1000-MWe Follow-on Study* was intended to optimize overall power costs in terms of as large a number of significant variables as possible.

Basically, the reactor and plant components are designed on the basis of 17 independent variables which, if they were all fixed, would result in one unique plant with a unique set of components. (The variables must be chosen with care or else a real plant cannot be designed.) Figure 1, which gives many of the principle parameters of the Reference Plant, has the search variables encircled.

The operation of the program is quite simple. Initial values of each of the 17 variables are fed into the computer. (The more skill the operator has in selecting these values, the quicker the computer will come out with the answer.) The computer may be instructed that any number of these variables are to be fixed, i.e. steam pressure and/or temperature, etc. The computer then goes through a complete plant calculation and comes out with the cost of power. If a set of variables that will not give a real plant has been inserted, the code will correct the offending variable. If the offending variable has been fixed, the computer will either stop the calculation or run to its time limit.

After going through the first solution, the computer will change one of the variables a small amount and recalculate the power cost. This same variable is then changed in a logical pattern that depends on the size and sign of the last change in variable and the size and sign of the resulting change in power cost. When succeeding runs are within a specified tolerance, the program goes on to the next variable and repeats. It will go through all the variables several times until the changes are within a prescribed limit. Obviously, the smaller the tolerance, the longer the machine must run.

A large percentage of the normally fixed design parameters (maximum cladding temperature, maximum centerline temperature, steam generator material property versus temperature, costs, etc.) may be arbitrarily changed. The resulting optimizations are useful as sensitivity studies.

Three codes are required to perform the optimization or parametric studies. The first is the Westinghouse-developed FABROC code which is a computational (not an optimizing) code which gives fuel cycle cost as a function of a large number of parameters. In the optimization studies reported here,

*Developed jointly on Westinghouse and AEC funds.

runs are made in which reactor core height, and reactor outlet temperature are systematically varied (other variables such as dwell time and blanket thickness were already optimized in a previous analysis discussed in Appendix I). These results are made into appropriate equations by another code described as FITFAB. These equations are fed into the plant optimization code SFBROPT which performs the overall optimization.

FABROC AND FITFAB CODES

The FABROC code is a sodium-cooled fast breeder reactor economics code. Sufficient quantities are specified at the input so that the code will provide fuel cycle costs for a specific design. The code can be used to provide fuel cycle costs over a range of values of the input variables (e.g. core height). The inputs specified are as follows:

1. Fuel (oxide, carbide etc.)
- ✓ 2. Average burnup (single or range of variables)
- * 3. Core height (single or range of variables)
- ✓ 4. Thermal power (in core)
- ✓ 5. Dwell time (single or range of variables)
- ✓ + 6. Radial blanket thickness (6, 10, and 14 inches)
7. Pitch (square or triangular)
8. Minimum rod spacing (mechanical)
- ✓ 9. Cost of fissile plutonium (\$/kg) (single or range of variables)
- ✓ 10. Thermal conductivity of fuel (computed for oxide)
11. Theoretical density of heavy metal (%)
- * 12. Mixed mean outlet coolant temperature
13. Bond material (Na or He)
- ✓ 14. Maximum fuel centerline temperature
- ✓ 15. Maximum cladding surface temperature
16. Radial form factor
- + 17. Axial blanket thickness
18. Plenum height (computed for non-vented fuel rods)
- ✓ 19. Fuel swelling rate
- ✓ 20. Maximum sodium velocity

The remaining parameters required to specify the design are computed internally. Those quantities marked with * were fed into the SFBROPT code for overall system optimization. Those variables marked with ✓ were varied separately for use in the parametric studies. Those items marked + were varied to arrive at what appeared to be an optimum.

The code calculates and prints out the following quantities :

1. Density of core, axial blanket, and radial blanket pellets
2. Axial form factor
3. Fuel rod pitch
4. Sodium Reynold's number
5. Bond thickness
6. O.D. of fuel rods
7. Core radius
8. Total radius
9. Total height
10. Core volume
11. Total number of rods in core and radial blanket
12. Number of rods per assembly in core and radial blanket
13. Number of assemblies in core and radial blanket
14. Sodium velocity and pressure drop (nozzle to nozzle)
15. Volume fractions in core of fuel, cladding, control, structure and sodium
16. Maximum fuel volume fraction which will give non-positive coefficient of reactivity with sodium voiding of core
17. Maximum fuel volume fraction which will give non-positive coefficient of reactivity with sodium voiding in core and axial blanket
18. Fabrication and assembly costs of core and radial blanket
19. Reprocessing time
20. Mass of core
21. Power density of core
22. Fabrication costs (mill/kWh)
23. Plutonium credit (mill/kWh)
24. Plutonium inventory (mill/kWh)
25. Shipping costs (mill/kWh)
26. Reprocessing costs (mill/kWh)
27. Total fuel cycle cost (mill/kWh)
28. Doubling time
29. Breeding ratio
30. Inlet coolant temperature
31. Avarage power (kW/ft)
32. Maximum power (kW/ft)

A large number of runs were made varying core height and outlet coolant temperature. Based on these, the fuel cycle costs, core temperature rise, and core pressure drop as a function of reactor height and outlet coolant temperature were put into equation form for inclusion in the overall SFBROPT optimization code using the FITFAB code.

Separate equations were prepared for each of the individually varied parameters included in the parametric study.

A comprehensive description of FABROC and FITFAB codes as applied to task III of the 1000-MWe Follow-on Study is contained in Appendix I.

SFBROPT OPTIMIZATION CODE

SFBROPT consists of a plant model which will calculate the cost of electricity given 17 independent variables (Table 1) and an optimization algorithm which will move the 17 independent variables to minimize the cost of electricity. Inputs to the program are starting values for each of the independent variables plus other constants which are not changed by the optimization. Output is a tabulation of the main parameters of the power producing system. The independent variables can be held to specific values or any range of values desired. Provision was also made for restricting many other calculated quantities to specific values or inequality relationships. Thus, there are many problem options that can be run that represent a plant that is constrained in various ways. Operation of the program in the most unconstrained mode gives the general optimum solution. Constraining any quantity away from its optimum value will increase the cost of electricity, but the solution is still an optimum solution within the specified framework. One is not completely free in specifying constraints since it is easily possible to devise a physically impossible situation. If this is the case, SFBROPT will either be rejected by the computer because of a numerical error, or run to the time limit trying to find the solution.

A detailed description of the SFBROPT optimization code is contained in Appendix II.

ACCURACY

Careful reviews of a number of computer runs indicate that the program (as finally debugged) does an accurate job of calculating power cost (based on inputs and assumptions which are also printed out.)

The optimizing program optimizes to a probable error of ± 0.009 mill/kWh. With a lower error setting this accuracy would be greater, but the running time would be considerably lengthened.

Because the program optimized the total power costs, large variations in compensating parameters can and do occur. As an example, in a single-module run at a low cladding temperature (1189°F), one run gave a 3.0930 mills/kWh power cost while an identical run gave 3.0888 mills/kWh -- 0.0042 mill/kWh or 0.136% less; certainly a small difference. However, this second run gave an IHX area 64% larger than the first. This characteristic

Table 1. Independent Variables

1. Reactor outlet temperature ($^{\circ}\text{F}$)
2. Core height (ft)
3. Secondary hot leg temperature ($^{\circ}\text{F}$)
4. Secondary cold leg temperature ($^{\circ}\text{F}$)
5. Steam temperature ($^{\circ}\text{F}$)
6. Feedwater temperature ($^{\circ}\text{F}$)
7. Steam pipe velocity (ft/sec)
8. Mass velocity on secondary side of IHX $\frac{\text{lbm}}{\text{hr-ft}^2}$
9. Mass velocity on primary side of IHX $\frac{\text{lbm}}{\text{hr-ft}^2}$
10. Mass velocity of sodium in SG $\frac{\text{lbm}}{\text{hr-ft}^2}$
11. Mass velocity of water in SG $\frac{\text{lbm}}{\text{hr-ft}^2}$
12. Specific speed of primary pump
13. Specific speed of secondary pump
14. Steam pressure (psig)
15. Primary pipe velocity (ft/sec)
16. Secondary pipe velocity (ft/sec)
17. Electrical output desired (MW)

makes it difficult to get smooth curves of a secondary parameter, since some other parameter is being varied. This can be seen in the curves of pressures and temperatures through the system plotted against reactor bulk outlet temperature (See Figures 18, 19, and 20).

The program does permit fixing as many parameters as we chose (so long as we do not involve restrictions that prohibit a solution). Doing this we are able to determine the cost penalty of errors in design or of conservatism -- or of insufficient conservatism in a given area.

SHORTCOMINGS OF THE PROGRAM

There are a number of improvements which should be incorporated into the overall optimization program. These are:

1. The reactor code at present is not an optimizing code and is not integrated into the overall optimizing program. Because of this (a) we do not involve a sufficient number of reactor search variables in the overall optimization, and (b) a considerable amount of manual work and a large number of FABROC runs must be made and analyzed before the effect of a change in a reactor parameter can be evaluated in terms of the overall power cost. Because of these two factors, future work should make the reactor code into an integral part of the whole optimizing program.
2. The program lacks sufficient data to permit optimization of back pressure, which is currently a constant set at 1-1/2 inches mercury. With the increased use of wet cooling towers, the potential requirement of using dry cooling towers in the 1990s and the peaking of load in the hottest months of the year may require considerably higher back pressures and higher maximum temperatures.
3. The program lacks data to permit optimization of reheat cycles.

PLANT OPTIMIZATION

SUMMARY

The SFBROPT program was utilized to optimize the design of LMFBR plants and reactor for both the four-module basic core (designed for non-positive sodium voiding coefficient) and for a single-module basic core.

It was then possible to put sufficient constraints on these programs so that the same plant was used for both types of cores with only minimum increases in power costs. This included selecting standard steam pressures and temperatures.

The effect of including reactor cores having slightly different core temperature rises and pressure drops was also included with only minimum additional penalties.

The SFBROPT code has proven to be a powerful tool not only for determining the theoretical optimum plant, but for including realistic modifications that are desired.

INTRODUCTION

The objective of the optimization study is to establish an optimum plant, i.e. to have all the pertinent information required to specify the plant and its major components. In the case of this study, this result includes not only pressures and temperatures throughout the plant, but such information as diameter and length of steam generator tubing, etc.

It was also desired to establish whether invoking constraints on the plant parameters that had previously been selected in conjunction with Task II would seriously affect the cost of power; i.e. remove the plant design too far from the optimum plant design.

CONSTRAINTS

The bulk of the Westinghouse 1000-MWe Follow-on Study effort was based upon a four-module reactor core designed so that sodium voiding of one core and associated axial blankets would not result in a large positive coefficient of reactivity. During the course of the study, the advantages from a safety standpoint of this sodium voiding criterion became less clear, while at the same time, the economic advantages of the unspooled single-module core became more apparent. In view of the advantages of the single-module

core, it was fully treated in the plant optimization and parametric studies. To maintain the core ΔT and the nominal design bulk outlet temperature the same (230°F ΔT , 1000°F bulk outlet) for both the single- and four-module plants, the cladding temperature was decreased by approximately 64°F in the single-module plant.

Figure 2 plots reference design points of core bulk ΔT versus core bulk outlet temperature for the 1000-MWe Follow-on-Study plants of AI, GE, B&W, CE, and Westinghouse as presented at the November, 1968 meeting held at Argonne National Laboratory. The considerably lower bulk outlet temperature and temperature rise of the Westinghouse reactor results from (a) the use of four modules, (b) the use of carbide fuel, (c) the use of an unorificed core, and (d) a difference in conservatism. These differences have a substantial effect on the optimization of the plant, particularly in temperatures throughout the plant. Parametric studies described in the next section indicate that a 100°F increase in the cladding temperature (which is equivalent to 100°F higher bulk outlet temperature at the same ΔT) results in an optimum with the following characteristics: 51°F increase in bulk sodium outlet temperature; 74°F increase in reactor temperature rise; and 22°F increase in steam temperature (300-pound pressure) as well as substantial (12%) decreases in steam generator and IHX area. Power costs were also reduced 0.14 mill/kWh. The ΔT versus bulk outlet temperature curve for the Westinghouse four-module core reactor also shown in Figure 2.

As previously noted, the criterion for the four-module reactor was that voiding of the core of one module would not result in a positive coefficient of reactivity. As dwell time increases, fuel rod diameter increases, increasing both the size of the core and the heavy metal volume fraction (for a given power). This in turn makes the sodium voiding coefficient of reactivity more positive. With the four-module reactor, this limited the dwell time to 26.2 months. The next larger number of modules that could be conveniently arranged is seven. With this many modules, going to a more optimum dwell time would not have resulted in lower power costs. The parametric study of the four-module core in which dwell time was varied showed that a considerable slope downward was still evident at 26.2 months.

In the case of the single-module plant, another consideration limited us to 26.2 months. Nuclear data in the FABROC program, which was originally developed for multimodule reactors, was only calculated to 3000-liter cores. The 26.2 month dwell time represented a 4500-liter core. We were unwilling to extrapolate this further for a Reference Plant design. However, in the parametric study, we did so with the indication that the optimum fuel dwell time was 36 months.

The one- and four-module plant design parameters are reported in detail in WARD-97. Table 2 lists some of the more pertinent parameters.

At the time the optimization program was run, the code constrained the feedwater temperature to 475°F. A later improvement of the code which permits feedwater temperature to be optimized was unded in the parametric studies. This difference does not significantly affect the results of the optimization studies.

A constrained back pressure of 1-1/2 inches mercury was used. While having the capability to vary back pressure would give more background (and is essential in any studies involving dry cooling towers) it was not felt to be a serious compromise in the present study. The location of the generating plant will under any circumstances have a major effect on the back pressure. In the South, where loads peak in mid-summer, high back pressures will undoubtedly give a lower capital cost; while in the North, with loads tending to peak in the winter, the optimum back pressure will undoubtedly be lower. Higher sodium bulk outlet temperatures would also be expected to increase the optimum back pressure.

Table 2. Reactor Design Parameters

	<u>One Module</u>	<u>Four Module</u>
Cost of fissile Pu (\$/Kg)	10,000	10,000
Fuel thermal conductivity (Btu/hr-ft-°F)	9.81	9.36
Maximum fuel CL temperature (°F)	2400	2640
Maximum cladding surface temperature (°F)	1236	1300
Average discharge burnup $\times 10^{-3}$ (MWD/T)	100	100
Fuel swelling ratio	0.028	0.024
Maximum allowable coolant velocity (ft/sec)	30	30
Dwell time (months)	26.2	26.2
Radial blanket thickness (in.)	10	11 ^a

^a Average of 11 to 15 in. between modules, 9 in. on exterior

OPTIMIZATION

The fast reactor optimization and parametric study program, SFBROPT, was used to determine the comparisons between plants with six different assumed sets of conditions. These conditions were: a general optimization, i.e., one in which none of the independent variables were held fixed; one using a reference core design in which the reactor inlet temperature is calculated from FABROC data, and with the steam conditions held at 900°F, 2400 psi; and one which used a reference core design with the reactor inlet temperature held at 770°F, and the steam conditions fixed at 900°F, 2400 psi. These three conditions were run for both a one-module and a four-module core design. A tabulation of the more important parameters obtained from this study is shown in Table 3, columns 1 through 6. Columns 7 and 8 represent reference plants capable of using either a one- or four-module core. Column 7 uses a core ΔP calculated by FABROC, column 8 uses a fixed ΔP derived by detailed calculations. Referring to columns 1 and 4, and one- and four-module general optimizations, it is seen that the primary hot leg temperature, T_1 , is optimized at 1018 and 1000°F, respectively.

The use of the general optimum one- or four-module core plants would necessitate a redesign of the cores and of the turbogenerator plant. It is felt that this would not be warranted since no particular new knowledge nor value could be derived. The question then becomes one of the cost penalty associated with using existing core and turbogenerator plant designs.

It is not possible to directly compare the optimum plants with plants using the Task II core design. This is because the optimum plant was calculated using FABROC data and the Task II core design was calculated using more detailed calculations. The principal difference, as it affects the optimization, is in the reactor inlet temperature (745 or 750 compared to 770°F), and nozzle-to-nozzle pressure drop (82 to 87 compared to 93.5 psi). These two effects were studied separately.

Columns 2 and 5, therefore, represent plants incorporating a Task II type core as depicted by FABROC. Comparing the four-module core general optimum to the FABROC reference core, the following is observed:

1. The steam temperature and pressure both decreased, decreasing the efficiency from 41.01 to 40.53. This effect increased the fuel cycle costs from 0.747 to 0.758 mill/kWh.
2. The decrease in the steam temperature effected larger log mean temperature differences across the IHX and steam generator, thereby decreasing their size and costs. However, the primary and secondary pumps increased slightly in cost, due primarily to slight increases in flow rate. The net effect of all these trade-offs was to decrease the plant costs by only 0.001 mill/kWh.

The overall effect of fixing the core and turbine was to increase the power generation costs by only 0.009 mill/kWh.

Table 3. 1000-MWe Optimization Study

Search Variables	Description of Parameters	One - Module Core			Four - Module Core			Reference Plant	
		General Optimum	Reference Core		General Optimum	Reference Core		FABROC Core P	Fixed Core P
			FABROC T ₂	Fixed T ₂		FABROC T ₂	Fixed T ₂		
		1	2	3	4	5	6	7	8
	Run No.	7	47	33	27	32			58
	Fuel Cycle Costs (m/kW-h)	.515	.511	.512	.747	.758	.757	.509(17)	.510(17)
	Capital Costs (m/kW-h)	2.552	2.560	2.562	2.575	2.574	2.582	2.574	2.575
	Total (m/kW-h)	3.067	3.071	3.074	3.322	3.331	3.340	3.083(17)	3.085(17)
	Steam Generators (10 ⁶ \$)	7.527	8.132	7.873	8.608	7.954	8.351	8.216	7.727
	IHX's (10 ⁶ \$)	3.117	3.137	2.993	3.402	3.248	2.748	2.997	3.247
	Primary Pumps (10 ⁶ \$)	2.940	2.544	2.847	2.595	2.644	2.859	2.827	2.869
	Intermediate Pumps (10 ⁶ \$)	1.071	1.102	1.118	1.081	1.123	1.154	1.119	1.170
	Primary Piping (10 ⁶ \$)	1.137	.889	1.003	.941	.943	1.003	1.002	1.001
	Intermediate Piping (10 ⁶ \$)	.545	.651	.679	.595	.581	.693	.672	.712
	Reactor Vessel (10 ⁶ \$)	1.960	1.867	1.843	2.301	2.283	2.271	1.842	1.878
	Capital Investment (\$/kW)	138.5	138.9	139.0	139.7	139.6	140.0	139.6	139.7
	Reactor Output (MWt)	2593	2590	2595	2560	2595	2595	2599	2605
	Net Plant Power (MWe)	1052	1051	1052	1052	1052	1051	1060	1060
	Turbine Plant H.R. (B/kW-h)	8223	8257	8256	8148	8255	8257	8208(9)	8208(9)
	Plant Efficiency (%)	40.57	40.56	40.53	41.09	40.53	40.51	40.77	40.69
H	Reactor Press. Drop (psi)	99.3	82.8	82.8	87.8		87.4	82.8(17)	93.5
	Fuel Assy Height (ft)	8.438	8.4 (7)	8.4 (7)	8.413	8.4 (7)	8.4 (7)	8.4 (7)	8.4 (7)
T1	Primary Hot Leg Temp (°F)	1018	1000 (7)	1000 (7)	1000 (8)	1000 (7)	1000 (7)	1000 (7)	1000 (7)
	Primary Cold Leg Temp (°F)	794	745	770 (7)	750	770 (7)	770 (7)	770 (7)	770 (7)
T3	Inter. Hot Leg Temp (°F)	995	963	966	975	967	950	966 (10)	967
T4	Inter. Cold Leg Temp (°F)	644	631	640	636	639	638	640 (11)	658
T5	Steam Temp (°F)	946	900 (7)	900 (7)	934	900 (7)	900 (7)	900 (7)	900 (7)
P	Steam Press (psig)	2180	2400 (7)	2400 (7)	2495	2400 (7)	2400 (7)	2400 (7)	2400 (7)
T6	Feedwater Temp (°F)	475 (11)	475 (11)	475 (11)	475 (11)	475 (11)	475 (11)	500 (9)	500 (9)
(2)	STEAM GENERATOR								
	Heat Transfer Area (10 ³ ft ²)	53.33	60.83	56.84	65.42	56.68	62.33	61.54	55.62
	Tube Length (ft)	139	146	136	155	131	145	139	139
	Tube O.D. (in.)	.548	.554	.547	.542	.545	.535	.558	.549
	Number of Tubes	2683	2869	2926	3031	3103	2905	2905	2787
WG	Water Mass Velocity (10 ⁶ lb/ft ² -hr)	1.728	1.693	1.705	1.645	1.645	1.680	1.705 (12)	1.863
SC	Sodium Mass Velocity (10 ⁶ lb/ft ² -hr)	.775	.760	.765	.715	.735	.760	.765 (13)	.850
	Water Press Drop (psi)	351	295	287	321	260	395	297	352
	Sodium Press Drop (psi)	17.9	14.1	13.5	15.7	17.8	14.0	13.8	13.9
(2)	IHX								
	Heat Transfer Area (10 ³ ft ²)	43.96	45.37	45.04	51.08	49.22	47.14	45.10	47.69
	Tube Length (ft)	29.5	31.2	33.2	35.3	34.5	29.0	32.4	32.4
	Tube O.D. (in.)	.674	.726	.778	.707	.751	.828	.778	.727
	Number of Tubes	8227	7643	6666	7815	7249	6386	6680	7732
TG	Tube Mass Vel. (10 ⁶ lb/ft ² -hr)	2.675	2.625	2.675	2.625	2.625	2.575	2.675 (14)	2.800
SG	Shell Mass Vel. (10 ⁶ lb/ft ² -hr)	1.363	1.213	1.463	1.225	1.275	1.450	1.462 (15)	1.338
	Tube Press Drop (psi)	19.5	18.1	18.3	21.2	19.2	13.8	18.3	21.3
	Shell Press Drop (psi)	10.4	12.3	12.8	11.5	11.9	12.5	12.8	12.5
SS1	PRIMARY PUMP								
	Power (10 ³ hp)	12.24	9.53	10.63	9.93	10.07	11.06	10.66	11.71
	Specific Speed	3610	3640	3640	3640	3520	3550	3625 (15)	3400
(3)	Shaft Speed (rpm)	695	690	654	702	675	658	652	655
(4)	Cover Gas Press (psia)	49.9	50.0 (6)	50.0 (6)	49.6	48.4	50.0 (6)	49.9	50.0 (6)
	Flow Rate (10 ³ gpm)	153	133	149	135	136	149	149	149
	Head (ft-Na)	319	284	285	293	293	296	285	313
SS2	INTERMEDIATE PUMP								
	Power (10 ³ hp)	3.75	3.22	3.21	3.59	3.96	3.09	3.27	3.68
(3)	Specific Speed	7500 (6)	7470	7500 (6)	7500 (6)	7470	7500 (6)	7500 (7)	7500 (7)
	Shaft Speed (rpm)	1038	864	843	979	989	776	852	867
(5)	Cover Gas Press (psia)	58.7	45.1	43.5	53.9	57.6	40.9	44.6	47.3
	Flow Rate (10 ³ gpm)	94.9	99.9	102	96.8	101	107	102	94.5
	Head (ft-Na)	149	121	119	140	147	109	120	128
V1	PIPING								
	Primary Flow Velocity (ft/sec)	25.4	28.2	27.9	26.9	27.2	27.9	27.9 (7)	28.0 (7)
	Primary Pipe O.D. (in.)	51.8	45.8	48.6	47.1		48.6	48.8	48.6
V2	Inter. Flow Velocity (ft/sec)	35.0 (6)	30.8	30.2	32.7	35.0 (6)	30.8	30.5 (18)	30.5 (7)
	Inter. Pipe O.D. (in.)	34.8	38.0	38.9	36.4		39.3	38.7	39.8
V3	Steam Flow Velocity (ft/sec)	300 (6)	300 (6)	300 (6)	270	270	300 (6)	300 (7)	300 (7)
	Steam Pipe O.D. (in.)	30.5	29.1	29.2	30.8		29.2	29.6	29.7
	Wall Thickness (in.)	3.86	3.86	3.87	4.30		3.87	3.92	3.93

- (1) Minimum Value
 (2) Constrained Between 0.5 and 1.0 in.
 (3) Constrained Between 300 and 1200 RPM
 (4) Constrained to 50 psia Max.
 (5) Constrained to 135 psia Max.
 (6) Maximum Value
 (7) Fixed Value
 (8) Reflects 30 fps Core Velocity Constraint
 (9) Values Corresponding to those from Detailed Heat Balance

- (10) Constrained Between 950 and 966°F. Ref Run No's. 32 and 33
 (11) Constrained Between 638 and 640°F. Ref Run No's. 32 and 33
 (12) Constrained Between 1.680 and 1.705 x 10⁶ lb/ft²-hr.
 (13) Constrained Between .760 and .765 x 10⁶ lb/ft²-hr.
 (14) Constrained Between 2.575 and 2.675 x 10⁶ lb/ft²-hr.
 (15) Constrained Between 1.450 and 1.463 x 10⁶ lb/ft²-hr.
 (16) Constrained Between 3550 and 3640
 (17) Value Corresponding to One Module Core
 (18) Constrained Between 30.2 and 30.8 fps.

The similar comparisons for the one-module core are more difficult inasmuch as the reactor inlet and outlet temperatures also changed. Nevertheless, the following observations can be made:

1. The steam temperature decreased while the pressure increased. In this region, these are opposing influences, and the net effect was to increase the turbine plant heat rate 0.4% (i.e., the effect of decreasing temperature being greater than that of increasing pressure.) However, both the primary and secondary pump power decreased, which, by itself, would improve plant efficiency. The trade-off between increasing heat rate and decreasing pump work was such that the net plant efficiency decreased only 0.01 percentage point. Therefore, the decrease in fuel cycle cost of 0.004 mill/kWh for this combination is due primarily to the decrease in reactor outlet temperature.
2. The capital costs for this combination increased 0.008 mill/kWh. The most significant portion of this increase is associated with an increase in the steam generator costs of \$695,000. This cost increase may be explained as follows:

The heat transfer area and the total number of tubes have increased. The increase in area must be explained by either an increase in total heat transferred, a decrease in the log mean temperature difference, or a decrease in the overall heat transfer coefficient. The quantity of heat transferred was essentially the same, eliminating this possibility. As a result of fixing the hot leg temperature, the temperature difference across the steam generator increased 14°F, however, at the same time, the cold leg temperature difference decreased 15°F. The effect of these changes are shown in Table 4, along with the corresponding overall heat transfer coefficients.

Table 4. Effects of Reference Plant Constraints
On Steam Generator Parameters

Heat Transfer Region	<u>General Optimum</u>		<u>Reference Core</u>	
	T_{LM}	U_o	T_{LM}	U_o
Superheat	111	691	111	684
Film Boiling	170	840	143	869
Nucleate Boiling	98	915	79	875
Economizer	115	771	99	739

As may be seen, the log mean temperature difference decreased in the reference core plant for all but the superheat region. This effect accounts for most of the increased area. However, the overall heat transfer coefficient also decreased for all but the film boiling region. These reductions may be explained by the decreases in both sodium and water mass velocities, which is the result of increasing the number of tubes. Similarly, the number of tubes increased to reduce the pressure drops for the sodium and water. This served to limit the increase in pumping costs brought about by the increased flow rates, which in turn resulted from the lower temperature differences.

As a result of reducing the degrees of freedom by fixing both the reactor conditions and the steam conditions, the one- and four-module reference core designs resemble each other more than do their corresponding general optimums.

Columns 3 and 6 represent approximately the same conditions as those shown in columns 2 and 4 except, in columns 2 and 4 the inlet temperature was calculated by FABROC, and in these runs it was determined from detailed calculations. The purpose of these runs was to determine the effect on the plant of the reactor equation model. In terms of the total capital costs differences, the model gave 0.002 mill/kWh less for a one-module core, and 0.008 mill/kWh less for the four-module core. Both variations are within the accuracy of the code.

Fixing the inlet temperature for both the one- and four-module cores, with many other parameters already fixed, caused dissimilar results. For the one-module core, the steam generator and IHX both decreased in cost while the primary and intermediate pumps both increased. For the four-module core, both the pumps again increased; however, the steam generator increased while the IHX decreased in cost. A similar observation can be seen in the intermediate hot and cold leg temperatures. For the one-module core, both temperatures increased, and for the four-module core they both decreased.

The most reasonable explanation for these differences is probably associated with the sensitivity of the optimization logic. Apparently, the effects of the intermediate loop temperatures, in the vicinity of the optimum value, are a relatively weak function. However, changing these temperatures up or down effects changes in the pumps and heat transfer equipment, generally in opposing, but compensating, directions.

Comparing columns 3 and 6 with each other, they still represent a fair deviation from one another in regard to the plant design details. The actual plant costs, however, differ by only 0.02 mill/kWh.

Column 7 represents the first attempt at combining the results of columns 3 and 6 into a single-plant design capable of operating near optimum with either a one- or four-module core. The principal difference between either columns 3 or 6 and column 7 is in the turbine plant. In columns 1 through 6, the heat rate is calculated in the program. In column 7, the feedwater fixed at 5000°F and the heat rate was input at 8208 Btu/kWh, these values corresponding to those obtained from a detailed

heat balance from the Westinghouse Large Steam Turbine Division. One additional change increased the net output to 1060 MW to more nearly correspond to the heat balance calculations.

The plant costs and plant design parameters fell roughly between the two extremes shown in columns 3 and 6. For example, the capital costs were 2.574 mills/kWh compared to 2.562 mills/kWh for the one-module core and 2.582 mills/kWh for the four-module core.

For this run, only one of the parameters associated with either the turbogenerator plant or the reactor was not fixed to correspond to detailed calculations. That parameter was the nozzle-to-nozzle pressure drop through the reactor. For this and the previous columns the value as calculated by FABROC was used.

Column 8 is identical to column 7 except the pressure drop is held at 93.5 psi. The most significant change was to increase the intermediate cold leg temperature from 640 to 658°F, which caused the steam generator area and cost to decrease with an increase in the IHX area and cost. These changes also increased the primary and intermediate pump powers with a corresponding reduction in efficiency.

The plant described in column 8 is what is proposed for the reference (pseudo-optimized), interchangeable one- and four-module-core plant. The capital costs for this plant are 2.575 mills/kWh which is 0.023 mill/kWh greater than the best optimum (that for a one-module core general optimum), but still small enough to be within the probable accuracy of the cost relations and equal to the four-module core general optimum. The plant efficiency is comparable to the one-module core general optimum and only 1.4% less than the four-module general optimum. In other words, this plant represents a good compromise between the two optimums and uses previously designed reactor cores and turbogenerator plants.

CONCLUSIONS

The use of the optimization code permits a comparison between the power cost of a four-module reactor designed for non-positive sodium voiding reactivity coefficient and a single-module core of optimum economic geometry. The difference in power cost was 0.255 mill/kWh in favor of the single-module plant.

To obtain the same reactor bulk temperature rise and outlet temperature for the one-module plant as for the four-module plant, the cladding and fuel centerline temperature were reduced 64 and 240°F, respectively. Thermal conductivity and swelling were both adjusted for the new fuel centerline temperature. The parametric studies reported on Page give us a mechanism for interpolating the differences in power cost if these four parameters had been unchanged from the four-module case. In addition, we can obtain an indication of further improvements in power costs if the dwell time is increased from 26.2 to 36 months. These results are given in Table 5.

This would give a cost differential between a one- and four-module plant of 0.408 mill/kWh.

Table 5. Further Reduction In One-Module Core Plant

	<u>Mill/Kwh</u>
1. Fuel Swelling	-0.0085
2. Fuel Centerline Temperature	-0.1216
3. Thermal Conductivity	+0.0048
4. Cladding Temperature	-0.0700
5. Dwell Time	<u>-0.0578</u>
Total	-0.1531

The optimization code also permits assessment of the penalty of going to values of pressure and temperature different from those optimized by the code, i.e. standard values or conditions where we instinctively feel we will have greater reliability.

The reference plant selected is believed to be a logical result of going to standard conditions and incorporating the results of detailed calculations into a plant which is suitable for either a single-module or a four-module core reactor. While the increase in power cost over the general optimum (0.018 mill/kWh) is within the code tolerance, we would have expected a 0.019 mill/kWh increase associated with the reduction of reactor ΔT of 20°F (which is the equivalent of a reduction of bulk outlet temperature of 16°F at the same ΔT).

PARAMETRIC STUDIES

INTRODUCTION

The parametric studies as performed are basically sensitivity studies. Such studies guide development efforts to the best and quickest payoffs. The studies presented here, which utilize the technology we believe will be available in the 1980s, were performed with one parameter varied at a time with the program completely optimizing all the other variables to arrive at a minimum power cost. Two additional values of each parameter were used, one higher and one lower than that used in the optimization. These values were selected partly to make sure the expected possible range was covered and partly as a compromise between sufficiently small steps so that linearity would be assured and sufficiently large steps so that the basic inaccuracies of the program would have a minimum effect on the slopes.

Three categories of parameters were considered. These were:

1. Economic parameters including plutonium cost and relative fabrication costs. Relative fabrication costs are those which vary with the maturity of the industry and the scale. (Those that varied with the design, i.e. ratio of cost-to-pin diameter, etc. were not varied.)

Technical parameters: These, to a great extent, will be determined by the laws of nature and technical ingenuity. Because the final values in many cases are still unknown, the effect of missing or overreaching goals is extremely important. These include maximum permissible sodium velocity, maximum burnup, fuel swelling rate, fuel centerline temperature, fuel thermal conductivity, and maximum cladding temperature.

2. Secondary parameters: These have to do with gaining an insight into the plant by varying design parameters over ranges of known satisfactory service. Included are steam pressure and temperature, reactor bulk outlet temperature (the technological basis of the reactor design is kept constant so that, as reactor bulk outlet temperature increases, reactor temperature rise decreases), blanket thickness, dwell time, IHX log mean temperature difference, and steam generator log mean temperature difference.
3. Sixty-six optimization runs were made. These are listed on Table 6. Two control runs (*for one-module and + for four-module) were made. Then 23 additional runs were made with the single-module plant, using in each run only one parameter (listed) different from those * used in the the control run. An additional 42 runs were made for the four-module plant in the same manner with + being the control parameters.

Table 6. Parametric Study Variables

	<u>1 Mod</u>	<u>4 Mod</u>
Cost of fissile plutonium, (\$100/kg)	5-10 [*] -20	5-10 ⁺ -20
Fuel fabrication cost multiplier	.5 - 1.0 [*] - 1.5	.5 - 1.0 ⁺ - 1.5
Maximum allowable coolant velocity (ft/sec)	20 - 30 [*] - 40	20 - 30 ⁺ - 40
Average discharge burnup (1000 MWD/T)	50 - 100 [*] - 150	50 - 100 ⁺ - 150
Fuel swelling rate (V/V per 10,000 MWD/T)	.014-.028 [*] -.056	.012-.024 ⁺ -.048
Fuel $\bar{Q}$ temperature ($^{\circ}$ F)	2136-2400 [*] -2545	2350-2640 ⁺ -2800
Fuel thermal conductivity (Btu/hr-ft- $^{\circ}$ F)	7-9.81 [*] -12	7-9.36 ⁺ -12
Cladding surface ($^{\circ}$ F)	1189-1236 [*] -1284	1250-1300 ⁺ -1350
Steam conditions, Pressure psia/Temp. ($^{\circ}$ F)		3500/850-908-948- 960-990 2400/850-900-930- 942-960-1020 1000/850-900-958- 1000
Bulk reactor outlet Na temperature ($^{\circ}$ F)	950-999 [*] -1050- 1100	900-950, 1011 ⁺ , 1050, 1100
Radial blanket (in.)	6-10 [*] -14	
Dwell time (months)	18-26.2 [*] -36	12-18-26.2 ⁺
Steam generator lmt d ($^{\circ}$ F)		108.2-110.5 ⁺ -119
IHX hot lmt d ($^{\circ}$ F)		55-64 ⁺ -87.5

* All same run - optimum single module plant

+ All same run - optimum four module plant

RESULTS

Results of the 66 runs are tabulated in printout form in Appendix III and are plotted in curve form in Figures 3 through 27.

DISCUSSION

There were no real surprises in the results. The sign of the slopes of power costs as a function of the various parameters were what was expected. In detail, these results were as follows:

ECONOMIC PARAMETERS

PLUTONIUM COSTS: Both four-module and single-module core plants were optimized for minimum power costs with plutonium costs of 5,000, 10,000, and 20,000 \$/kg. Figure 3 shows the results of this analysis. The results are quite linear in the case of the four-module plant, a \$15,000 /kg increase in plutonium cost results in a power cost increase of about 0.12 mill. In the case of the single-module plant, the value of the plutonium bred slightly exceeds the inventory cost of plutonium, so the same increase in plutonium cost is accompanied by a small (0.02 mill) decrease in power cost.

In general, it can be concluded that variations in the cost of plutonium will have a relatively small effect on power costs. The cost of uranium is significant because the power costs of LMFBR's nuclear competitor, the light water reactor, is very sensitive to uranium cost. A reduction in interest rate below the ten percent would tend to make the slopes of these curves more negative, while an increase in interest rate would tend to make them more positive.

FABRICATION COSTS: Both the fuel cycle costs and the power costs are quite sensitive to the fabrication costs, which are shown on Figure 4. Here we have power costs at a standard fabrication cost which is our best estimate of what it will be in the 1980s. Also given are a 50% higher and 50% lower fabrication cost. Both power costs are then extrapolated to zero fabrication cost. The curves for the four-module and single-module reactor plants are substantially parallel with a 50% change in fabrication cost being worth about 0.33 mill/kWh. The fabrication cost equations include the cost of the pellets, cladding, and assembly, and depend on the diameter and a length of the rods, the number of rods in each assembly, and whether the assembly is canned or not. It is an oversimplification to report fabrication costs in terms of a cost per kilogram of heavy metal.

TECHNICAL PARAMETERS

This sensitivity study includes parameters we consider most likely to be changed either upward or downward as the state-of-the-art progresses and more knowledge is obtained. Failure to achieve current goals in some of these parameters can be quite serious, while failure in others will have minor adverse effects. Conversely, exceeding goals in some parameters can have very favorable results, while in other cases the gains are marginal.

SODIUM VELOCITY: We have limited the maximum sodium velocity to 30 ft/sec. As shown in Figure 5, there is a penalty of approximately 0.07 mill with the four-module core in going from 30 to 20 ft/sec maximum velocity. There is, however, no gain in increasing the maximum sodium velocity from 30 to 40 ft/sec. In the case of the single-module core, there is a linear increase in power cost of 0.02 mill/kWh going from 30 to 20 ft/sec and a similar linear decrease of about 0.02 mill/kWh going from 30 to 40 ft/sec.

In summary, the effects of allowable sodium velocity appear to be quite minimal.

BURNUP: The effects of average burnup in MWD/T are shown in Figure 6. As can be seen, the effects on the four-module and single-module plants are substantially the same. In the single-module plant, for instance, there is a reduction of power cost of 0.26 mill, as burnup increases from 50,000 to 100,000 MWD/T. In the model that we use, the sodium bond thickness increases to allow a space for swelling, which is assumed to be proportional to burnup. This reduces the fuel volume ratio and makes the reactor less economical from a nuclear standpoint. A larger swelling rate would undoubtedly reduce the optimum average burnup below the 130,000 MWD/T indicated. A lesser swelling, on the other hand, might increase it. As explained previously, nuclear restraints kept the maximum dwell time at 26 months. Since, in general, higher burnups optimize at higher dwell times, the use of higher dwell times might have indicated a considerable improvement at 150,000 MWD/T.

SWELLING RATE: The effects of swelling rate are shown on Figure 7 for the four-module and single-module core plant in terms of power cost. A doubling of the swelling rate from that presently estimated results in a power cost increase of approximately 0.07 mill/kWh. While significant, it is not serious.

CENTERLINE TEMPERATURE: The effects of centerline temperature are shown on Figure 8. As can be seen, this is not a very significant parameter. A change of 400°F in centerline temperature is worth only about 0.04 mill. This is undoubtedly due to the extremely high conductivity of the carbide fuels and the small gains realized by either higher conductivity or higher centerline temperature.

THERMAL CONDUCTIVITY: Figure 9 shows the effect of thermal conductivity on power cost. A reduction of thermal conductivity of 30% increases power cost by only 0.04 mill.

CLADDING TEMPERATURE: The effects of maximum cladding temperature shown in Figure 10 appear to be substantial. A decrease of 50°F in cladding temperature results in an increase in power cost of 0.09 mill/kWh. At a given reactor temperature rise, the mean bulk outlet temperature is dependent almost in a one-to-one relationship on cladding temperature. In the optimization program, as cladding temperature was changed, the reactor outlet temperature was changed about half as rapidly as the cladding temperature while the reactor ΔT was also changed almost as much as cladding temperature. That is, a 50°F increase in allowable cladding temperature was accompanied by approximately a 25°F increase in outlet temperature and about a 40°F increase in reactor temperature rise. This results in a substantially lower sodium pumping power. It appears that a considerably higher reactor outlet temperature and reactor temperature rise than either our single- or four-module reactor provides would be advantageous from the standpoint of both plant capital cost and plant efficiency.

SECONDARY PARAMETERS

The studies in which secondary parameters were varied, while not of great significance in determining the effects on power cost of failure to achieve or over achieve development goals, does however give insight into the overall plant operation and optimization.

STEAM PRESSURE AND TEMPERATURE: Figure 11 shows for the four-module plant, the effects of steam temperature on power costs with steam pressure parameters at 1000, 2400, and 3500 psi. Going from 1000 to 3500 psi results in power cost improvement of 0.17 mill/kWh, with the optimum steam temperature going from 880 to 960°F. The overall optimum, as can be seen, occurred at 2725 psia pressure and at a 0.01-mill higher power cost than the 3500-psia optimum. This was caused by a slight discontinuity between the subcritical and supercritical programs which prevented the optimization logic from going from subcritical to supercritical pressure if it started in the subcritical regime. When this was discovered, it was decided that the higher pressure optimum did not justify the additional problems of going to a supercritical boiler. The reasonableness of the results of this steam pressure temperature study gives us considerable confidence in the overall results.

REACTOR BULK OUTLET TEMPERATURE: Among the most illuminating of the parametric studies were those in which reactor bulk sodium outlet temperature was varied. The temperature rise across the reactor is a strong function of bulk reactor outlet temperature varying in an almost inverse linear manner from 379°F ΔT at a bulk outlet temperature of 900°F, to 93°F ΔT at a bulk outlet temperature of 1100°F in the four-module core

and 356°F ΔT at 950°F to 74°F ΔT at 1100°F in the one-module case. At 1000°F bulk outlet temperature, these ΔT s were almost identical at 250°F for the two-reactor configurations.

Figure 12 shows fuel cycle cost, plant capital costs, and power costs for the case of one- and four-module cores with 475°F constant feedwater temperature and optimized feedwater temperatures (the result of a later code modification).

Figures 13, 14, 15, and 16 plot temperatures on the water side and the sodium side of the steam generator against water side enthalpy with parameters of sodium bulk outlet temperature. Figure 13 gives the four-module core with constant (475°F) feedwater temperature. Figure 14 gives the one-module core for the constant feedwater temperature. Figure 15 gives the four-module core with variable (optimized) feedwater temperature and Figure 16 gives the single-module core with variable feedwater temperature.

On these curves the start and end of boiling define the steam dome with the reduction in temperature in the boiling region representative of the drop in saturation temperature associated with the drop in pressure. In Figure 13, it can be seen that at 950°F the pinch point is down to about 8°F. In Figure 14 the single-module core which shows a greater ΔT at low temperatures has a pinch point of about the same magnitude and has had to reduce its outlet steam temperature (and enthalpy) considerably to get this high pinch ΔT . If we examine Figure 15 with variable feedwater temperature, we see that at 950° the use of a feedwater temperature of 322° has resulted in an increase in pinch point from 8 to 39°. A 900° run was also possible with about a 10° pinch point and only a 642° steam temperature. In the case of the single-module plant with variable feedwater temperature, we were not able to get a reasonable 900° run. However, at 950° the pinch point was increased from 8 to 25°F and the steam outlet temperature was increased from 785 to 868°F. The only way to operate at lower reactor bulk outlet temperatures without these pinch point limitations would be to arbitrarily derate the reactor (by calling for a lower cladding temperature for instance).

Figures 17, 18, 19 reflect reactor inlet and outlet, IHX inlet and outlet, and steam generator inlet and outlet temperatures as a function of reactor bulk outlet temperatures for the constant and variable feedwater temperature for one- and four-module plants.

Figure 20 gives steam pressure as a function of bulk reactor outlet temperature (variable feedwater temperature) and varies with steam temperature in a reasonable manner.

Figures 21 and 22 plot costs of primary pumps, primary piping, IHX, and steam generator as functions of bulk outlet temperature (variable feedwater temperature) for the one- and four-module plant, respectively.

As can be seen, the big savings in going from the 900 to 950° range to 1000° is in the steam generator and IHX associated with increasing ΔT s and reducing surface area. At temperatures much above 1000°F, the greatly

increased sodium flow in the primary loop (associated with the greatly reduced reactor ΔT) cause substantial increases in the primary pump and piping costs. The increases in cost of the steam generator and IHX at the highest temperature reflect both the increased pipe thickness associated with increased pressures and temperatures and the less favorable geometry associated with trying to keep the pressure drop in those apparatus down in light of the high sodium flows.

BLANKET THICKNESS: The effect of varying blanket thickness between 6 and 14 inches on power cost for a single-module core is given in Figure 23. The blanket thickness was not varied for the four-module core because of the difficulty of assessing the effect of this variable on module dynamic interaction as well as its effect on the sodium voiding reactivity coefficient. The effect of this variable on doubling time is also shown on Figure 24. As the breeding increases greatly at the inner few inches of the blanket, it is expected that elimination of the blanket entirely would result in a substantially higher power cost -- even if the required extra shielding were not considered.

The optimum blanket thickness will depend to a great extent on the interplay among plutonium cost, relative fabrication costs, and the cost of money. Reductions in fabrication cost or interest would tend to increase the optimum blanket thickness. A reduction in plutonium cost would tend to decrease the thickness of the blanket (which would in turn reduce the supply of plutonium and increase the cost of plutonium).

It would have been desirable to run the effect of blanket thickness with several values of plutonium, interest, and fabrication. Without such depth, it is difficult to draw meaningful conclusions. In addition, the relative dwell time of the blanket to that of the core will have some effect on the optimum blanket thickness. This was not studied in depth.

DWELL TIME: The effect of dwell time on power cost for one- and four-module plants is shown on Figure 25. In the case of the four-module plant, the dwell time was not extended beyond 26.2 months because, as dwell time is increased (for the same burnup), both reactor volume and reactor fuel volume fraction increase. This would lead to an excessively high positive sodium voiding coefficient and violate the design restraint for the four-module core. Going to a larger number of modules would have invoked a cost penalty that might have counteracted gains achieved by going to a higher dwell time.

The single-module plant was optimized at 26.2-month dwell time rather than the more favorable 36 months because going beyond the 4500-liter core required by 26.2 months was an unjustified stretching of our nuclear data (which had already been extrapolated from a 3000-liter core). In view of the relatively larger fuel pins that others use (compared to our 0.30-inch pin at 26.2 months) we would expect that a 36-month dwell time would be better than 26.2 months. This is indicated on Figure 25.

STEAM GENERATOR HOT-END TEMPERATURE DIFFERENCE: The program was run with hot-end temperature differences of 22 and 58°F as well as three "optimum" runs which gave 39, 40, and 44°F. As shown in Figure 26, the effect on power cost was minor and well within the program tolerance. These results are plotted against the hot-end temperature difference (which is the way the calculation was treated) rather than against log mean temperature difference. The reason for this is that the logic would not necessarily give the same results as would programming to a specific LMTD. This becomes academic in the present case.

IHX HOT-END TEMPERATURE DIFFERENCE: Again the program was run with hot-end temperature fixed (at 17 and 33°F as well as optimized at 19, 22, and 24°F.) The results plotted against IHX hot-end temperature difference on Figure 27 show, as might have been expected, a rather small effect in the range chosen. The rather small effect of hot-end temperature difference in both the steam generator and the IHX seems to bear out the findings of others.

PLANT COST STUDIES

SUMMARY

A detailed cost analysis of the 1000-MWe Follow-on Study LMFBR plant summarized on Table 7 indicates a cost of \$173/kWe $\pm$ 18%. This study was the result of a joint effort by United Engineers and Constructors and the Westinghouse Electric Corporation. A description of the conceptual design used in this cost estimate is reported in WARD-97.

This plant cost coupled with a single-module core fuel cycle cost of 0.519 mill/kWh and an estimated operating and maintenance cost of 0.40 mill/kWh gives an overall power cost of 4.109 mill/kWh with a probable range of 3.4 to 4.8 mills/kWh.

A detailed analysis of the cost elements that make up this study and those that make up the optimization program used in the optimization and parametric studies indicate that, although the basic plant cost resulting from the optimization study was \$139.6/kWe, this difference should have little or no effect on the design parameters of the optimum plant.

INTRODUCTION

The plant cost study reported in this section is the result of a combined effort by United Engineers and Constructors and Westinghouse.

At the initiation of our subcontract to United Engineers, we jointly delineated the responsibility for estimating material and labor on each item on the detail account summary contained on Table 8. In general, United Engineers estimated all labor costs and material costs of structures and improvements (account #21), Accessory Electric Equipment (account #24), Miscellaneous Power Plant Equipment (account #25), as well as all of the piping and some of the systems in the Reactor Plant Equipment (account #22) and Turbine-Generator Units (account #23) accounts. This estimate covers the Westinghouse 1000-MWe Follow-on Study reference plant which is described in some detail in WARD-97. Costs applicable to mid-1968 have been used.

RESULTS

The results of the plant cost study are summarized by major account number in Table 7 and are given in detail in Table 9.

Table 7. 1000-MWe Plant Cost Summary

<u>Account Number</u>		<u>Cost \$1000</u>		
		<u>Material</u>	<u>Labor</u>	<u>Total</u>
20	Land & Land Rights	360		360
21	Structures & Improvements	9,800	9,760	19,560
22	Reactor Plant Equipment	55,801	12,089	67,890
23	Turbine Generator Unit	31,032	3,280	34,120
24	Accessory Electric Equipment	3,660	1,860	5,520
25	Miscellaneous Power Plant Equipment	<u>1,260</u>	<u>280</u>	<u>1,540</u>
		101,913	27,269	129,182
			$\times .4 =$	<u>51.673</u>
				180,855
			$\div 1045.2 \text{ MW} = \$173.03/\text{kW}$	
Capital Cost	3.190	Mill/kWh		
Fuel Cycle Cost	0.519	Mill/kWh		
O & M	<u>0.400</u>	Mill/kWh		
Power Cost	4.109	Mill/kWh		

It is obvious that the estimates of the cost of an LMFBR plant can not at this time have the same accuracy as similar estimates of a conventional plant. However, there are elements of this plant that are very similar to a conventional plant. To take advantage of this fact, the plant has been broken down cost-wise into three elements, the turbine plant, the reactor plant and the auxiliary systems.

The turbine plant includes account numbers 23 and 24; "Turbine Generator Unit" and "Accessory Electric Equipment." It also contains that part of account #21 "Structures and Improvements" and account #25 "Miscellaneous Plant Equipment" that can be attributed to the turbine plant, either directly or in a prorated manner.

The reactor plant includes those parts of account #22 "Reactor Plant" and #21 "Structures and Improvements" and the associated prorated part of account #25 "Miscellaneous Plant Equipment" that are associated with the production of steam on a minute-by-minute basis.

The auxiliary systems are that part of accounts #21 "Structures and Improvements", #22 "Reactor Plant" and #25 "Miscellaneous Plant Equipment" that are

associated with keeping the plant in operation over the long term. These include:

1. Sodium Service System
2. NaK Service System
3. Auxiliary Cooling System
4. Cover Gas System (Argon)
5. Compartment Inerting System (Nitrogen)
6. Hot Cell Environmental System
7. Refueling System
8. Radioactive Maintenance System
9. Engineered Safeguards
10. Reactor Containment

It is possible to estimate costs in the first category, "Turbine Plant", with a high degree of accuracy, say within 5 to 10% not including escalation. In the second category, "Reactor Plant," while a large effort has been expended in the present study, there are many new items. Therefore, we would expect our accuracy of estimateing to be in the 20 to 30% range. In the last category, "Auxiliary Systems," which make up 25.8% of the whole cost, the accuracy is poorest. This is partly because of the large number of small items that must be considered and because we have not yet given them the same attention that we have to the reactor plant components. Because of this, we would expect an accuracy in the 30 to 50% error range. If we assume the worst in each case, we can project the results shown in Table 8.

Table 8. Accuracy of Plant Cost Results

<u>Category</u>	<u>\$/Kw</u>	<u>Estimated Accuracy</u>	<u>Range of Costs \$/Kw</u>
Turbine Plant	61.60	$\pm 10\%$	55.44 to 67.76
Reactor Plant	66.79	$\pm 30\%$	46.75 to 86.83
Auxiliary Systems	44.64	$\pm 50\%$	22.32 to 66.96

If we take the square root of the sum of the squares of the errors, then we get an error of $\pm \$30.62/\text{kW}$ on a range of cost for \$142.41 to \$203.65/kW, or $\pm 17.7\%$. While this may appear to be a rather poor accuracy, past experience indicates that at this stage in development it is probably as realistic as can be developed.

RELATIONSHIP OF PLANT COST STUDIES TO OPTIMIZATION STUDIES

The development of the code used in the "Plant Optimization Study" and the "Parametric Studies" was initiated over two years ago, while the cost analysis of the reference 1000-MW conceptual design is of very recent origin. It is not surprising therefore that there is a substantial difference in plant cost \$139.6/kW for the optimization program and \$173/kW for the detailed cost analysis. These differences may be attributed to both the substantial increase in construction costs over the past two years and the fact that the detailed study included many small items that were left out of the optimization study.

The optimization study was in general comprised of two sets of costs. The first were primarily reactor plant and turbine plant components whose costs were related intimately with the various cycle and component parameters. These items were calculated in some detail in the optimization program and their costs were also calculated in detail. The second sets of costs were those which could not be very clearly tied in with the basic plant parameters. These costs in general were held to be proportional to the 0.6 power of the thermal power. In the optimization study the items in the first category amounted to 48.9% of the total while in the detailed cost analysis reported here this same group amounted to 49.0% of the costs. In this group the turbine plant items were 25.4% of the total plant in the optimization study and 27.3% of the total plant in the detail cost analysis. From these relatively small percentage changes, it would appear that the substantial change in total plant cost which occurred between the optimization study and the detail cost analysis reported here would have little effect on the optimum plant parameters.

CONCLUSIONS

While the detailed results of this cost study are quite revealing, we must be careful not to rely on absolute costs developed today to predict the state of technology 15 years from now.

It would appear that the 36% of the cost represented by the turbine plant is not going to change much. The major areas of gain are probably in the various auxiliary systems which account for about 20% of the cost. The fluid system, which accomplishes the transformation from reactor sodium to turbine steam, amounts to about 24% of the total plant cost; while considerable work has been done in this area, there is still considerable potential.

We can predict with a high degree of certainty that the cost of power in the mid-80s from LMFBR carbide-fueled plants will fall in the range of 3.4 to 4.8 mills/kWh. Unfortunately, this is too wide a range to be used directly for major decisions.

Table 9. Estimate of Construction Cost

1000-MWe LMFBR Nuclear Power Plant

<u>Account Number</u>	<u>Description</u>	<u>Materials and Equipment</u>	<u>Labor</u>	<u>Total</u>
<u>NUCLEAR PRODUCTION PLANT</u>				
20	<u>LAND AND LAND RIGHTS</u>			
	<u>Land and Privilege Acquisition</u>			
	Purchase cost of land	\$ 360,000	\$ -	\$ 360,000
	Total Cost - Account No. 20 Land and Land Rights -	360,000	-	360,000
21	<u>STRUCTURES AND IMPROVEMENTS</u>			
211	<u>Ground Improvements</u>			
211.1 & .2	<u>General Yard Improvements</u> Clearing and rough grading site, roads and parking lots, fencing, landscaping, storm drainage, sanitary sewers, potable water on site, yard fire protection, outdoor lighting	260,000	340,000	600,000
211.3	<u>Railroads</u> On-site and off-site railroad tracks	285,000	100,000	385,000
211.4	<u>Waterfront Improvements</u> Barge unloading dock and shore protection	40,000	35,000	75,000
		585,000	475,000	1,060,000
	<u>Turbine-Generator Building, Control Room and Auxiliary Switchgear and Change House</u>			
212.A1	Excavation and backfill	50,000	100,000	150,000
212.A3	Substructure	375,000	325,000	700,000
212.A4	Superstructure	1,590,000	1,500,000	3,090,000
212.A6	Building services	350,000	250,000	600,000
		2,365,000	2,175,000	4,540,000
21	<u>FUEL SERVICE BUILDING</u>			
212.B1	Excavation and backfill	15,000	10,000	25,000
212.B3	Substructure	115,000	160,000	275,000
212.B4	Superstructure	195,000	250,000	445,000
212.B6	Building services	40,000	25,000	65,000
		365,000	445,000	810,000
	<u>Auxiliary Building</u>			
212.C1	Excavation and backfill	2,000	1,000	3,000
212.C3	Substructure	28,000	31,000	59,000
212.C4	Superstructure	158,000	210,000	368,000
212.C6	Building services	25,000	15,000	40,000
		213,000	257,000	470,000

<u>Account Number</u>	<u>Description</u>	<u>Materials and Equipment</u>	<u>Labor</u>	<u>Total</u>
<u>NUCLEAR PRODUCTION PLANT (Cont'd)</u>				
<u>STRUCTURES AND IMPROVEMENTS</u>				
<u>Steam Generator Building</u>				
212.D1	Excavation and backfill	\$ 120,000	\$ 90,000	\$ 210,000
212.D3	Substructure	260,000	370,000	630,000
212.D4	Superstructure	540,000	400,000	940,000
212.D6	Building services	70,000	30,000	100,000
		<u>990,000</u>	<u>890,000</u>	<u>1,880,000</u>
<u>Secondary Sodium and Sodium Potassium Tanks Building</u>				
212.E1	Excavation and backfill	2,000	2,000	4,000
212.E3	Substructure	27,000	41,000	68,000
212.E4	Superstructure	100,000	162,000	262,000
212.E6	Building services	8,000	8,000	16,000
		<u>137,000</u>	<u>213,000</u>	<u>350,000</u>
<u>Ventilation Building</u>				
212.F3	Substructure	5,000	4,000	9,000
212.F4	Superstructure	17,000	9,000	26,000
212.F6	Building services	2,000	3,000	5,000
		<u>24,000</u>	<u>16,000</u>	<u>40,000</u>
<u>Maintenance Cell</u>				
212.G1	Excavation and backfill	60,000	40,000	100,000
212.G3	Substructure	238,000	294,000	532,000
212.G4	Superstructure	-	-	-
212.G6	Building services	10,000	8,000	18,000
		<u>308,000</u>	<u>342,000</u>	<u>650,000</u>
<u>Primary Sodium Storage Vault</u>				
212.H1	Excavation and backfill	50,000	40,000	90,000
212.H3	Substructure	227,000	300,000	527,000
212.H4	Superstructure	-	-	-
212.H6	Building services	4,000	9,000	13,000
		<u>281,000</u>	<u>349,000</u>	<u>630,000</u>
<u>Containment Cooling System Building</u>				
212.I1	Excavation and backfill	1,000	1,000	2,000
212.I3	Substructure	16,000	15,000	31,000
212.I4	Superstructure	50,000	27,000	77,000
212.I6	Building services	20,000	10,000	30,000
		<u>87,000</u>	<u>53,000</u>	<u>140,000</u>
<u>Plumbing Equipment Building</u>				
212.J1	Excavation and backfill	9,000	7,000	16,000
212.J3	Substructure	26,000	32,000	58,000
212.J4	Superstructure	-	-	-
212.J6	Building services	3,000	3,000	6,000
		<u>38,000</u>	<u>42,000</u>	<u>80,000</u>
212.K	Service and Office Building	<u>300,000</u>	<u>300,000</u>	<u>600,000</u>
212.L	Warehouse and Garage Building	<u>35,000</u>	<u>25,000</u>	<u>60,000</u>
212.M	Guard House	<u>11,000</u>	<u>9,000</u>	<u>20,000</u>

<u>Account Number</u>	<u>Description</u>	<u>Materials and Equipment</u>	<u>Labor</u>	<u>Total</u>
<u>NUCLEAR PRODUCTION PLANT (Cont'd)</u>				
<u>STRUCTURES AND IMPROVEMENTS</u>				
	<u>Exhaust Vent Structure</u>			
212.N1	Excavation and backfill	\$ 3,000	\$ 2,000	\$ 5,000
212.N2	Concrete foundation	25,000	20,000	45,000
212.N5	Vent stack	80,000	100,000	180,000
		<u>108,000</u>	<u>122,000</u>	<u>230,000</u>
	<u>Containment Building</u>			
219.1	Excavation and backfill	330,000	205,000	535,000
219.3	Substructure	1,195,000	930,000	2,125,000
219.4	Superstructure	2,400,000	2,885,000	5,285,000
219.6	Building Services	28,000	27,000	55,000
		<u>3,953,000</u>	<u>4,047,000</u>	<u>8,000,000</u>
	Total Cost - Account No. 21 Structures and Improvements	<u>9,800,000</u>	<u>9,760,000</u>	<u>19,560,000</u>
22	<u>REACTOR PLANT EQUIPMENT</u>			
221	<u>Reactor Equipment</u>			
221.1	Reactor Vessel			
221.11	Vessel Support	65,000	45,000	110,000
221.12	Vessel and Shield Plug	2,230,000	250,000	2,480,000
221.13	Vessel Internals	2,020,000	200,000	2,330,000
221.2	<u>Reactor Controls</u>	2,285,000	45,000	2,330,000
221.3	<u>Reactor Shielding</u>	510	490	1,000,000
221.4	Auxiliary Thermal Systems (NaK)	1,199,000	387,000	1,586,000
	(Na)	2,094,000	356,000	2,450,000
221.6	<u>Reactor Plant Gas System</u>			
221.61	Cover Gas System (Argon)	2,733,000	1,092,000	3,865,000
221.63	Compartment Inerting System	1,386,000	546,000	1,932,000
221.7	<u>Reactor Plant Cranes and Hoists</u>	1,250,000	200,000	1,450,000
221.8	<u>Hot Cell Environmental System</u>	1,000,000	500,000	1,500,000
222	<u>Heat Transfer Systems</u>			
222.1	<u>Reactor Coolant System</u>			
	Supports, casings, inlets and insulation	430,000	150,000	580,000
222.11	Pumps and Drives	3,036,000	64,000	3,100,000
222.12	Piping and Valves	930,000	870,000	1,800,000
222.2	<u>Intermediate Coolant System</u>			
	Supports and ties and insulation	231,000	89,000	320,000

<u>Account Number</u>	<u>Description</u>	<u>Materials and Equipment</u>	<u>Labor</u>	<u>Total</u>
222.21	Pumps and Drives	\$ 915,000	\$ 46,000	\$ 961,000
222.22	Piping and Valves	720,000	880,000	1,600,000
222.23	Intermediate Heat Exchangers	3,255,000	82,000	3,337,000
222.3	<u>Steam Generators</u>	7,860,000	147,000	8,007,000
222.4	<u>Reactor Coolant Receiving Supply and Treatment System (Including intermediate system)</u>	4,267,000	878,000	5,145,000
223	<u>Nuclear Fuel Handling and Storage Equipment</u>	5,740,000	1,060,000	6,800,000
225	<u>Radioactive Waste Treatment and Disposal</u>			
225.1	<u>Liquid Waste</u>	300,000	200,000	500,000
225.2	<u>Gaseous Waste</u>	300,000	200,000	500,000
225.3	<u>Solid Wastes</u>	25,000	5,000	30,000
226	<u>Instrumentation and Control</u>			
226.1	<u>Reactor Plant I&C</u>	2,400,000	160,000	2,560,000
226.5	<u>Radiation Monitoring</u>	100,000	40,000	140,000
226.7	<u>I&C Wiring and Tubing</u>	200,000	500,000	700,000
227	<u>Feedwater Supply and Treatment</u>			
227.1	<u>Raw Water Supply System</u>	50,000	50,000	100,000
227.2	<u>Make-up Water Supply</u>	429,000	131,000	560,000
227.3	<u>Steam Generator Feedwater Purifica- tion and Treatment Systems</u>	517,000	163,000	680,000
227.4	Feedwater Heaters	1,685,000	40,000	1,725,000
227.5	Feedwater Pumps and Drives	1,860,000	95,000	1,955,000
228	<u>Steam, Condensate and Feedwater Piping</u>	2,200,000	1,800,000	4,000,000
229	<u>Maintenance Equipment</u>	<u>1,539,000</u>	<u>328,000</u>	<u>1,867,000</u>
	Total Cost - Account No. 22 Reactor Plant Equipment			\$67,890,000

<u>Account Number</u>	<u>Description</u>	<u>Materials and Equipment</u>	<u>Labor</u>	<u>Total</u>
23	<u>TURBINE-GENERATOR UNITS</u>			
231	<u>Turbine-Generators</u>			
231.1	<u>Foundation</u>	\$ 325,000	\$ 325,000	\$ 650,000
231.2	<u>Turbine-Generators</u>	25,780,000	1,007,000	26,787,000
232	<u>Circulating Water System</u>			
232.1	<u>Pumping & Regulating Equipment</u>	471,000	249,000	720,000
232.2	<u>Circulating Water Lines</u>	728,000	592,000	1,320,000
232.3	<u>Intake and Discharge Structures</u>	702,000	458,000	1,160,000
232.4	<u>Fouling, Corrosion Control and Water Treatment System</u>	37,000	13,000	50,000
233	<u>Condensers</u>	2,465,000	360,000	2,825,000
234	<u>Central Lubrication System</u>	45,000	15,000	60,000
235	<u>Turbine Plant Boards, Instruments and Controls</u>	350,000	150,000	500,000
236	<u>Turbine Plant Piping</u>	50,000	50,000	100,000
237	<u>Auxiliary Equipment for Generators</u>	49,000	31,000	80,000
238	<u>Other Turbine Plant Equipment</u>	30,000	30,000	60,000
	Total Cost - Account No. 23 Turbine-Generator Units	31,032	3,280	34,312,000
24	<u>ACCESSORY ELECTRICAL EQUIPMENT</u>			
241	<u>Switchgear</u>			
241.1	<u>Generator Main and Neutral Circuits</u>	35,000	15,000	50,000
241.2	<u>Station Service</u>	730,000	70,000	800,000
242	<u>Switchboards</u>			
242.1	<u>Main Control Boards</u>			
242.2	<u>Auxiliary Power, Battery & Signal Boards</u>	22,000	8,000	30,000
242.3	<u>Motor Control Centers</u>	175,000	25,000	200,000
243	<u>Protective Equipment</u>	90,000	30,000	120,000
244	<u>Electrical Structures</u>	250,000	350,000	600,000
245	<u>Conduit</u>	150,000	250,000	400,000

<u>Account Number</u>	<u>Description</u>	<u>Materials and Equipment</u>	<u>Labor</u>	<u>Total</u>
246	<u>Power and Control Wiring</u>	\$1,275,000	\$ 925,000	\$2,200,000
247	<u>Station Service Equipment</u>	933,000	187,000	1,120,000
	Total Cost-Account No. 24 Accessory Electrical Equipment	3,660,000	1,860,000	5,520,000
25	<u>MISCELLANEOUS POWER PLANT EQUIPMENT</u>			
251	Cranes and Hoisting Equipment	277,000	33,000	310,000
252	<u>Compressed Air and Vacuum Cleaning Systems</u>	110,000	90,000	200,000
253	<u>Other Power Plant Equipment</u>	573,000	77,000	650,000
253.5	<u>Auxiliary Steam Generating Equipment</u>	300,000	80,000	380,000
	Total Cost-Account No. 25 Miscellaneous Power Plant Equipment	1,260,000	280,000	1,540,000
	Total Plant Direct Cost			\$129,182,000
	Indirect Costs		x 0.4	<u>51,673,000</u>
	Total Plant Costs			\$180,855,000
				÷ 1,045,200 KW = \$173.03/KW

APPENDIX I

FABROC AND FITFAB REACTOR CODES

INTRODUCTION

The development of computer codes to study the overall optimization of the 1000-MWe four-module and alternate LMFBR designs is being performed along two parallel paths. The development of a plant optimization code is being carried out under the AEC 1000-MWe Follow-on Study. The representation of the reactor and the development of methods, which will yield consistent designs and associated fuel cycle costs, have been carried out under a privately funded Westinghouse contract. The purpose of this report is to give details of how the reactor is represented in the plant optimization code.

Optimization of the reactor design can be made with the FABROC code which has been developed entirely with Westinghouse funding. This code has been used extensively to provide information by which the salient interface points between the reactor and the plant can be connected, and to yield fuel cycle costs in terms of the interface parameters. The FABROC code will obtain reactor designs which satisfy all the specified design constraints and then obtain fuel cycle costs. These fuel cycle costs include contributions from fuel rod fabrication and assembly, nuclear depletion and accretion, spent fuel shipping and reprocessing, together with the associated inventory charges. All costs are corrected to give their present worth values at the middle of the equilibrium fuel cycle. The nuclear depletion and accretion data in the FABROC code are handled through the use of equations which have been fit to a wide range of one-dimensional depletion analyses.

The FABROC code ensures that the mechanical design of the fuel assembly is acceptable. The present version of FABROC will yield the core height for the minimum fuel cycle cost or the fuel cycle cost as a function of the core height. The equations given in this report are for reactor cores that do not necessarily have an integral number of fuel assemblies. Slight changes to the fuel cycle cost will have to be made once the plant optimization is completed to accommodate the requirement of an integral number of fuel assemblies.

ALGEBRAIC REPRESENTATION OF THE REACTOR

The important interface points between the reactor and the plant are:

1. Nozzle outlet coolant temperature
2. Nozzle inlet coolant temperature
3. Nozzle-to-nozzle pressure drop
4. Reactor dimensions

It was found that a reasonable manner in which these interface parameters could be expressed was to treat them as functions of reactor outlet coolant temperature (T_o) and reactor height (H).

The nozzle outlet coolant temperature is given by:

$$T_o^N = (1 - B)T_o + B T_{in} \quad (1)$$

where T_o and T_{in} are the mixed mean outlet coolant temperature from the reactor and the nozzle inlet coolant temperature, respectively, and B is the bypass flow fraction. It has been assumed that the nozzle inlet coolant temperature and the reactor inlet coolant temperature are equal.

The nozzle-to-nozzle pressure drop is given by:

$$\Delta P = g(T_o^N, H) + \left(\frac{V}{V_o}\right)^2 P_o \quad (2)$$

where $g(T_o^N, H)$ is a function to be determined and P_o is the nozzle-to-nozzle pressure drop external to the reactor at some velocity V_o . V is the average coolant velocity associated with the given T_o and H .

The inlet coolant temperature required in Equation (1) is given by:

$$T_{in} = f(T_o^N, H) \quad (3)$$

The overall reactor height is given by:

$$H = H_C + H_{LB} + H_{UB} + H_P \quad (4)$$

where H_C = reactor core height

H_{LB} = lower blanket thickness

H_{UB} = upper blanket thickness

H_P = fuel rod plenum length

The overall reactor diameter is given by:

$$D_{total} = h(H) + K$$

where K is a constant obtained from the thickness of the radial blanket and reflector. $h(H)$ is a fraction to be determined.

The fuel cycle cost is expressed in mills/kWth since an overall plant efficiency can only be obtained when the reactor data are used in conjunction with a plant optimization code.

The fuel cycle cost can be expressed as a function of T_o^N and H:

$$F_{cc} = C(T_o^N, H) \quad (6)$$

The problem now remains to obtain the functions $g(T_o^N, H)$: $f(T_o^N, H)$: $h(H)$; and $C(T_o^N, H)$. The generation of these functions is described in the next section of this report.

THE FITFAB CODE

In order to obtain a parametric fit to obtain equations of the form (1) through (6) for both the optimization and the parametric studies, calculations were made with the FABROC code for core heights of 3, 4, and 5 feet and for nozzle outlet coolant temperatures in the range of 900 to 1130°F. Two equations were found to be the most accurate representation for the pressure drop and fuel cycle cost, while one equation was sufficient to represent the inlet coolant temperature. These equations are generated by the FITFAB code.

The first equation is a quadratic of the form:

$$f(x,y) = a_1x^2y^2 + a_2x^2y + a_3xy^2 + a_4xy + a_5x^2 + a_6y^2 + a_7x + a_8y + a_9 \quad (7)$$

which fits data from FABROC in which the constant minimum mechanical fuel rod spacing is used and the sodium coolant velocity is less than the maximum of 30 ft/sec. The second equation is linear and of the form:

$$f(x,y) = a_1xy + a_2x + a_3y + a_4 \quad (8)$$

which fits data from FABROC in which the sodium coolant velocity is 30 ft/sec. These two equations are then used to describe the pressure drop and the fuel cycle cost. The equation for the inlet coolant temperature is a single function of the form of Equation (7). The equation for the overall reactor diameter is given as a quadric in terms of the core height only.

The coefficients for these equations are obtained by solving series of simultaneous equations, which are obtained from the output of the FABROC code. The fitting was carried out by the FITFAB code. Table 10 lists the version of the code that fits Equation (7) for the four-module reference design.

Table 10. FITFAB Listing

```

PROGRAM FITFAB (INPUT,OUTPUT,PUNCH)
DIMENSION TOUT(9),CORHT(9),DELTAP(9),COST(9),VELOC(9),X(9,12)
DIMENSION TITLE(7),TIN(9)
000003 2 FORMAT (4(2X,E13.6)/2X,E13.6,17X,F13.6)
000003 3 FORMAT (1H0.5(E13.6,5X))
000003 4 FORMAT (*0CORRECTED INPUT DATA//1H0,3X*VELOCITY*12X*TOUT*9X*PRESS
000003 1URE DROP*6X*CORE HEIGHT*11X*COST*)
000003 5 FORMAT (1H0* DETERMINANT EQUALS ZERO--PROGRAM IS TERMINATED*)
000003 6 FORMAT (7A10)
000003 7 FORMAT (11H0FCCOST = (.E13.6,13H)*H*H*T*T + (.F13.6,11H)*H*H*T + (
000003 1,E13.6, 7H)*H*T*T / 4H + (.F13.6, 9H)*H*H + (.F13.6,9H)*T*T + (.F1
000003 23.6,9H)*H*T + (.E13.6,3H)*H / 4H + (.E13.6,7H)*T + (.E13.6,1H))
000003 8 FORMAT (10H0VELOC = (.E13.6,13H)*H*H*T*T + (.F13.6,11H)*H*H*T + (
000003 1,E13.6, 7H)*H*T*T / 4H + (.E13.6, 9H)*H*H + (.F13.6,9H)*T*T + (.F1
000003 23.6,9H)*H*T + (.E13.6,3H)*H / 4H + (.E13.6,7H)*T + (.E13.6,1H))
000003 9 FORMAT (11H0DELTAP = (.E13.6,13H)*H*H*T*T + (.F13.6,11H)*H*H*T + (
000003 1,E13.6, 7H)*H*T*T / 4H + (.E13.6, 9H)*H*H + (.F13.6,9H)*T*T + (.F1
000003 23.6,9H)*H*T + (.F13.6,3H)*H / 4H + (.E13.6,7H)*T + (.E13.6,1H))
000003 11 FORMAT (1H1,7A10)
000003 17 FORMAT (6X,10H0FCCOST = (.E13.6,13H)*H*H*T*T + (.E13.6, 9H)*H*H*T +
000003 1 / 5X,2H1(.F13.6,11H)*H*T*T + (.F13.6,9H)*H*H + (.E13.6,5H)*T*T /
000003 25X,4H2+ (.E13.6,9H)*H*T + (.F13.6,7H)*H + (.E13.6,5H)*T + / 5X,2H3
000003 3(.E13.6,1H))
000003 18 FORMAT (6X, 9H0VELOC = (.E13.6,13H)*H*H*T*T + (.E13.6, 9H)*H*H*T +
000003 1 / 5X,2H1(.E13.6,11H)*H*T*T + (.E13.6,9H)*H*H + (.E13.6,5H)*T*T /
000003 25X,4H2+ (.E13.6,9H)*H*T + (.E13.6,7H)*H + (.E13.6,5H)*T + / 5X,2H3
000003 3(.E13.6,1H))
000003 19 FORMAT (6X,10H0DELTAP = (.E13.6,13H)*H*H*T*T + (.E13.6, 9H)*H*H*T +
000003 1 / 5X,2H1(.F13.6,11H)*H*T*T + (.E13.6,9H)*H*H + (.E13.6,5H)*T*T /
000003 25X,4H2+ (.E13.6,9H)*H*T + (.F13.6,7H)*H + (.E13.6,5H)*T + / 5X,2H3
000003 3(.E13.6,1H))
000003 60 READ 6,(TITLE(I),I=1,7)
000015 PRINT 11, (TITLE(I),I=1,7)
000027 PRINT 4
000033 DO 10 I=1,9
000035 READ 2,TIN(I),TOUT(I),CORHT(I),DELTAP(I),VELOC(I),COST(I)
000054 CORHT(I) = CORHT(I) + 5.08
000057 TOUT(I) = .92*TOUT(I) + .08*TIN(I)
000062 DELPRDP = 40.5*VELOC(I)**2/729.
000065 DELTAP(I) = DELTAP(I) + DELPRDP
000067 COST(I) = .955 * COST(I)
000071 10 PRINT 3, VELOC(I),TOUT(I),DELTAP(I),CORHT(I),COST(I)
000111 DO 20 J =1,9
000113 X(J,1) = CORHT(J)*CORHT(J)*TOUT(J)*TOUT(J)
000117 X(J,2) = CORHT(J)*CORHT(J)*TOUT(J)
000121 X(J,3) = CORHT(J)*TOUT(J)*TOUT(J)
000124 X(J,4) = CORHT(J)*CORHT(J)
000126 X(J,5) = TOUT(J)*TOUT(J)
000130 X(J,6) = CORHT(J)*TOUT(J)
000132 X(J,7) = CORHT(J)
000133 X(J,8) = TOUT(J)
000135 X(J,9) = 1.0
000136 X(J,10) = COST(J)
000140 X(J,11) = VELOC(J)
000141 20 X(J,12) = DELTAP(J)
000144 CALL MATRIX (10,9,12,0,X,9,GARBAGE)
000153 IF(GARBAGE .EQ. 0.0) GO TO 50
000154 PRINT 7,(X(I,10),I=1,9)
000166 PRINT 8,(X(I,11),I=1,9)
000200 PRINT 9,(X(I,12),I=1,9)
000212 PUNCH 17,(X(I,10),I=1,9)
000224 PUNCH 18,(X(I,11),I=1,9)
000236 PUNCH 19,(X(I,12),I=1,9)
000250 GO TO 60
000251 50 PRINT 5
000255 STOP
000257 END

```

OPTIMIZATION STUDIES

In order to generate equations of the form (1) through (6), a preliminary study was made with the FABROC code to determine the optimum fuel residence time. All of the nuclear depletion data that are available in FABROC have been obtained for a three-cycle fuel management scheme. These data were obtained by establishing an equilibrium fuel cycle by means of an iteration between a point depletion code and a one-dimensional, multi-group, diffusion theory code. In the three-cycle fuel management scheme, one third of the core and one sixth of the radial blanket assemblies are removed at each reload interval. It has been shown that there is little difference in the fuel cycle cost between two- and three-cycle fuel management schemes. The results of this present study are applicable to the two-cycle fuel management scheme of the reference design.

It was found that the optimum fuel residence time with a non-positive sodium voiding coefficient was 26 months. Figure 28 shows the fuel cycle cost as a function of the fuel rod diameter for three core heights. The fuel rod diameter as a function of fuel residence time is shown in Figure 29. Each point on this curve corresponds to a minimum fuel cycle cost with respect to core height.

Certain regions of impossible design were determined in this study. These regions are the following:

1. the region in which the outlet coolant temperature is so low that the inlet coolant temperature is lower than the required minimum;
2. the region where the outlet coolant temperature is too high, which can not be obtained with the given design data; and
3. the region where the coefficient of reactivity obtained by voiding both the core and axial blankets is non-negative.

When the coolant velocity goes to the maximum allowable value, the velocity is reduced to the maximum allowable value by increasing the distance between the fuel rods. In consequence, the fuel cycle cost is increased.

The FABROC code is run for a range of core heights and permissible outlet coolant temperatures to obtain points at which Equations (1) to (6) can be fitted. Fitting of the data is then carried out with the FITFAB code.

PARAMETRIC ANALYSIS

GENERAL APPROACH

The following parameters relevant to the reactor design have been studied in order to determine their effect on the cost of generation of electricity:

1. Fissile plutonium cost (\$/gm)
2. Thermal conductivity of the fuel ($\frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}$)

3. Maximum fuel centerline temperature (°F)
4. Maximum clad surface temperature (°F)
5. Average discharge burnup (MWD/T)
6. Fabrication and reprocessing costs
7. Fuel swelling ratio
8. Maximum velocity constraints ($\frac{\text{ft}}{\text{sec}}$)
9. Dwell times (months)
10. Effective radial blanket thickness (inches) [This was studied only for the single-module plant.]

The parametric equations were generated in a similar way to those generated in the optimization study; all parameters were kept fixed except the one under consideration. The equations are generated for three values of the parameter being studied -- a low value, the reference design value, and a high value. The values used in the parametric study are given in Table 11 for the four-module design and in Table 12 for the single-module design.

Eighteen sets of equations were obtained for the nine parameters at the two extreme values for the four-module core, 20 sets of equations were obtained for the single-module core. The equations for the reference design values are the same for all cases and are those generated under the optimization study.

While the reactor equations were normally incorporated into the overall plant optimization program in equation form, some of them were plotted for inclusion in this report as follows.

Figures 30a through 30d are the four-module cores with 26 months dwell time and standard design parameters; Figure 30a gives fuel cycle cost as a function of reactor bulk sodium outlet temperature with parameters of core height A = 3 ft, B = 3-1/3 ft, C = 4 ft, D = 4-1/2 ft, E = 5 ft. The nearly horizontal curves represent cores that have pins as close together as is felt to be mechanically permissible. The curves with the steep upward slope represent a constant reactor sodium velocity of 30 ft/sec, which is our maximum allowable velocity. The constant spacing curves are used as bulk outlet temperature increases until they intersect the constant velocity curve which is then used for any higher bulk outlet temperature. Figure 30b gives core pressure drop in the same terms and Figure 30c gives sodium velocity in the constant spacing region. Figure 30d gives inlet sodium temperature.

Figures 31a through 31d reflect the same for the single-module cores.

Figures 32a through 32d and 33a through 33d give single-module cores with \$5,000 and \$20,000/kg fissile plutonium cost.

Figures 34a through 34d and 35a through 35d give uranium carbide fuel conductivity of 7.0 and 12.0 Btu/ft-°f-hr, respectively.

Figures 36a through 36d and 37a through 37d give 2136 and 2545°F fuel centerline temperatures.

Table 11. Parametric Study for Four Module Design

<u>Case</u>	<u>Variable</u>	<u>Values Used in Study</u>		
		<u>Min.</u>	<u>Reference Design</u>	<u>Max.</u>
A	Fissile Plutonium Cost (\$/gm)	5	10	20
B	Thermal conductivity of the fuel (btu/hr-ft-°F)	7	9.36	12
C	Maximum fuel centerline temperature (°F)	2350	2640	2800
D	Maximum clad surface temperature (°F)	1250	1300	1350
E	Average discharge burnup (MWD/kg)	50	100	150
F	Fabrication and reprocessing costs (multiplier)	.65	1.3	1.95
G	Fuel swelling ratio (%)	1.2	2.4	4.8
H	Maximum velocity constraints (ft/sec)	20	30	40
I	Dwell time (months)	12* 18	25.2	

* Two minimum values were run for dwell time for four module design.

Table 12. Parametric Study for Single Module Design

<u>Case</u>	<u>Variable</u>	<u>Values Used in Study</u>		
		<u>Min.</u>	<u>Reference Design</u>	<u>Max.</u>
A	Fissile plutonium cost (\$/gm)	5	10	20
B	Thermal conductivity of the fuel (btu/hr-ft-°F)	7	9.81	12
C	Maximum fuel centerline temperature (°F)	2136	2400	2545
D	Maximum clad surface temperature (°F)	1189	1236	1284
E	Average discharge burnup (MWD/kg)	50	100	150
F	Fabrication and reprocessing costs (multiplier)	.65	1.3	1.95
G	Fuel swelling ratio (%)	1.4	2.81	5.62
H	Maximum velocity constraint (ft/sec)	20	30	40
I	Dwell times (months)	18	26.2	36
J	Radial blanket thickness (effective) (in.)	6	10	14

Figures 38a through 38d and 39a through 39d give 1189 and 1284°F maximum cladding surface temperatures.

Figures 40a through 40c give 50,000 MWD/T burnup.

COMPARISON OF THE PARAMETERS CONSIDERED WITH THOSE REQUESTED

Several values of the parameters in this study were not entirely consistent with those requested in the contract. For instance, it was not possible to consider the bulk outlet sodium temperature rise of 800 to 1200°F. The lower limit could not be reached because of the requirement of having a minimum coolant temperature of 350°F. The upper limit could not be reached because of the limit of 1300°F in the maximum cladding surface temperature for the four-module plant. For these reasons, the bulk outlet sodium temperature was considered in the range of 900 to 1130°F.

The bulk sodium temperature rise across the core and the fuel specific power (kW/kg fissile) are both dependent variables in the optimization program and can not be varied specifically. The variation on the bulk core outlet sodium temperature, the maximum cladding temperature, and the fuel centerline temperature will result in variations in the bulk sodium temperature rise across the core.

The variations in the average discharge burnup will also provide variations in the fuel specific power.

SINGLE-MODULE REFERENCE DESIGN

The 1000-MWe LMFBR Follow-on Study requires an alternate to the four-module reference design. A description and selected parameters for the alternate design are presented in this section of the report.

CRITERIA FOR THE ALTERNATE DESIGN

The criteria selected at the beginning of the study for the alternate reference design are:

1. The design must be consistent with the reference plant design.
2. The fuel assembly designs must be identical with those for the reference design.
3. The reactor will have an unspoiled (single-module) geometry.
4. The coolant voiding effect will not be constrained to be negative.

Table 13 gives a summary of the pertinent parameters for the alternate design.

Table 13. Reactor Parameters

Thermal output (core and blankets) MWt	2600
Net electrical output MWe	1000
Number of modules	1
Core fuel	(U,Pu)C
Core - average discharge burnup (MWD/T)	100,000
Fuel rod array	square
Fuel assembly shape	square
Type of coolant	liquid sodium
Maximum coolant velocity (ft/sec)	29.3
Maximum clad surface temperature ($^{\circ}$ F)	1236
Maximum fuel centerline temperature ($^{\circ}$ F)	2400
Length to diameter ratio of the core	.864

PHYSICAL DESCRIPTION

The alternate conceptual design is a cylindrical reactor 132.5 inches in diameter (to the outside of the reflector) and 69.9 inches in height (from the bottom of the lower axial blanket to the top of the upper axial blanket).

Internally, the reactor is radially segmented into five regions (three core regions - one radial blanket region - one reflector region). Figure 41 shows a cross-sectional view of the reactor. Table 14 contains additional pertinent information on the physical description of the single-module design.

The above factors were calculated by performing one-dimensional buckling iteration calculations with MOBI, and the possibility of refinement of the values with two-dimensional calculations does exist.

Prompt neutron lifetime (ℓ) and the effective fraction of delayed neutrons (β_{eff}) were determined to be, respectively, 3.637×10^{-7} sec and 0.003414 by the LAMB code.

Table 14. Physical Description

<u>Region</u>	<u>Outer Radius (in.)</u>	<u>Volume (liters)</u>	<u>Number of Assemblies</u>
Inner Fuel	26.033	1392.156	76
Middle Fuel	37.298	1465.467	80
Outer Fuel	46.263	1538.718	84
Radial Blanket	59.725	2930.877	160
Reflector	66.238	1685.190	92

FUEL CYCLE COSTS

The fuel cycle cost for the single-module core design was calculated with the FABROC code and was found to be 0.51 mill/kWhe. This cost is for a fuel management scheme in which the radial blanket assemblies remain in the reactor twice as long as the core assemblies.

A breakdown of the component costs expressed as percentages of the total fuel cycle cost is given in Table 15.

Table 15. Components of the Fuel Cycle Cost

<u>Components</u>	<u>Per Cent Contribution to Fuel Cycle Cost</u>
Rod Fabrication	51
Assembly Fabrication	31
Plutonium Credit	-64
Plutonium Inventory	57
Shipping and Reprocessing	25

-7

SUMMARY

This design meets the first three criteria stated in the beginning of this section. With a core height of 39.9 inches and overall diameter of 132.5 inches, the design has dimensions compatible with the reference design. The fuel assemblies used in the study were identical with those for the reference design, and the alternate design has a single-module configuration. Voiding of the coolant from the core and axial blankets results in a reactivity change of +\$10.4, while the calculated Doppler coefficient $(T \frac{dk}{dt})$ was -0.00252.

The volume fractions of the various materials in the reactor are given in Table 16 for the core, axial blankets, and the radial blanket. The reflector consists of 80% Inconel 600 and 20% sodium.

The plutonium fuel fractions ($\frac{Pu}{Pu + U}$) in each of the three core enrichment zones at the beginning of life are:

Inner fuel zone	0.15
Middle fuel zone	0.18
Outer fuel zone	0.21

Table 16. Volume Fractions of the Reactor Constituents

<u>Material</u>	<u>Volume Fraction</u>		
	<u>Core</u>	<u>Axial Blankets</u>	<u>Radial Blankets</u>
(U, Pu)C	0.2759	-	-
UC	-	0.2759	-
UO ₂	-	-	0.4618
Cr	0.0091	0.0091	-
Na	0.5897	0.5723	0.3041
SS 304 (Cladding)	0.0720	0.0894	0.1649
Mo	0.0533	0.0533	0.0692

NUCLEAR CHARACTERISTICS

The nuclear characteristics for the alternate design were obtained with the MOBI and SIZZLE computer codes and standard 6602M cross-section data.

The radial power distributions for both the beginning and the end of life are presented in Figure 42.

The nuclear hot channel factors at the beginning and end of core life are:

<u>Time in Life</u>	<u>Radial</u>	<u>Axial</u>
Beginning	1.209	1.252
End	1.259	1.221

APPENDIX II

THE SFBROPT OPTIMIZATION CODE

SUMMARY

SFBROPT (Sodium Fast Breeder Reactor Optimization) consists of a plant model which will calculate the plant details and cost of electricity given 17 independent variables, and an optimizing algorithm which will choose the 17 variables to minimize the cost of electricity. The manner in which the plant model is tied to the optimization is shown in Figure 43 which is a simplified flow diagram of OPT, the executive program of SFBROPT. Subroutine CALC carries out the engineering and cost calculations, and STEP51 contains the optimization logic.

INTRODUCTION

A schematic of the plant model is shown in Figure 44. For each of the major components shown, SFBROPT contains a subroutine which will carry out the engineering analysis necessary for overall plant design and cost evaluation. The entire plant heat balance and costing is tied together in Subroutine CALC, a flow diagram for which is given in Figure 45. Write ups on each of the major subroutines are given later.

The plant calculations in the present version of SFBROPT are based heavily on the 1000-MWe Task II concept. Changes in basic concept will require reprogramming to be accurately represented. The many auxiliary and subsystems of the (e.g. startup system, emergency cooling system, cover gas system, refueling system) are not optimized since their design is set more by the job they must perform than by the cost of electricity. Stated conversely, we have optimized the main power producing system only. The costs of smaller subsystems are included as simple functions of reactor power and are nearly constant. The same is true for buildings and containment structures.

OVERALL OPTIMIZATION CODE

OPTIMIZATION TECHNIQUE

There are many programming techniques which can be used to optimize a constrained function of many variables. For many of these convergence can be rigorously proven for certain classes of problems. The optimization logic in SFBROPT is not such a rigorous mathematical technique, but is a heuristic method which was originally developed by Hooke and Jeeves of Westinghouse

and later refined and used successfully by Wiesman, et al. [1] in the optimization of PWRs. The version of pattern search used in SFBROPT is not exactly the same as that used by the inventors but is similar in operation.

ALGORITHM FOR MINIMIZING AN UNCONSTRAINED FUNCTION

The problem is to minimize an objective function of n variables.

e. g., $R = R(X_1, X_2, X_3, \dots, X_n)$

The Xs are called the independent variables. In SFBROPT, R is the cost per unit power of electricity: the independent variables are given on page The algorithm is contained in Subroutine STEP51. After an initial base point is chosen by the user the procedure is as follows:

1. Move each variable in the direction that decreases the cost of electricity. This is a trial and error procedure in which the variable is moved first in one direction. An entire plant design is calculated and the cost of electricity found. If this is not successful, the other direction is tried and the cost re-evaluated. These moves are called search moves.
2. After all the variables have been moved with search moves, an extrapolation is made from the search point. The direction of the extrapolation is the direction of a vector connecting the previous base point to the search point. The magnitude of the move is the distance between the search point and the base point.
3. When none of the variables can be moved to gain an improvement in the objective function the search is concluded.

STEP51 also contains provisions which prevent the independent variables from being moved beyond the input minimum and maximum vlaues. By setting the minimum equal to the maximum the value of any of the independent variables can be fixed.

CONSTRAINT PROBLEMS

In developing the plant model many constraints must be satisfied. For example in the steam generator, pressure drop and heat transfer relationships are satisfied.

e.g., $\Delta P = fL \frac{\rho V^2}{2g}$

$$Q = UA \Delta T_{LM}$$

See: Steam Generator Section.

In SFBROPT many such constraints are satisfied in the plant model because explicit or rapid iterative solutions to the equations exist.

Constraints which cannot be satisfied automatically in the plant model are handled with the optimization. This is done by adding a penalty to the cost of electricity whenever the constraint is not satisfied. Constraints handled in this manner can be of either the equality type

$$\text{e.g.,} \quad g_1(X_1, X_2, X_3, \dots, X_n) = g_{10}$$

or inequality type

$$\text{e.g.,} \quad g_2(X_1, X_2, \dots, X_n) \begin{matrix} < \\ > \end{matrix} g_{20}$$

The penalty is applied in the following manner

$$S = \sum_{i=1}^{NC} \lambda_i (G_i)^2$$

where :

$$G_i = g_i - g_{i0} \quad \text{for equality constraints}$$

$$G_i = 0 \quad \text{for inequality constraints where the constraint is satisfied}$$

$$G_i = g_i - g_{i0} \quad \text{for inequality constraints when the constraint is not satisfied}$$

NC = number of constraints

the quantity to be minimized becomes

$$R + S$$

the λ s are evaluated as follows:

$$\lambda_i = \frac{0.10R}{(g_i - g_{i0})^2 \delta X}$$

δX = step size

$(g_i - g_{i0})$ and R are evaluated at the starting point.

The optimizing algorithm is modified as shown in Figure 43. The optimization is now concluded when all the constraints are satisfied and no improvement can be found in the objective function.

SFBROPT INPUT

1. Downtime per year (hr)
2. Desired electrical output (MWe)
3. Power factor
4. Capital charges
5. Ligament of steam generator (space between tubes) (in.)
6. Ligament of IHX (in.)
7. Condenser Pressure (psia)
8. Length of primary and secondary piping (ft)

INDEPENDENT VARIABLES

1. Reactor outlet temperature (°F)
2. Core height (ft)
3. Secondary hot-leg temperature (°F)
4. Secondary cold-leg temperature (°F)
5. Steam temperature (°F)
6. Feedwater temperature (°F)
7. Steam pipe velocity (ft/sec)
8. Mass velocity on secondary side of IHX ($\frac{\text{lbm}}{\text{hr-ft}^2}$)
9. Mass velocity on primary side of IHX ($\frac{\text{lbm}}{\text{hr-ft}^2}$)
10. Mass velocity of sodium in steam generator ($\frac{\text{lbm}}{\text{hr-ft}^2}$)
11. Mass velocity of water in steam generator ($\frac{\text{lbm}}{\text{hr-ft}^2}$)
12. Specific speed of primary pump
13. Specific speed of secondary pump
14. Steam pressure (psig)
15. Primary pipe velocity (ft/sec)
16. Secondary pipe velocity (ft/sec)
17. Electrical output desired (MWe)

For each independent variable the maximum and minimum value, step size, and starting point must be specified.

The following information is input for additional control by using penalties:

1. minimum and maximum tube diameters for steam generator and IHX,
2. minimum and maximum limits for pump speeds,
3. ranges for acceptable cover gas pressure on the primary and secondary side,
4. allowable difference between water and sodium temperatures at steam generator pinch point, and
5. maximum allowable length of steam generator tubes.

COMPONENT SUBPROGRAMS

CALCULATION OF TURBINE PLANT HEAT RATE

The goal of this calculation is to provide a value of heat rate as close to that calculated by the turbine vendor as possible. No attempt is made to select the more detailed design parameters, such as number and placement of feedwater heaters, or amount of reheat. The only plant parameters selected by SFBROPT are throttle steam temperature and pressure and final feed temperature.

PLANT DESIGN

Nine detailed plant heat balances were provided by the Westinghouse Large Steam Turbine Division. All plants were basically of the same design, having the following characteristics:

1. tandem compound low-pressure turbine,
2. single high-pressure turbine,
3. condenser pressure of 1.5 inches mercury,
4. seven stages of regenerative feedwater heating, and
5. live steam reheat.

CALCULATION

The method used is to make a simplified estimation of heat rate and then apply a correction factor to match the nine detailed calculations more closely.

The heat rate of a power cycle is given by:

$$\text{Heat Rate} = \frac{\text{Heat Added}}{\text{Work Done}} \times 3412.19$$

This is easily calculated for a Rankine cycle (referring to Figure 46).

$$\text{Heat Added} \approx h_1 - h_3 \quad (\text{Precisely } h_1 - h_4, \text{ but } h_1 - h_3 \text{ gives good results})$$

$$\text{Work Done} = h_1 - h_2 - \Delta W_{\text{pump}}$$

$$\Delta W_{\text{pump}} = \frac{144}{778.2} \times v \times \Delta P$$

where:

$$\Delta P = (\text{steam throttle pressure} - \text{condenser pressure}) + DP_{11} + DP_7 + 253$$

$$DP_7 = \text{pressure drop through steam generator (psia)}$$

$$DP_{11} = \text{pressure drop through steam piping (psia)}$$

$$253 = \text{estimated sum of other system losses (psia)}$$

$$v = \text{specific volume of water at point 3 (ft}^3/\text{lbm)}$$

$$h_i = \text{specific enthalpy at point i (Btu/lbm)}$$

Figure 46 gives the results of this estimation. Comparison with the detailed heat balances (column 3) is given in column 5, which is column 3 divided by column 4. The results of the expression

$$1 - 5.325 \times 10^{-5} T^2 + 7.529 \times 10^{-9} P^2 + 3.338 \times 10^{-4} T \\ - 2.255 \times 10^{-7} T^2 + 5.562 \times 10^{-10} PT$$

obtained with a least squares curve fit to the numbers in column 5 is given in column 6. It can be seen that by applying this correction factor to the Rankine estimation, the detailed plant heat balances are matched to within one percent.

The above calculation gives a value of heat rate independent of final feed temperature. It was not possible to correlate heat rate with the nine detailed heat balances since feedwater temperature was restricted over a narrow range of values (475 to 525°F) and there are too few points to give an intelligent least squares fit to an equation of three variables. Another source of information was used to arrive at the following correction equation as a function of feedwater temperature.

$$H.R. = H.R. \times (1.127 - 2.86 \times 10^{-4} FT)$$

where FT = feedwater temperature.

ANALYSIS OF SODIUM PUMPS

The analysis of the primary and secondary pumps is based upon a Westinghouse sodium pump study and is similar for both pumps.

The following tabulation gives the reference designs used.

Primary

PRC1	Specific speed 1500 to 5000 Removable concentric casing Single suction
PRC2	Specific speed, 5000 to 7500 Same as PRC1 otherwise

Secondary

PFC1	Specific speed 1500 to 7500 Fixed concentric casing Single suction
PFC2	Specific speed 5000 to 7500 Same as PFC1 otherwise

Detailed drawings of these are given in Reference (1)

Wound rotor induction motor with liquid rheostat

Hydrostatic bearings

Gas type seals

PUMP SELECTION

For geometrically similiar pump impellers the specific speed is a constant, at the point of best efficiency.

$$N_S = \frac{NQ^{1/2}}{H^{3/4}}$$

where: N_S = specific speed
 Q = flow rate (gpm)
 H = developed head (ft)
 N = speed (rpm)

Thus, once three of the four parameters N , Q , H , or N_S are picked, the pump geometry is specified. Flow rate and head are set by system requirements leaving one degree of freedom in pump selection. The variable used in this selection is N_S .

HYDRAULIC PARAMETER CURVES

Reference (2) contains curves of pump head, flow, efficiency, dimensions, and weight, versus specific speed at a constant rpm, for ten different design frameworks each covering a different range of specific speed e.g.,

$$H = f(N_S)_{n=k} \quad (2)$$

These curves, called hydraulic parameter curves, represent the performance and size of the best anticipated design within each framework. Polynomial expressions have been fit for curves relating to four basic designs, providing two designs for each loop.

The correlations match the curves to within one percent.

CALCULATION OF PUMP POWER

With the efficiency (η) obtained from the hydraulic performance curves the power is calculated from:

$$HP = \frac{DP \times W \times 144}{\rho \times \eta \times NLOPP \times 3600 \times 550} \quad (3)$$

where:

DP = loop pressure drop (psia)
W = flow rate (lb/hr)
 η = efficiency
NLOPP = number of parallel loops
HP = power in horsepower
 ρ = fluid density (lb/ft³)

CALCULATION OF NPSH

Equation (1) is solved for N:

$$N = \frac{N_S H^{0.75}}{Q^{0.5}}$$

The suction specific speed is defined as:

$$S_n = \frac{NQ^{1/2}}{NPSH^{3/4}} \quad (4)$$

where:

Q = flow (gpm)

NPSH = net positive suction head

for single suction pumps $S_n \leq 8000$ to avoid cavitation. Taking as the limiting case $S_n = 8000$, the minimum required NPSH is found:

$$NPSH = \left(\frac{rpm}{8000}\right)^{4/3} 0^{2/3}$$

CALCULATION OF COVER GAS PRESSURE

The cover gas pressure must be adequate to provide the NPSH required when pressure drops and available static heads are considered.

The equations derived from the 1000-MWe Task II Study are as follows:

PRIMARY

$$PO1 = NPSH_1 \times \frac{\rho_1}{144} - 20 \times \frac{\rho_2}{144} + DP3 + 0.75 \times DP9$$

PO1 = primary cover gas pressure (psia)

ρ_1 = density of Na at cold leg temperature (lb/ft³)

ρ_2 = density of Na at average between hot and cold leg temperature (lb/ft³)

DP3 = IHX shell side pressure drop (psia)

DP9 = Primary piping pressure drop

SECONDARY

$$PO2 = NPSH_2 \times \frac{\rho_3}{144} - 40 \times \frac{\rho_4}{144} + DP6 + 0.25 \times DP10$$

PO2 = secondary cover gas pressure (psia)

ρ_3 = density of Na at secondary cold leg temperature

ρ_4 = density of Na at average between cold and hot leg temperatures (lb/ft³)

DP6 = steam generator shell side pressure drop

DP10 = secondary sodium loop pressure drop

COSTING

The ratio:

$$R = \frac{\frac{Q_1 N_1}{H_1}}{\frac{Q_0 H_0}{H_0}}$$

gives the relative size between the model pump for which the hydraulic parameter curves were calculated (subscript 0) and the similar pump of the size to be used. Using R, the full-scale dimensions are calculated and the costing procedure of Reference (2) followed. The costing procedure provides curves giving the cost of the various components which make up the pump. These curves have been correlated with least squares.

STEAM GENERATOR

The steam generator calculations are based on the 1000-MWe Task I concept which is a shell and tube once-through design consisting of six serpentine tube bundles in one large cylindrical shell. The calculations can be classified in two types:

Packaging

Heat transfer - pressure drop

The heat transfer calculations need not change significantly as long as the steam generator remains of the shell-tube type. The packaging relationships are based on the serpentine geometry and are only valid for the present concept.

INPUT

The subroutine requires the following input from other parts of the program.

WT1 - X(5) - steam temperature at outlet (°F)
ST1 - X(3) - hot-leg Na temperature (°F)
WT5 - X(6) - feedwater temperature (°F)
ST5 - X(4) - cold-leg sodium temperature (°F)
WP1 - X(14) - water pressure at 1 psi
WG - X(11) - water mass velocity (lb/ft² - hr)
SG - X(10) - sodium mass velocity (lb/ft² - hr)
POWN - X(20) - total reactor power (Btu/hr)
ALIGI - tube ligament

All water properties are calculated from Westinghouse computerized steam tables. Sodium properties are calculated as a function of temperature from correlations within SFRROPT.

OUTPUT

From the above eight variables plus the fluid properties the following are calculated:

1. Heat transfer area
2. Number of tubes
3. Tube diameter
4. Shell dimensions and weight
5. Pressure drop
6. Heat transfer coefficients and LMTD

PACKAGING

The uniform flow cross section of the steam generator implies the mass velocities are constant throughout, and it is possible to specify the flow area per tube on both the shell and tube sides.

Shell side flow area/tube

$$S_{SH} = (3P^2 - 2 P d_o - \frac{\pi d_o^2}{4}) \quad (5)$$

$$S_{SH} = (SF/SG) \frac{1}{n} \quad (6)$$

Tube Side flow area/tube

$$S_T = \left(\frac{\pi di^2}{4} \right) \quad (7)$$

$$S_T = \left(\frac{WF}{WG} \right) \frac{1}{n} \quad (8)$$

where

WF = water flow rate (lb/hr)

WG = water mass velocity (lb/ft² - hr)

SF = sodium flow rate (lb/hr)

SG = sodium mass velocity (lb/ft² - hr)

n = number of tubes

P = tube pitch (ft)

do = tube outside diameter (ft)

di = tube inside diameter (ft)

Additional Equations:

Pitch is defined as diameter plus ligament

$$\text{i. e. } P = do + L \quad (9)$$

Tube stress sets the wall thickness as (10)

$$di = \frac{do}{\left(1 - \frac{WP}{\sigma - 0.6 WP} \right)}$$

where:

WP = the design pressure taken as the maximum system pressure
+ 300 psi

σ = tube material strength psi: calculated as a function of
temperature.

Defining S,

$$\frac{1}{S} = \frac{do}{di} = 1 + \frac{WP}{\sigma - 0.6WP}$$

Equations (5) through (10) are solved for do

$$do = \frac{2.5468L + 2.95441L \sqrt{RS^2 + 0.42441}}{RS^2 - 0.27324}$$

S is multiplied by a correction factor of

$(1.2 - \frac{0.2}{S})$ to give a 20% increase in the wall thickness as a safety factor to allow for bending and corrosion.

HEAT TRANSFER

Subcritical

The steam generator is divided into four heat transfer regions due to the variation in fluid properties on the water side. The boundaries between the region are the saturated vapor line, 40% quality, and the saturated liquid line. The calculations are carried out as if there were four separate heat exchangers connected in series. Each region involves the iterative solution of the following equations.

$$Q = W_3 C_p \Delta T - \text{water side}$$

$$Q = W_2 \Delta H - \text{sodium side}$$

$$U = \frac{1}{\frac{d_o}{d_i h_f} + \frac{d_o}{d_i h_u} + \frac{1}{h_s} + \frac{d_o}{2K} \log \left(\frac{d_o}{d_i} \right)}$$

$$\Delta P = \frac{f L \rho V^2}{D 2g} \quad \text{water and sodium sides}$$

$$Q = UA \Delta T_{LM}$$

where:

$$h_w = \text{water side film coefficient (Btu/hr-ft}^2\text{-}^\circ\text{F)}$$

$$h_s = \text{sodium side film coefficient (Btu/hr-ft}^2\text{-}^\circ\text{F)}$$

$$A = \text{heat transfer area (ft}^2\text{)}$$

$$W = \text{flow rate (lbm/hr)}$$

$$f = \text{friction and resistance factor}$$

$$h_f = \text{fouling resistance (Btu/hr-ft}^2\text{-}^\circ\text{F)}$$

$$\Delta T_{LM} = \text{log mean temperature difference}$$

$$U = \text{overall heat transfer coefficient (Btu/hr-ft}^2\text{-}^\circ\text{F)}$$

Q = heat transferred (Btu/hr)

H = specific enthalpy (Btu/lb)

The evaluation of the film coefficients is based on Westinghouse correlations^[3]. The pressure drop calculations allow for the two-phase flow and bend losses. On the water side, in the superheated and two-phase regions, the pressure drop and heat transfer equations must be solved simultaneously since for a compressible fluid the properties are pressure dependent.

Supercritical

One heat transfer region is used on both the sodium and water side for the supercritical analysis. The Westinghouse computerized steam tables are not complete in the supercritical region. This has required calculating properties in subregions surrounding the vacant region and averaging to approximate the properties.

CROSSOVER

The steam generator model has been programmed to model a steam generator with a supercritical water inlet that drops to a subcritical outlet from frictional losses. The programming provides for crossover to any one of the four subcritical regions. The programming for this contingency is very involved but has proved unnecessary since the small range of steam conditions for which crossover occurs are of little interest and parametric studies can be performed without them.

COSTING

The cost of a steam generator is calculated from an equation of the following form.

$$\text{cost} = A + B \times \text{SGSWT} + G \times \text{SGTWT} + D \times \text{TNT}$$

where:

A, B, C, and D are constants.

SGSWT = steam generator shell weight

SGTWT = steam generator tube weight

TNT = total number of tubes

The constants were determined by correlating data received from quotes on four Westinghouse Tampa Division designs. The correlation matches the quotes to within five percent.

INTERMEDIATE HEAT EXCHANGER

The subroutine for the analysis of the IHX is called IHX. It is similar to the steam generator subroutine in that it both packages and carries out the heat transfer and pressure drop calculations.

INPUT

The following input quantities are required:

POWN - X(20) - Total reactor power (Btu/hr)

T1 = X(1) - Primary hot-leg temperature (°F)

T2 = Primary cold-leg temperature (°F)

T3 = X(3) Secondary hot-leg temperature

T4 = X(4) Secondary cold-leg temperature

X(8) - Mass velocity on secondary side of IHX

X(9) - Mass velocity on primary side of IHX

ALIG - Tube ligament

The fluid properties are calculated as a function of temperature.

OUTPUT

1. Heat transfer area
2. Number of tubes
3. Tube diameter
4. Pressure drop
5. Heat transfer coefficient and LMTD

PACKAGING

The flow area per tube on both the shell and tube side can be specified, (see Figure 47).

$$\begin{array}{c} \text{SHELL SIDE} \\ S_{SH} = \left(\frac{\sqrt{3}}{2} P^2 - \frac{\pi d_o^2}{4} \right) \end{array} \quad (11)$$

$$S = \frac{\left(\frac{W_1}{G_{SH}} \right)}{\frac{1}{n}} \quad (12)$$

$$\begin{array}{c} \text{TUBE SIDE} \\ S_T = \frac{\pi d_i^2}{4} \end{array} \quad (13)$$

$$S_T = \frac{1}{n} \frac{W_2}{G_T} \quad (14)$$

where:

S_{SH} = shell side flow area/tube

S_T = tube side flow area/tube

P = pitch

d_i = inside tube diameter (ft)

d_o = outside tube diameter (ft)

G_{SH} = shell side mass velocity (lbm/hr-ft²)

G_T = tube side mass velocity (lbm/hr-ft²)

W_1 = primary flow rate (lbm)

W_2 = secondary flow rate (lbm/hr)

ADDITIONAL EQUATIONS

$$P = d_o + L \text{ (pitch = diameter = ligament)} \quad (15)$$

$$d_i = d_o - 2t \text{ where: } t = \text{tube wall thickness} \quad (16)$$

$$t = 0.65 d_o \quad (17)$$

Solving Equations (11) through (17) for d_o gives

$$d_o = \frac{1.456808L + 1.206983 L \sqrt{R + 1.321178}}{R - 0.13630}$$

Once the inside diameter of the tube is known the number of tubes can be found by solving Equations (13) and (14). The heat transfer analysis gives the necessary tube length.

HEAT TRANSFER

The necessary heat transfer area is found by means of the conventional log mean temperature difference type of analysis. Once the tube lengths are known the pressure drop is calculated by the conventional Darcy-Weisbach method.

$$\Delta P = f \frac{L}{D} \frac{\rho V^2}{2}$$

Where f is a dimensionless friction factor dependent on the Reynolds number and tube geometry.

COSTING

The cost of an IHX is calculated from an equation of the following form.

$$\text{COST} = A + B \times \text{AIHX} + C \times \text{TN}$$

where:

A, B, and C are constants

AIHX = area of the IHX

TN = number of tubes in the IHX

The constants were determined by the same method used on the steam generator.

PIPING

The primary, intermediate, and steam piping are analyzed in similar manner. The procedure given below for the primary piping is similar for

the others.

INPUT

X(15)

PBENDS - number of bends

W1 - flow rate (lb/hr)

X(17) - pipe length (ft)

OUTPUT

1. Pipe dimensions

(a) Diameter

(b) Wall thickness

(c) Weight

2. Pressure drop

ANALYSIS

The diameter can be found from the flow rate and velocity

$$DIAP = \left[\frac{W1}{N \times p \times X(15) \times \pi \times 900} \right]^{0.5}$$

where

DIAP = diameter of primary pipe (ft)

p = density (lb/ft³)

Once the diameter is calculated, the pipe Reynolds number and friction factor for bends and straight lengths are calculated, which makes possible the calculation of pressure drop.

The wall thicknesses are set as follows:

1 = Primary and Secondary

t = .0155 x diameter

2 = Steam Piping

$$t = \frac{P \times \text{diameter}}{2 \times (SM - 0.6 \times P)}$$

where:

SM = material strength of Type 304 stainless steel in psi calculated as a function of temperature.

$P = \text{design pressure calculated as } X(14) + 300.$

$X(14) = \text{steam pressure}$

COSTING

The cost of the primary, secondary and steam piping is calculated from

$$\text{Cost} = A \times W$$

where:

$A = \text{constant}$

$W = \text{weight of piping}$

APPENDIX III

DETAILED RESULTS OF PARAMETRIC ANALYSIS (PRINTOUT)

ONE MODULE CORE

BULK SODIUM TEMPERATURE AT REACTOR OUTLET NOZZLE °F

	950	OPT	1050	1100
FUEL CYCLE COSTS M/KW-HR	.5030	.5189	.6131	.8121
CAPITAL COSTS M/KW-HR	2.5710	2.5194	2.5530	2.8287
TOTAL COSTS M/KW-HR	3.0740	3.0382	3.1660	3.6408
STEAM GENERATORS 10E6 \$	9.582	8.243	8.347	8.880
IHXs 10E6 \$	4.187	3.214	2.732	4.044
PRIMARY PUMPS 10E6 \$	2.039	2.559	3.948	9.521
INTERMEDIATE PUMP 10E6 \$	1.156	1.063	1.040	1.071
PRIMARY PIPING 10E6 \$	.741	.947	1.493	3.195
INTERMED PIPING 10E6 \$	.597	.581	.545	.552
REACTOR VESSEL 10E6 \$	1.581	1.554	1.827	2.219
CAPITAL INVEST. \$/KW	139.47	136.67	138.49	153.45
REACTOR POWER MWT	2757.5	2620.0	2575.0	2560.0
NET ELECTRICAL OUT. MWE	1051.9	1051.9	1051.9	1051.6
NET TURBINE PLANT H.R.	8783.1	8351.6	8127.4	7862.5
PLANT EFFICIENCY	.3815	.4015	.4085	.4108
REACTOR PRESSURE DROP	85.17	80.50	100.07	96.26
FUEL ASSEMBLY WEIGHT	9.63	8.30	8.00	8.02
PRIMARY HOT LEG TEMP F	950.0	999.0	1050.0	1100.0
PRIMARY COLD LEG TEMP F	604.1	742.4	884.5	1026.3
INTER. HOT LEG TEMP F	912.0	970.0	1020.0	1068.0
INTER. COLD LEG TEMP F	544.0	616.0	660.0	720.0
STEAM TEMP. F	868.0	920.0	987.0	1010.0
FINAL FEED TEMP. F	300.0	300.0	403.0	473.0
STEAM PRESSURE PSIG	2340.0	2725.0	2735.0	2935.0
STEAM GENERATOR				
H.T. AREA 10E3 SQ-FT	82.94	61.03	61.58	61.35
TUBE LENGTH FT	229.27	147.73	157.59	131.31
TUBE O.D. IN	.584	.546	.567	.626
NUMBER OF TUBES	2364.2	2890.8	2631.7	2848.8
H2O M.V. 10E6 LB/FT2-HR	1.6720	1.6675	1.7350	1.6040
NA M.V. 10E6 LB/FT2-HR	.8600	.7200	.7550	.6890
H2O PRESSURE DROP PSI	388.93	260.68	327.14	210.32
NA PRESSURE DROP PSI	51.15	17.51	6.46	2.20
IHX				
H.T. AREA 10E3 SQ-FT	83.48	48.12	33.05	20.51
TUBE LENGTH FT	95.64	33.83	19.60	6.59
TUBE OD IN	.9854	.7382	.7554	.5301
NUMBER OF TUBES	3383	7359	8525	22421
TUBE M.V. 10E6 LB/SQFT -HR	3.0700	2.5000	2.0000	1.5950
SHELL M.V. 10E6 LB/SQFT -HR	1.6500	1.2500	1.6250	1.8200
TUBE PRESSURE DROP PSI	51.153	17.505	6.461	2.205
SHELL PRESSURE DROP PSI	16.748	11.334	10.946	11.121
PRIMARY PUMPS				
POWER 10E3 HP	7.60	9.17	16.90	37.22
SPECIFIC SPEED	3250.0	3640.0	3550.0	3130.0
SHAFT SPEED RPM	720.5	665.4	595.1	343.0
COVER GAS PRESSURE PSIA	49.59	46.44	49.99	42.44
FLOW RATE 10E3 GPM	101.45	133.79	209.86	481.57
HEAD FT NA	291.87	271.52	326.44	322.12
INTERMEDIATE PUMPS				
POWER 10E3 H.P.	5.385	3.269	2.676	2.584
SPECIFIC SPEED	6561.2	7440.0	7470.0	7500.0
SHAFT SPEED RPM	1199.0	931.2	832.4	778.1
COVER GAS PRESSURE PSIA	68.55	50.14	44.90	43.07
FLOW RATE 10E3 GPM	94.05	94.49	92.31	96.22
HEAD FT-NA.	214.46	129.88	109.52	102.37

PIPING

PRIMARY FLOW VEL FT/SEC	25.250	26.600	26.288	28.000
PRIMARY PIPE O.D. IN.	41.085	45.824	57.542	44.167
INTER. FLOW VEL. FT/SEC	31.675	32.650	34.062	35.000
INTER. PIPE O.D. IN	29.41	34.88	33.77	34.00
STEAM FLOW VEL. FPS	300.00	220.00	300.00	300.00
STEAM PIPE O.D. IN	27.162	31.844	28.349	29.672
WALL THICKNESS IN	3.465	4.727	4.393	5.041

	6 IN RAD BLANKET	14IN RAD BLANKET	.014 SWELING	.056 SWELING	50K BURNUP	150K BURNUP
FUEL CYCLE COSTS M/KW-HR	.4800	.5705	.4715	.6042	.8041	.4782
CAPITAL COSTS M/KW-HR	2.5139	2.5226	2.5202	2.5031	2.4950	2.5376
TOTAL COSTS M/KW-HR	2.9939	3.0931	2.9917	3.1072	3.2991	3.0158
STEAM GENERATORS 10E6 \$	8.664	8.308	8.557	8.249	7.426	8.205
IXXS 10E6 \$	3.346	3.216	3.248	3.172	3.085	3.384
PRIMARY PUMPS 10E6 \$	2.553	2.586	2.622	2.589	2.619	2.674
INTERMEDIATE PUMP 10E6\$	1.027	1.040	1.016	.990	1.031	1.062
PRIMARY PIPING 10E6 \$	.862	.979	.883	.855	.865	.965
INTERMED PIPING 10E6 \$	.552	.562	.573	.526	.518	.608
REACTOR VESSEL 10E6 \$	1.346	1.766	1.547	1.564	1.603	1.610
CAPITAL INVEST. \$/KW	136.37	136.84	136.71	135.78	135.34	137.66
REACTOR POWER MWT	2607.5	2617.5	2620.0	2612.5	2620.0	2622.5
NET ELECTRICAL OUT.MWE	1051.8	1051.6	1051.7	1051.8	1051.9	1051.9
NET TURBINE PLANT H.R.	8311.0	8331.3	8348.4	8329.7	8349.2	8345.4
PLANT EFFICIENCY	.4034	.4017	.4014	.4026	.4015	.4011
REACTOR PRESSURE DROP	77.02	92.64	79.05	74.66	73.96	92.04
FUEL ASSEMBLY HEIGHT	8.25	8.52	8.07	8.65	9.50	8.01
PRIMARY HOT LEG TEMP F	999.0	1001.0	996.0	1009.0	1022.0	993.0
PRIMARY COLD LFG TEMP F	742.7	747.0	744.6	754.8	769.2	746.8
INTER. HOT LFG TEMP F	979.0	978.0	977.0	990.0	996.0	968.0
INTER. COLD LEG TEMP F	608.0	612.0	600.0	600.0	624.0	616.0
STEAM TEMP. F	938.0	930.0	944.0	944.0	929.0	924.0
FINAL FEED TEMP. F	372.0	380.0	382.0	372.0	396.0	404.0
STEAM PRESSURE PSIG	2790.0	2710.0	2500.0	2645.0	2500.0	2495.0
STEAM GENERATOR						
H.T AREA 10E3 SQ-FT	66.39	61.69	67.13	62.40	51.56	61.16
TURE LENGTH FT	164.89	152.18	174.22	162.09	133.29	147.97
TURE O.D. IN	.554	.544	.553	.560	.562	.540
NUMBER OF TURES	2776.6	2848.2	2661.4	2624.6	2630.1	2922.6
H2O M.V. 10F6LR/FT2-HR	1.6825	1.7025	1.6825	1.6825	1.6625	1.6375
NA M.V. 10E6LR/FT2-HR	.7075	.7075	.7300	.7100	.7450	.7200
H2O PRESSURE DROP PSI	286.98	284.74	347.34	295.66	252.17	285.22
NA PRESSURE DROP PSI	21.13	21.23	22.28	19.60	17.12	15.09
IXX						
H.T. AREA 10E3 SQ-FT	50.75	49.49	49.32	46.64	45.24	49.86
TURE LENGTH FT	36.71	37.29	37.04	34.30	32.65	32.35
TURE OD IN	.7036	.7316	.7048	.6919	.7257	.7294
NUMBER OF TURES	7506	6929	7216	7507	7295	8072
TURE M.V.10F6LR/SQFT -HR	2.5625	2.6125	2.6250	2.5250	2.4875	2.3500
SHEL M.V.10F6LR/SQFT -HR	1.2687	1.3500	1.3500	1.3000	1.3000	1.2000
TURE PRESSURE DROP PSI	21.133	21.232	22.277	19.597	17.117	15.085
SHELL PRESSURE DROP PSI	13.424	11.301	13.662	13.874	13.791	11.619
PRIMARY PUMPS						
POWER 10E3 HP	9.20	10.32	9.62	9.19	9.21	10.71
SPECIFIC SPEED	3610.0	3610.0	3535.0	3580.0	3565.0	3550.0
SHAFT SPEED RPM	665.0	713.0	653.8	649.2	639.8	692.7
COVER GAS PRESSURE PSIA	49.97	49.66	49.91	49.93	49.32	50.00
FLOW RATE 10E3 GPM	133.27	135.15	136.56	135.03	136.59	139.61
HEAD FT NA	273.45	302.90	279.44	270.17	268.47	304.55

INTERMEDIATE PUMPS						
POWER 10F3 M.P.	3.353	3.410	3.196	3.119	3.432	2.960
SPECIFIC SPEED	7470.0	7470.0	7470.0	7500.0	7500.0	7500.0
SHAFT SPEED RPM	1016.9	1007.0	996.0	1027.0	1032.9	863.8
COVER GAS PRESSURE PSIA	54.20	54.03	50.80	53.39	58.17	44.53
FLOW RATE 10E3 GPM	89.63	91.27	88.48	85.33	90.16	95.11
HEAD FT-NA.	140.25	140.12	135.25	136.80	143.00	116.75

PIPING						
PRIMARY FLOW VEL FT/SEC	29.100	25.975	29.100	29.725	29.725	27.225
PRIMARY PIPE O.D. IN.	43.725	46.604	44.254	43.547	43.796	46.251
INTER. FLOW VEL. FT/SEC	32.650	32.650	31.087	32.650	35.000	31.400
INTER. PIPE O.D. IN.	33.99	34.30	34.62	33.19	32.93	35.68
STEAM FLOW VEL. FPS	250.00	290.00	290.00	250.00	270.00	220.00
STEAM PIPE O.D. IN.	29.843	27.915	28.680	30.308	29.702	32.986
WALL THICKNESS IN	4.561	4.150	4.033	4.457	4.139	4.576

	\$5000/ KG	\$20000/ KG	LOW FAR COST	HIGH FAR COST	20FT/S MAX VEL	40FT/S MAX VEL
FUEL CYCLE COSTS M/KW-HR						
FUEL CYCLE COSTS M/KW-HR	.5274	.5107	.2778	.7476	.5252	.5126
CAPITAL COSTS M/KW-HR	2.5123	2.5133	2.4962	2.5391	2.5381	2.5095
TOTAL COSTS M/KW-HR	3.0397	3.0240	2.7741	3.2867	3.0633	3.0222
STEAM GENERATORS 10E6 \$						
STEAM GENERATORS 10E6 \$	8.432	8.173	8.249	8.564	9.066	8.240
EXCH 10E6 \$	3.316	3.243	3.068	3.538	3.753	3.345
PRIMARY PUMPS 10E6 \$	2.545	2.632	2.662	2.557	2.795	2.588
INTERMEDIATE PUMP 10E6 \$	1.034	1.037	1.028	1.025	1.075	1.022
PRIMARY PIPING 10E6 \$	.932	.890	.864	.993	.795	.943
INTERMED PIPING 10E6 \$	.538	.521	.529	.547	.546	.508
REACTOR VESSEL 10E6 \$	1.667	1.553	1.482	1.744	1.364	1.642
CAPITAL INVEST. \$/KW	136.28	136.34	135.41	137.74	137.68	136.13
REACTOR POWER MWT						
REACTOR POWER MWT	2650.0	2620.0	2635.0	2607.5	2620.0	2650.0
NET ELECTRICAL OUT.MWE	1051.6	1051.8	1050.8	1052.0	1050.3	1051.6
NET TURBINE PLANT M.R.	8431.7	8344.5	8408.5	8287.9	8394.6	8432.5
PLANT EFFICIENCY	.3968	.4015	.3988	.4034	.4009	.3968
REACTOR PRESSURE DROP	95.91	77.45	65.95	106.45	52.56	92.03
FUEL ASSEMBLY HEIGHT	8.70	8.23	8.01	8.89	8.00	8.55
PRIMARY HOT LEG TEMP F	996.0	1003.0	1003.0	999.0	979.0	999.0
PRIMARY COLD LEG TEMP F	732.6	753.1	754.6	740.3	689.7	741.4
INTER. HOT LEG TEMP F	974.0	981.0	981.0	981.0	950.0	980.0
INTER. COLD LEG TEMP F	600.0	612.0	604.0	610.0	600.0	598.0
STEAM TEMP. F	936.0	943.0	928.0	940.0	917.0	938.0
FINAL FEED TEMP. F	328.0	390.0	332.0	390.0	376.0	328.0
STEAM PRESSURE PSIG	2730.0	2455.0	2890.0	2685.0	2625.0	2700.0
STEAM GENERATOR						
H.T. AREA 10E3 SQ-FT	63.19	61.14	60.65	65.42	71.17	61.01
TUBE LENGTH FT	158.97	157.77	153.99	161.94	170.35	155.89
TUBE O.D. IN	.538	.550	.555	.553	.534	.546
NUMBER OF TUBES	2822.0	2689.9	2710.7	2787.8	2986.7	2736.0
H2O M.V. 10E6LB/FT2-HR	1.6900	1.6700	1.7175	1.6625	1.6525	1.6700
NA M.V. 10E6LB/FT2-HR	.7100	.7400	.7200	.7050	.7100	.7125
H2O PRESSURE DROP PSI	296.94	320.86	257.70	290.35	315.57	282.48
NA.PRESSURE DROP PSI	21.39	18.80	22.11	19.78	20.17	19.85
HX						
H.T. AREA 10E3 SQ-FT	51.43	48.53	46.13	54.14	59.23	50.63
TUBE LENGTH FT	38.31	34.74	35.78	37.39	39.70	36.35
TUBE OD IN	.7264	.7175	.7154	.7028	.7251	.7064
NUMBER OF TUBES	7060	7437	6882	7870	7858	7531
TUBE M.V.10E6LB/SQFT -HR	2.5750	2.5125	2.6875	2.4500	2.4500	2.5000
SHEL M.V.10E6LB/SQFT -HR	1.3000	1.3000	1.4250	1.2000	1.0500	1.2750
TUBE PRESSURE DROP PSI	21.385	18.799	22.113	19.780	20.167	19.855
SHELL PRESSURE DROP PSI	11.675	13.408	14.829	10.228	12.074	11.727

PRIMARY PUMPS						
POWER 10E3 HP	10.41	9.53	8.80	11.14	6.00	10.34
SPECIFIC SPEED	3460.0	3610.0	3655.0	3460.0	3700.0	3550.0
SHAFT SPEED RPM	710.8	656.5	616.6	745.9	576.1	704.3
COVER GAS PRESSURE PSIA	49.68	49.97	49.62	49.93	39.79	49.97
FLOW RATE 10E3 GPM	131.57	137.67	139.35	132.00	117.34	134.77
HEAD FT NA	313.55	274.69	250.55	335.10	200.76	304.14

INTERMEDIATE PUMPS						
POWER 10E3 H.P.	3.538	3.567	3.563	3.310	3.822	3.549
SPECIFIC SPEED	7500.0	7500.0	7470.0	7485.0	7500.0	7485.0
SHAFT SPEED RPM	1053.4	1054.9	1072.1	1008.5	1043.5	1082.1
COVER GAS PRESSURE PSIA	58.16	59.99	59.13	54.02	60.94	60.94
FLOW RATE 10E3 GPM	90.19	90.62	89.07	89.67	95.18	88.30
HEAD FT-NA.	146.84	147.59	149.86	138.37	150.29	150.44

PIPING						
PRIMARY FLOW VEL FT/SEC	26.600	29.100	30.350	25.038	27.850	26.913
PRIMARY PIPE O.D. IN.	45.453	44.431	43.769	46.918	41.988	45.725
INTER. FLOW VEL. FT/SEC	33.750	35.000	33.900	32.963	35.000	35.000
INTER. PIPE O.D. IN	33.54	33.01	33.26	33.84	33.81	32.60
STEAM FLOW VEL. FPS	260.00	290.00	295.00	210.00	200.00	220.00
STEAM PIPE O.D. IN	28.982	28.903	26.739	33.154	33.558	31.618
WALL THICKNESS IN	4.349	4.004	4.178	4.922	4.827	4.709

	1189	1284
	CLAD	CLAD
FUEL CYCLE COSTS M/KW-HR		
CAPITAL COSTS M/KW-HR	2.5604	2.4722
TOTAL COSTS M/KW-HR	3.0930	2.9832
STEAM GENERATORS 10E6 \$	8.951	7.771
HXs 10E6 \$	3.667	2.954
PRIMARY PUMPS 10E6 \$	2.617	2.270
INTERMEDIATE PUMP 10E6 \$	1.082	.981
PRIMARY PIPING 10E6 \$	1.030	.762
INTERMED PIPING 10E6 \$	.555	.501
REACTOR VESSEL 10E6 \$	1.676	1.582
CAPITAL INVEST. \$/KW	138.89	134.11

REACTOR POWER MWT	2720.0	2620.0
NET ELECTRICAL OUT.MWE	1051.8	1051.6
NET TURBINE PLANT H.P.	8635.6	8377.3
PLANT EFFICIENCY	.3867	.4014
REACTOR PRESSURE DROP	106.40	68.74
FUEL ASSEMBLY HEIGHT	9.19	8.80
PRIMARY HOT LEG TEMP F	948.0	1031.0
PRIMARY COLD LEG TEMP F	687.9	738.6
INTER. HOT LEG TEMP F	928.0	998.0
INTER. COLD LEG TEMP F	568.0	600.0
STEAM TEMP. F	876.0	931.0
FINAL FEED TEMP. F	302.0	356.0
STEAM PRESSURE PSIG	2800.0	2730.0

STEAM GENERATOR		
H.T AREA 10E3 SQ-FT	69.85	56.55
TUBE LENGTH FT	171.85	149.65
TUBE O.D. IN	.522	.580
NUMBER OF TUBES	2972.3	2489.2
H2O M.V. 10E6 LB/FT2-HR	1.8100	1.6675
NA M.V. 10E6 LB/FT2-HR	.7250	.7250
H2O PRESSURE DROP PSI	327.04	241.45
NA PRESSURE DROP PSI	23.34	16.45

IMX		
M.T. AREA 10E3 SQ-FT	58.04	42.24
TUBE LENGTH FT	40.64	31.37
TUBE OD IN	.7185	.7080
NUMBER OF TUBES	7593	7265
TUBE M.V. 10E6 LR/SQFT -HR	2.6000	2.4500
SHELL M.V. 10E6 LR/SQFT -HR	1.2625	1.1500
TUBE PRESSURE DROP PSI	23.341	16.448
SHELL PRESSURE DROP PSI	10.387	12.904
PRIMARY PUMPS		
POWER 10E3 HP	11.41	7.44
SPECIFIC SPEED	3460.0	3670.0
SHAFT SPEED RPM	731.9	674.9
COVER GAS PRESSURE PSIA	49.83	47.57
FLOW RATE 10E3 GPM	135.28	117.43
HEAD FT NA	332.13	250.75
INTERMEDIATE PUMPS		
POWER 10E3 H.P.	3.982	3.023
SPECIFIC SPEED	7485.0	7440.0
SHAFT SPEED RPM	1067.6	1017.1
COVER GAS PRESSURE PSIA	62.36	53.60
FLOW RATE 10E3 GPM	95.36	83.89
HEAD FT-NA.	155.55	134.95
PIPING		
PRIMARY FLOW VEL FT/SEC	24.725	29.100
PRIMARY PIPE O.D. IN.	47.794	41.104
INTER. FLOW VEL. FT/SEC	34.525	33.750
INTER. PIPE O.D. IN	34.08	32.38
STEAM FLOW VEL. FPS	260.00	240.00
STEAM PIPE O.D. IN	27.791	30.308
WALL THICKNESS IN	4.109	4.535

	THERMAL K=7	THERMAL K=12	18 MO DWELL	26 MO DWELL	2136 F CL TEMP	2545 F CL TEMP
FUEL CYCLE COSTS M/KW-HR	.5759	.4959	.6175	.5039	.5781	.5027
CAPITAL COSTS M/KW-HR	2.4998	2.5234	2.5407	2.4766	2.4837	2.5214
TOTAL COSTS M/KW-HR	3.0757	3.0193	3.1582	2.9804	3.0617	3.0241
STEAM GENERATORS 10E6 \$	8.306	8.306	8.197	7.316	7.352	8.123
IMXS 10E6 \$	3.165	3.236	3.067	2.590	2.536	3.297
PRIMARY PUMPS 10E6 \$	2.463	2.749	2.887	2.635	2.648	2.676
INTERMEDIATE PUMP 10E6 \$	1.012	1.037	1.040	1.019	1.002	1.051
PRIMARY PIPING 10E6 \$	.778	.929	1.118	.919	.922	.909
INTERMED PIPING 10E6 \$	.541	.588	.609	.506	.498	.598
REACTOR VESSEL 10E6 \$	1.500	1.560	1.721	1.566	1.724	1.527
CAPITAL INVEST. \$/KW	135.60	136.88	137.82	134.34	134.73	136.78
REACTOR POWER MWT	2610.0	2620.0	2625.0	2730.0	2740.0	2620.0
NET ELECTRICAL OUT. MWE	1051.9	1051.9	1051.9	1051.6	1051.9	1051.7
NET TURBINE PLANT M.R.	8332.5	8342.4	8334.3	8697.7	8704.1	8352.4
PLANT EFFICIENCY	.4030	.4015	.4007	.3852	.3839	.4014
REACTOR PRESSURE DROP	64.89	80.70	103.40	76.63	98.67	74.99
FUFL ASSEMBLY HEIGHT	8.63	8.00	8.00	9.10	9.41	8.00
PRIMARY HOT LEG TEMP F	1007.0	998.0	998.0	1006.0	1008.0	998.0
PRIMARY COLD LFG TEMP F	739.7	758.6	768.9	739.4	741.2	753.5
INTER. HOT LEG TEMP F	983.0	976.0	973.0	974.0	977.0	974.0
INTER. COLD LEG TEMP F	604.0	612.0	614.0	573.0	565.0	616.0
STEAM TEMP. F	940.0	942.0	929.0	913.0	912.0	935.0
FINAL FEED TEMP. F	380.0	388.0	408.0	300.0	300.0	390.0
STEAM PRESSURE PSIG	2605.0	2485.0	2465.0	2260.0	2250.0	2490.0

STEAM GENERATOR							
H.T AREA	10E3 SQ-FT	62.91	63.26	62.45	51.71	52.74	60.14
TURE LENGTH	FT	161.51	159.87	159.39	147.53	152.85	147.83
TURE O.D. IN		.552	.544	.558	.529	.536	.535
NUMRER OF TURES		2696.3	2776.1	2679.6	2531.5	2458.3	2902.5
H2O M.V. 10E6LB/FT2-HR		1.6925	1.6587	1.6775	1.8050	1.8150	1.6425
NA M.V. 10E6LB/FT2-HR		.7150	.7300	.7600	.7650	.7450	.7150
H2O PRESSURE DROP PSI		309.38	321.87	313.47	363.21	369.99	295.31
NA.PRESSURE DROP PSI		20.81	17.22	16.21	27.85	28.01	16.29
IMX							
H.T. AREA	10E3 SQ-FT	47.74	46.90	43.77	40.92	39.22	48.01
TURE LENGTH	FT	36.05	32.11	30.42	40.29	38.69	32.04
TURE OD	IN	.7128	.7061	.7208	.7844	.7628	.7144
NUMRER OF TURES		7097	7901	7627	4946	5076	8010
TURE M.V.10E6LB/SQFT -HR		2.5875	2.4750	2.5000	3.0250	3.0437	2.4250
SHEL M.V.10E6LB/SQFT -HR		1.2750	1.2937	1.3812	1.7750	1.7750	1.2375
TURE PRESSURE DROP PSI		20.810	17.217	16.210	27.854	28.014	16.287
SHELL PRESSURE DROP PSI		14.973	13.260	10.553	14.161	13.991	13.137
PRIMARY PUMPS							
POWER	10E3 HP	8.07	10.23	12.47	9.11	11.13	9.48
SPECIFIC SPEED		3610.0	3550.0	3497.5	3170.0	3170.0	3685.0
SHAFT SPEED	RPM	634.7	645.7	695.8	577.4	668.1	649.3
COVER GAS PRESSURE	PSIA	49.92	49.94	49.88	43.73	49.94	49.64
FLOW RATE	10E3 GPM	127.88	143.82	150.90	134.10	134.56	140.67
HEAD	FT NA	250.00	282.90	329.21	270.52	329.34	267.19
INTERMEDIATE PUMPS							
POWER	10E3 H.P.	3.272	3.013	2.914	3.884	3.770	2.990
SPECIFIC SPEED		7470.0	7500.0	7470.0	7485.0	7485.0	7470.0
SHAFT SPEED	RPM	1024.3	914.0	870.6	1189.6	1198.9	886.5
COVER GAS PRESSURE	PSIA	54.06	46.89	43.94	66.65	66.04	45.49
FLOW RATE	10E3 GPM	87.77	91.85	93.33	86.20	84.09	93.45
HEAD	FT-NA.	139.65	122.99	117.14	168.00	166.95	120.10
PIPING							
PRIMARY FLOW VEL	FT/SEC	30.975	29.100	25.350	27.500	27.500	29.100
PRIMARY PIPE O.D. IN.		41.535	45.395	49.801	45.137	45.216	44.903
INTER. FLOW VEL.	FT/SEC	32.650	31.400	30.775	34.375	34.062	31.400
INTER. PIPE O.D. IN		33.65	35.08	35.71	32.52	32.28	35.38
STEAM FLOW VEL.	FPS	270.00	250.00	300.00	300.00	300.00	210.00
STEAM PIPE O.D. IN		29.300	30.994	28.475	27.966	28.037	33.713
WALL THICKNESS	IN	4.246	4.332	3.924	3.563	3.558	4.700

		2400 / 850	2400 / 900	2400 / 930	2400 / 942	2400 / 960	2400 / 1020
FUEL CYCLE COSTS	M/KW-HR	.7629	.7580	.7603	.7616	.7739	.7813
CAPITAL COSTS	M/KW-HR	2.5332	2.5376	2.5440	2.5441	2.5269	2.5928
TOTAL COSTS	M/KW-HR	3.2960	3.2956	3.3044	3.3057	3.3008	3.3741
STEAM GENERATORS	10E6 \$	7.687	7.687	8.414	8.515	7.792	9.884
IMXS	10E6 \$	3.258	3.034	3.258	3.310	2.957	3.284
PRIMARY PUMPS	10E6 \$	2.416	2.631	2.560	2.571	3.082	3.537
INTERMEDIATE PUMP	10E6 \$	1.054	1.069	1.038	1.018	1.000	.952
PRIMARY PIPING	10E6 \$	.981	1.048	.934	1.016	1.109	1.218
INTERMED PIPING	10E6 \$	.525	.645	.601	.506	.512	.538
REACTOR VESSEL	10E6 \$	2.183	2.187	2.040	2.095	2.170	2.145
CAPITAL INVST.	\$/KW	137.41	137.65	138.00	138.01	137.07	140.65

REACTOR POWER MWT	2770.0	2667.5	2627.5	2642.5	2632.5	2560.0
NET ELECTRICAL OUT. MWE	1051.6	1051.8	1051.5	1050.9	1052.0	1051.3
NET TURBINE PLANT H.R.	8802.9	8476.5	8362.6	8406.4	8345.2	8107.1
PLANT EFFICIENCY	.3796	.3943	.4007	.3977	.3996	.4107
REACTOR PRESSURE DROP	112.12	109.00	98.70	104.26	105.40	101.94
FUEL ASSEMBLY HEIGHT	9.56	9.05	8.71	8.80	8.50	8.01
PRIMARY HOT LEG TEMP F	973.0	996.0	993.0	994.0	1020.0	1041.0
PRIMARY COLD LEG TEMP F	683.2	739.1	732.7	734.9	799.1	852.5
INTER. HOT LEG TEMP F	944.0	963.0	968.0	974.0	998.0	1032.0
INTER. COLD LEG TEMP F	561.0	608.0	604.0	592.0	612.0	628.0
STEAM TEMP. F	850.0	900.0	930.0	942.0	960.0	1020.0
FINAL FEED TEMP. F	300.0	386.0	300.0	372.0	379.0	417.0
STEAM PRESSURE PSIG	2400.0	2400.0	2400.0	2400.0	2400.0	2400.0

STEAM GENERATOR						
H.T. AREA 10E3 SQ-FT	55.96	55.34	65.19	65.98	58.31	80.67
TUBE LENGTH FT	144.81	139.25	165.06	170.29	161.28	215.00
TUBE O.D. IN	.547	.534	.541	.543	.564	.592
NUMBER OF TUBES	2699.8	2840.8	2790.4	2723.5	2450.2	2420.5
H2O M.V. 10E6 LB/FT2-HR	1.6950	1.7175	1.6975	1.6575	1.7100	1.6600
NA M.V. 10E6 LB/FT2-HR	.7500	.7500	.8450	.7150	.7730	.7130
H2O PRESSURE DROP PSI	261.90	296.56	351.57	347.61	347.18	469.40
NA PRESSURE DROP PSI	25.11	19.44	19.98	19.14	10.74	8.48

IMX						
H.T. AREA 10E3 SQ-FT	49.82	46.08	50.71	50.28	47.04	54.45
TUBE LENGTH FT	37.91	34.87	37.81	36.35	35.70	39.31
TUBE O.D. IN	.7038	.7604	.7479	.7159	.8749	.9042
NUMBER OF TUBES	7132	6638	6851	7381	5753	5851
TUBE M.V. 10E6 LB/SQFT -HR	2.7625	2.6500	2.5500	2.4750	2.1000	1.8000
SHELL M.V. 10E6 LB/SQFT -HR	1.2500	1.3750	1.3125	1.2750	1.6250	1.7750
TUBE PRESSURE DROP PSI	25.109	19.439	19.979	19.142	10.736	8.479
SHELL PRESSURE DROP PSI	9.576	10.175	11.701	10.173	12.674	14.472

PRIMARY PUMPS						
POWER 10E3 HP	10.80	11.66	10.68	11.04	13.52	15.43
SPECIFIC SPEED	3445.0	3445.0	3415.0	3520.0	3145.0	3100.0
SHAFT SPEED RPM	781.9	740.5	713.1	743.1	632.2	580.3
COVER GAS PRESSURE PSIA	49.87	49.90	49.95	49.80	48.75	49.97
FLOW RATE 10E3 GPM	123.67	135.91	131.96	133.37	157.92	181.96
HEAD FT NA	343.67	340.37	321.09	328.13	344.08	343.87

INTERMEDIATE PUMPS						
POWER 10E3 H.P.	4.005	3.071	3.118	3.499	2.852	2.109
SPECIFIC SPEED	7500.0	7470.0	7500.0	7485.0	7470.0	7470.0
SHAFT SPEED RPM	1134.7	876.5	935.9	1075.6	933.6	812.9
COVER GAS PRESSURE PSIA	65.96	43.84	47.67	60.51	50.27	37.08
FLOW RATE 10E3 GPM	91.23	95.75	91.93	87.92	87.11	81.31
HEAD FT-NA	163.37	120.24	127.03	148.81	122.79	97.52

PIPING						
PRIMARY FLOW VEL FT/SEC	23.788	24.413	26.600	24.725	26.750	28.000
PRIMARY PIPE O.D. IN.	46.642	48.212	45.516	47.459	49.583	51.960
INTER. FLOW VEL. FT/SEC	35.000	29.837	30.775	35.000	34.250	30.500
INTER. PIPE O.D. IN	33.13	36.73	35.45	32.52	32.74	33.55
STEAM FLOW VEL. FPS	300.00	297.50	300.00	210.00	300.00	300.00
STEAM PIPE O.D. IN	26.737	28.269	28.632	33.978	28.726	30.254
WALL THICKNESS IN	3.444	3.749	3.865	4.620	3.049	4.518

	1000/ 850	1000/ 900	1000/ 958	1000/ 1000		
FUEL CYCLE COSTS M/KW-HR	.8304	.8409	.8312	.8382		
CAPITAL COSTS M/KW-HR	2.6251	2.6114	2.6438	2.6714		
TOTAL COSTS M/KW-HR	3.4555	3.4523	3.4750	3.5096		
STEAM GENERATORS 10E6 \$	7.204	7.027	7.304	7.723		
IMXS 10E6 \$	2.920	2.737	2.902	3.504		
PRIMARY PUMPS 10E6 \$	2.516	2.704	3.057	3.253		
INTERMEDIATE PUMP 10E6 \$	1.100	1.068	1.032	1.030		

PRIMARY PIPING	10E6 \$	1.055	1.146	1.297	1.233
INTERMED PIPING	10E6 \$	.568	.541	.584	.528
REACTOR VESSEL	10E6 \$	2.175	2.186	2.181	2.041
CAPITAL INVEST.	\$/KW	142.40	141.66	143.41	144.91
REACTOR POWER	MWT	3060.0	3020.0	2860.0	2785.0
NET ELECTRICAL OUT.	MWE	1051.9	1051.4	1051.7	1051.9
NET TURBINE PLANT H.P.		9706.7	9579.2	9070.9	8827.1
PLANT EFFICIENCY		.3437	.3481	.3677	.3777
REACTOR PRESSURE DROP		112.51	111.07	106.64	94.10
FUEL ASSEMBLY HEIGHT		9.80	9.39	8.69	8.10
PRIMARY HOT LEG TEMP F		942.0	981.0	1012.0	1024.0
PRIMARY COLD LEG TEMP F		657.2	702.4	778.0	809.8
INTER. HOT LEG TEMP F		922.0	943.0	982.0	1012.0
INTER. COLD LEG TEMP F		520.0	532.0	584.0	618.0
STEAM TEMP. F		850.0	900.0	958.0	1000.0
FINAL FEED TEMP. F		404.0	301.0	439.0	491.0
STEAM PRESSURE PSIG		1000.0	1000.0	1000.0	1000.0
STEAM GENERATOR					
H.T. AREA	10E3 SQ-FT	54.43	52.84	55.49	58.83
TUBE LENGTH	FT	158.72	159.85	153.55	156.64
TUBE O.D. IN		.504	.526	.524	.524
NUMBER OF TUBES		2599.7	2398.7	2632.0	2737.9
H2O M.V. 10E6 LB/FT2-HR		1.7700	1.6900	1.6350	1.6300
NA M.V. 10E6 LB/FT2-HR		.7300	.8700	.7800	.7400
H2O PRESSURE DROP PSI		662.56	642.98	658.53	730.93
NA PRESSURE DROP PSI		34.22	28.56	13.38	15.23
HX					
H.T. AREA	10E3 SQ-FT	43.76	36.71	37.21	48.08
TUBE LENGTH	FT	36.95	29.31	24.50	29.26
TUBE O.D. IN		.6937	.6468	.6842	.6575
NUMBER OF TUBES		6521	7397	8480	9545
TUBE M.V. 10E6 LB/SQFT-HR		3.2625	3.2000	2.4500	2.3250
SHELL M.V. 10E6 LB/SQFT-HR		1.4500	1.4625	1.3875	1.3500
TUBE PRESSURE DROP PSI		34.216	28.564	13.381	15.235
SHELL PRESSURE DROP PSI		9.663	9.204	8.945	11.010
PRIMARY PUMPS					
POWER	10E3 HP	11.36	12.11	13.42	13.29
SPECIFIC SPEED		3440.0	3550.0	3670.0	3640.0
SHAFT SPEED	RPM	766.0	747.4	706.2	643.7
COVER GAS PRESSURE PSIA		49.77	50.00	49.97	49.82
FLOW RATE	10E3 GPM	129.16	140.83	161.95	172.75
HEAD	FT-NA	344.84	339.02	330.07	307.91
INTERMEDIATE PUMPS					
POWER	10E3 H.P.	4.612	4.204	2.754	3.258
SPECIFIC SPEED		7500.0	7485.0	7485.0	7500.0
SHAFT SPEED	RPM	1191.5	1156.1	858.0	988.7
COVER GAS PRESSURE PSIA		70.64	67.67	43.48	54.95
FLOW RATE	10E3 GPM	95.13	92.15	91.22	90.45
HEAD	FT-NA.	179.30	169.07	112.84	135.19
PIPING					
PRIMARY FLOW VEL	FT/SEC	23.125	23.163	23.475	26.288
PRIMARY PIPE O.D. IN.		48.369	50.421	53.622	52.300
INTER. FLOW VEL.	FT/SEC	33.750	34.375	31.400	34.525
INTER. PIPE O.D. IN		34.48	33.64	35.00	33.24
STEAM FLOW VEL.	FPS	300.00	300.00	290.00	260.00
STEAM PIPE O.D. IN		38.517	38.907	41.800	45.294
WALL THICKNESS	IN	2.524	2.629	2.930	3.266

4 MODULE CORE

BULK SODIUM TEMPERATURE AT REACTOR OUTLET NOZZLES °F

	900	950	975	1050	1100
	4 MOD	4 MOD	4 MOD	4 MOD	4 MOD
FUEL CYCLE COSTS M/KW-HR	.7962	.7350	.7614	.8378	1.1665
CAPITAL COSTS M/KW-HR	2.7789	2.5926	2.5271	2.5610	2.7131
TOTAL COSTS M/KW-HR	3.5751	3.3275	3.2887	3.3988	3.8796
STEAM GENERATORS 10E6 \$	10.282	9.324	8.311	8.319	8.471
IHX 10E6 \$	6.094	4.060	3.073	2.750	3.204
PRIMARY PUMPS 10E6 \$	2.035	2.203	2.833	3.711	7.397
INTERMEDIATE PUMP 10E6 \$	1.215	1.185	1.007	1.109	1.087
PRIMARY PIPING 10E6 \$	.773	.990	1.122	1.422	2.137
INTERMED PIPING 10E6 \$	.855	.571	.533	.599	.603
REACTOR VESSEL 10E6 \$	1.856	2.150	2.183	2.186	2.537
CAPITAL INVEST. \$/KW	150.75	140.64	137.09	138.92	147.18
REACTOR POWER MWT	3000.0	2740.0	2625.0	2560.0	2550.0
NET ELECTRICAL OUT.MWE	1051.7	1051.9	1051.0	1051.7	1051.9
NET TURBINE PLANT H.P.	9549.1	8696.4	8330.9	8090.5	7911.7
PLANT EFFICIENCY	.3506	.3839	.4007	.4108	.4125
REACTOR PRESSURE DROP	83.92	115.14	106.78	100.18	90.28
FUEL ASSEMBLY HEIGHT	10.00	9.98	8.71	8.00	8.01
PRIMARY HOT LEG TEMP F	900.0	950.0	1011.0	1050.0	1100.0
PRIMARY COLD LEG TEMP F	520.7	629.5	776.4	875.3	1007.1
INTER. HOT LEG TEMP F	874.0	916.0	992.0	1012.0	1062.0
INTER. COLD LEG TEMP F	476.0	561.0	608.0	684.0	720.0
STEAM TEMP. F	642.0	865.0	952.0	978.0	1008.0
FINAL FEED TEMP. F	300.0	323.0	354.0	418.0	461.0
STEAM PRESSURE PSIG	1780.0	2460.0	2730.0	2845.0	2850.0
STEAM GENERATOR					
H.T. AREA 10E3 SQ-FT	101.93	78.09	62.65	59.24	56.60
TUBE LENGTH FT	268.46	209.84	162.50	140.27	123.44
TUBE O.D. IN	.627	.591	.555	.541	.603
NUMBER OF TUBES	2311.6	2407.0	2652.9	2981.2	2903.3
H2O M.V. 10E6 LB/FT2-HR	1.7280	1.6690	1.7075	1.7100	1.6040
NA M.V. 10E6 LB/FT2-HR	.8520	.8675	.7200	.7420	.6970
H2O PRESSURE DROP PSI	381.68	338.43	304.15	283.14	216.38
NA PRESSURE DROP PSI	79.81	47.38	18.12	6.83	2.31
IHX					
H.T. AREA 10E3 SQ-FT	128.81	79.55	44.93	34.64	23.34
TUBE LENGTH FT	150.41	85.96	33.06	20.47	9.02
TUBE O.D. IN	.9982	.9599	.7104	.7921	.6504
NUMBER OF TUBES	3277	3683	7307	8159	15186
TUBE M.V. 10E6 LB/SQFT -HR	3.0900	3.0650	2.5125	2.0750	1.5850
SHELL M.V. 10E6 LB/SQFT -HR	1.6600	1.6650	1.4250	1.5375	1.8200
TUBE PRESSURE DROP PSI	79.807	47.380	18.110	6.832	2.312
SHELL PRESSURE DROP PSI	20.649	13.218	10.361	10.647	15.510
PRIMARY PUMPS					
POWER 10E3 HP	7.51	9.89	12.46	15.86	29.85
SPECIFIC SPEED	2950.0	3190.0	3475.0	3580.0	3100.0
SHAFT SPEED RPM	665.7	787.6	711.2	617.2	387.5
COVER GAS PRESSURE PSIA	49.41	49.59	49.94	49.99	49.85
FLOW RATE 10E3 GPM	98.75	109.32	147.61	197.30	379.04
HEAD FT NA	293.49	354.11	336.80	325.23	327.29

INTERMEDIATE PUMPS						
POWER 10E3 H.P.	6.133	5.644	3.128	2.881	2.258	
SPECIFIC SPEED	5890.0	6580.0	7440.0	7500.0	7500.0	
SHAFT SPEED RPM	1197.9	1197.0	994.7	789.8	691.7	
COVER GAS PRESSURE PSIA	59.34	72.54	52.37	43.93	35.09	
FLOW RATE 10E3 GPM	93.13	97.22	87.23	101.16	97.50	
HEAD FT-NA.	245.73	217.93	134.46	107.97	8.27	
PIPING						
PRIMARY FLOW VEL FT/SEC	24.250	20.875	24.725	25.975	33.000	
PRIMARY PIPE O.D. IN.	41.403	46.863	49.885	56.147	68.832	
INTER. FLOW VEL. FT/SEC	21.937	34.175	32.963	33.900	32.500	
INTER. PIPE O.D. IN.	42.30	34.58	33.39	35.39	35.51	
STEAM FLOW VEL. FPS	300.00	285.00	300.00	280.00	300.00	
STEAM PIPE O.D. IN.	26.473	27.638	27.432	29.133	29.444	
WALL THICKNESS IN.	2.398	3.662	4.156	4.632	4.861	

	\$50000/ KG	\$200000/ KG	LOW FAR COST	HIGH FAR COST	20FT/S MAX-VEL	40FT/S MAX-VEL
FUEL CYCLE COSTS M/KW-HR						
FUEL CYCLE COSTS M/KW-HR	.7307	.8355	.4462	1.0771	.7889	.7594
CAPITAL COSTS M/KW-HR						
TOTAL COSTS M/KW-HR	3.2553	3.3728	2.9734	3.6172	3.3490	3.2922
STEAM GENERATORS 10E6 \$	8.304	8.582	8.128	8.449	9.081	8.438
INXS 10E6 \$	3.008	3.163	3.290	2.897	3.923	3.247
PRIMARY PUMPS 10E6 \$	2.849	2.659	2.806	2.677	2.278	2.646
INTERMEDIATE PUMP 10E6 \$	1.009	1.011	1.009	1.028	1.116	1.031
PRIMARY PIPING 10E6 \$	1.071	1.035	1.084	1.029	.694	.994
INTERMED PIPING 10E6 \$	.542	.532	.509	.558	.645	.515
REACTOR VESSFL 10E6 \$	2.143	2.187	2.161	2.177	1.691	2.069
CAPITAL INVEST. \$/KW	136.95	137.64	137.09	137.79	138.87	137.40
REACTOR POWER MWT						
REACTOR POWER MWT	2627.5	2625.0	2632.5	2635.0	2630.0	2630.0
NET ELECTRICAL OUT. MWE						
NET ELECTRICAL OUT. MWE	1051.8	1051.8	1051.8	1051.8	1051.8	1051.8
NET TURBINE PLANT H.R.						
NET TURBINE PLANT H.R.	8340.9	8340.1	8355.7	8372.9	8411.0	8355.7
PLANT EFFICIENCY						
PLANT EFFICIENCY	.4003	.4007	.3995	.3992	.3999	.3999
REACTOR PRESSURE DROP						
REACTOR PRESSURE DROP	104.57	106.28	104.91	106.20	54.16	101.54
FUEL ASSEMBLY HEIGHT						
FUEL ASSEMBLY HEIGHT	8.55	9.00	8.66	8.93	8.01	8.57
PRIMARY HOT LEG TEMP F						
PRIMARY HOT LEG TEMP F	1011.0	1001.0	1009.0	1001.0	969.0	999.0
PRIMARY COLD LEG TEMP F						
PRIMARY COLD LEG TEMP F	776.8	750.8	771.6	751.5	679.3	747.5
INTER. HOT LEG TEMP F						
INTER. HOT LEG TEMP F	989.0	980.0	993.0	969.0	935.0	978.0
INTER. COLD LEG TEMP F						
INTER. COLD LEG TEMP F	608.0	600.0	608.0	599.0	604.0	604.0
STEAM TEMP. F						
STEAM TEMP. F	950.0	940.0	950.0	926.0	900.0	932.0
FINAL FEED TEMP. F						
FINAL FEED TEMP. F	354.0	368.0	348.0	390.0	396.0	368.0
STEAM PRESSURE PSIG						
STEAM PRESSURE PSIG	2710.0	2685.0	2700.0	2505.0	2545.0	2705.0
STEAM GENERATOR						
H.T AREA 10E3 SQ-FT	62.43	65.94	59.96	66.04	72.34	63.29
TUBE LENGTH FT	159.77	166.71	155.84	169.93	167.07	159.13
TUBE O.D. IN.	.546	.550	.556	.558	.532	.549
NUMBER OF TUBES	2732.0	2745.4	2642.2	2661.7	3108.6	2769.3
H2O M.V. 10E6 LB/FT2-HR	1.7075	1.6925	1.6825	1.6925	1.6250	1.7075
NA M.V. 10E6 LB/FT2-HR	.7100	.7050	.7225	.7450	.7250	.7125
H2O PRESSURE DROP PSI	307.24	309.12	285.86	327.99	306.72	295.79
NA PRESSURE DROP PSI	17.13	18.98	18.62	15.57	19.55	19.98

IMX						
H.T. AREA 10E3 SQ-FT	41.95	46.84	46.87	41.11	63.34	47.87
TURE LENGTH FT	29.89	34.23	32.15	29.81	41.09	34.25
TURE OD IN	.6904	.7088	.6692	.7319	.7522	.6961
NUMBER OF TURES	7767	7373	8320	7198	7827	7671
TURE M.V.10E6LR/SQFT -HR	2.5250	2.5250	2.4875	2.5000	2.4250	2.5625
SHFL M.V.10E6LR/SQFT -HR	1.3750	1.3250	1.3000	1.3312	1.0250	1.2875
TURE PRESSURE DROP PSI	17.133	18.977	18.614	15.575	19.552	19.976
SHFL PRESSURE DROP PSI	10.923	10.398	10.413	10.421	15.476	10.963
PRIMARY PUMPS						
POWER 10E3 HP	12.41	11.62	12.20	11.70	6.71	11.25
SPFCIFIC SPEED	3415.0	3460.0	3475.0	3445.0	3700.0	3460.0
SHAFT SPEED RPM	694.9	730.7	708.6	725.9	626.0	716.6
COVER GAS PRESSURE PSIA	49.98	49.99	49.80	49.99	49.36	49.94
FLOW RATE 10E3 GPM	147.99	137.71	146.14	138.60	117.34	137.14
HEAD FT NA	334.84	335.36	332.97	335.82	224.28	325.85
INTERMEDIATE PUMPS						
POWER 10E3 H.P.	3.049	3.249	3.369	3.044	3.451	3.604
SPECIFIC SPEED	7485.0	7500.0	7500.0	7500.0	7440.0	7500.0
SHAFT SPEED RPM	970.9	1019.6	1059.3	935.4	890.7	1077.4
COVER GAS PRESSURE PSIA	50.71	54.62	58.40	49.53	48.10	61.09
FLOW RATE 10E3 GPM	87.98	87.96	87.25	90.61	101.04	89.60
HEAD FT-NA.	129.89	138.26	144.69	125.72	127.99	150.64
PIPING						
PRIMARY FLOW VEL FT/SEC	25.975	25.038	25.350	25.350	31.913	25.975
PRIMARY PIPE O.D. IN.	48.732	47.909	49.026	47.764	39.224	46.941
INTER. FLOW VEL. FT/SEC	32.650	33.275	34.525	32.650	31.400	35.000
INTER. PIPE O.D. IN	33.69	33.37	32.63	34.18	36.75	32.83
STEAM FLOW VEL. FPS	300.00	270.00	250.00	300.00	230.00	300.00
STEAM PIPE O.D. IN	27.456	29.019	30.043	28.115	31.612	27.390
WALL THICKNESS IN	4.130	4.308	4.506	3.917	4.392	4.071

	K=7	K=12	2350 F FUEL CI	2800 F FUEL CL	1250 F CLAD	1350 F CLAD
FUEL CYCLE COSTS M/KW-HR						
FUEL CYCLE COSTS M/KW-HR	.8046	.7304	.8061	.7259	.7901	.7366
CAPITAL COSTS M/KW-HR	2.5235	2.5550	2.5179	2.5475	2.5908	2.5005
TOTAL COSTS M/KW-HR	3.3282	3.2854	3.3240	3.2734	3.3809	3.2371
STEAM GENERATORS 10E6 \$	8.119	8.006	8.546	8.152	8.861	8.156
IMXS 10E6 \$	3.366	3.545	3.229	3.293	3.605	3.123
PRIMARY PUMPS 10E6 \$	2.595	2.717	2.592	2.779	3.051	2.316
INTERMEDIATE PUMP 10E6\$	1.008	1.077	1.006	1.033	1.103	.979
PRIMARY PIPING 10E6 \$	1.060	1.044	.946	1.138	1.214	.930
INTERMED PIPING 10E6 \$	.498	.574	.494	.541	.578	.471
REACTOR VESSFL 10E6 \$	2.066	2.193	2.069	2.238	2.013	2.247
CAPITAL INVEST. \$/KW	136.89	138.60	136.58	138.19	140.54	135.64
REACTOR POWER MWT						
REACTOR POWER MWT	2620.0	2645.0	2630.0	2615.0	2635.0	2635.0
NET ELECTRICAL OUT.MWE	1051.3	1052.0	1051.7	1051.9	1051.7	1051.6
NET TURBINE PLANT H.R.	8338.5	8397.2	8363.7	8302.0	8345.8	8388.7
PLANT EFFICIENCY	.4013	.3977	.3990	.4023	.3991	.3991
REACTOR PRESSURE DROP	97.20	106.76	96.91	104.69	106.56	107.36
FUEL ASSEMBLY HEIGHT	9.10	9.00	9.15	8.91	8.27	9.49
PRIMARY HOT LEG TEMP F	1011.0	989.0	1008.0	1003.0	971.0	1022.0
PRIMARY COLD LEG TEMP F	757.1	742.7	749.8	766.9	754.8	731.6
INTER. HOT LEG TEMP F	994.0	966.0	990.0	984.0	954.0	1000.0
INTER. COLD LEG TEMP F	608.0	616.0	600.0	616.0	616.0	590.0
STEAM TEMP. F	940.0	906.0	949.0	939.0	924.0	946.0
FINAL FEED TEMP. F	356.0	386.0	332.0	402.0	404.0	328.0
STEAM PRESSURE PSIG	2800.0	2620.0	2840.0	2535.0	2500.0	2800.0

STEAM GENERATOR							
H.T. AREA 10E3 SQ-FT	59.38	58.06	64.17	60.90	68.82	60.39	
TURE LENGTH FT	151.93	138.95	164.03	154.06	162.68	162.84	
TURE O.D. IN	.569	.550	.556	.559	.533	.579	
NUMBER OF TURES	2625.3	2901.0	2689.4	2703.4	3030.8	2448.7	
H2O M.V. 10F6LR/FT2-HR	1.6600	1.6300	1.6850	1.6550	1.6400	1.6900	
NA M.V. 10E6LR/FT2-HR	.7150	.7300	.7000	.7325	.7300	.7200	
H2O PRESSURE DROP PSI	247.04	239.42	280.65	290.39	322.79	266.15	
NA PRESSURE DROP PSI	19.34	15.99	22.06	17.43	17.31	23.26	
IMX							
H.T. AREA 10E3 SQ-FT	49.16	51.49	49.49	48.28	54.60	47.48	
TURE LENGTH FT	34.10	32.00	37.95	33.11	34.86	38.01	
TURE OD IN	.6751	.7013	.7089	.7059	.7273	.6952	
NUMBER OF TURES	8158	8763	7026	7889	8226	6864	
TURE M.V. 10F6LR/SQFT -HR	2.4750	2.3750	2.5875	2.4500	2.4250	2.6250	
SHFL M.V. 10E6LR/SQFT -HR	1.2250	1.1500	1.3500	1.3125	1.3500	1.2500	
TURE PRESSURE DROP PSI	19.343	15.988	22.057	17.430	17.315	23.265	
SHFL PRESSURE DROP PSI	9.481	10.124	11.769	9.662	10.305	9.733	
PRIMARY PUMPS							
POWER 10E3 HP	10.49	11.90	10.66	12.02	13.46	10.03	
SPFCIFIC SPEED	3610.0	3430.0	3400.0	3610.0	3490.0	3505.0	
SHAFT SPEED RPM	718.9	717.8	698.8	728.2	687.9	795.7	
COVER GAS PRESSURE PSIA	47.29	49.51	49.19	49.98	49.86	49.80	
FLOW RATE 10E3 GPM	135.65	140.67	133.69	145.84	159.89	118.72	
HEAD FT NA	307.02	336.03	317.13	327.80	334.67	334.56	
INTERMEDIATE PUMPS							
POWER 10E3 H.P.	3.454	3.384	3.597	3.304	3.696	3.516	
SPFCIFIC SPEED	7470.0	7485.0	7500.0	7500.0	7500.0	7470.0	
SHAFT SPEED RPM	1085.1	936.6	1133.6	994.4	965.0	1179.7	
COVER GAS PRESSURE PSIA	60.41	52.42	63.34	54.45	56.32	64.70	
FLOW RATE 10E3 GPM	86.62	96.46	85.90	90.78	99.46	81.75	
HEAD FT-NA.	149.49	131.64	156.74	136.57	139.44	160.78	
PIPING							
PRIMARY FLOW VEL FT/SEC	24.100	25.350	26.600	24.100	24.725	24.100	
PRIMARY PIPE O.D. IN.	48.473	48.112	45.811	50.225	51.878	45.411	
INTER. FLOW VEL. FT/SEC	35.000	33.750	35.000	33.750	34.525	35.000	
INTER. PIPE O.D. IN	32.29	34.66	32.17	33.65	34.78	31.40	
STEAM FLOW VEL. FPS	210.00	240.00	260.00	270.00	240.00	270.00	
STEAM PIPE O.D. IN	32.399	30.760	28.915	29.821	31.642	28.377	
WALL THICKNESS IN	4.972	4.389	4.512	4.227	4.396	4.370	

	.012 SWELING	.048 SWELING	50000 MWD/TON	150000 MWD/TON
FUEL CYCLE COSTS M/KW-HR				
FUEL CYCLE COSTS M/KW-HR	.7117	.8540	1.1162	.6874
CAPITAL COSTS M/KW-HR	2.5375	2.5183	2.5072	2.5568
TOTAL COSTS M/KW-HR	3.2492	3.3723	3.6234	3.2442
STEAM GENERATORS 10E6 \$	8.374	8.118	8.095	8.223
IMXS 10E6 \$	3.182	3.204	3.065	3.289
PRIMARY PUMPS 10E6 \$	2.708	2.723	2.679	2.683
INTERMEDIATE PUMP 10E6\$	1.020	1.012	1.019	1.049
PRIMARY PIPING 10E6 \$	1.103	1.011	1.008	1.090
INTERMED PIPING 10E6 \$	.530	.499	.531	.572
REACTOR VESSEL 10E6 \$	2.235	2.111	2.086	2.200
CAPITAL INVEST. \$/KW	137.65	136.61	136.01	138.70

REACTOR POWER MWT	2640.0	2630.0	2600.0	2640.0
NET ELECTRICAL OUT. MWE	1050.9	1051.6	1051.9	1051.8
NET TURBINE PLANT H.R.	8391.7	8354.2	8271.4	8384.5
PLANT EFFICIENCY	.3981	.3998	.4046	.3984
REACTOR PRESSURE DROP	106.94	100.82	90.74	108.19
FUEL ASSEMBLY HEIGHT	8.91	9.00	9.73	8.95
PRIMARY HOT LEG TEMP F	999.0	1012.0	1027.0	989.0
PRIMARY COLD LEG TEMP F	753.6	766.7	783.1	741.3
INTER. HOT LEG TEMP F	978.0	995.0	1004.0	966.0
INTER. COLD LEG TEMP F	600.0	608.0	630.0	604.0
STEAM TEMP. F	936.0	942.0	961.0	908.0
FINAL FEED TEMP. F	348.0	346.0	362.0	402.0
STEAM PRESSURE PSIG	2700.0	2815.0	2800.0	2515.0

STEAM GENERATOR				
H.T. AREA 10E3 SQ-FT	63.30	58.78	58.50	62.72
TURE LENGTH FT	160.66	150.00	147.96	157.27
TURE O.D. IN	.553	.560	.555	.566
NUMBRER OF TURES	2721.6	2674.9	2720.7	2689.9
H2O M.V. 10E6LB/FT2-HR	1.6675	1.6850	1.6800	1.6550
NA M.V. 10E6LB/FT2-HR	.7175	.7075	.7150	.7500
H2O PRESSURE DROP PSI	285.48	254.97	267.86	277.81
NA PRESSURE DROP PSI	18.43	21.84	17.57	18.34

IMX				
H.T. AREA 10E3 SQ-FT	45.70	46.81	45.17	49.49
TURE LENGTH FT	32.14	34.42	33.18	34.79
TURE OD IN	.6896	.6756	.7260	.7267
NUMBER OF TURES	7877	7689	7163	7478
TURF M.V. 10E6LB/SQFT -HR	2.5250	2.6250	2.5000	2.5000
SHEL M.V. 10E6LB/SQFT -HR	1.3000	1.3500	1.3625	1.3000
TURE PRESSURE DROP PSI	18.431	21.841	17.570	18.339
SHELL PRESSURE DROP PSI	9.584	11.322	11.302	9.745

PRIMARY PUMPS				
POWER 10E3 HP	11.85	11.56	10.60	11.84
SPECIFIC SPEED	3550.0	3430.0	3670.0	3520.0
SHAFT SPEED RPM	736.6	700.7	704.2	740.1
COVER GAS PRESSURE PSIA	49.78	49.90	49.99	49.97
FLOW RATE 10E3 GPM	141.27	141.20	140.92	139.57
HEAD FT NA	333.19	326.24	299.70	336.44

INTERMEDIATE PUMPS				
POWER 10E3 H.P.	3.310	3.609	3.250	3.286
SPECIFIC SPEED	7485.0	7500.0	7500.0	7485.0
SHAFT SPEED RPM	1018.1	1123.9	1006.5	959.5
COVER GAS PRESSURE PSIA	55.46	62.92	54.48	51.68
FLOW RATE 10E3 GPM	88.92	86.73	89.13	92.87
HEAD FT-NA.	139.36	155.95	137.11	132.55

PIPING				
PRIMARY FLOW VEL FT/SEC	24.100	26.288	26.288	24.100
PRIMARY PIPE O.D. IN.	49.449	47.338	47.289	49.154
INTER. FLOW VEL. FT/SEC	33.750	35.000	33.750	32.650
INTER. PIPE O.D. IN	33.31	32.32	33.35	34.59
STEAM FLOW VEL. FPS	230.00	280.00	280.00	290.00
STEAM PIPE O.D. IN	31.121	27.980	28.370	28.500
WALL THICKNESS IN	4.629	4.317	4.409	3.941

	12 MO. DWELL	18 MO. DWELL
FUEL CYCLE COSTS M/KW-HR	1.2798	.9554
CAPITAL COSTS M/KW-HR	2.5836	2.5656
TOTAL COSTS M/KW-HR	3.8635	3.5210
STEAM GENERATORS 10E6 \$	8.785	8.877
IMXS 10E6 \$	3.585	3.231
PRIMARY PUMPS 10E6 \$	2.776	2.629
INTERMEDIATE PUMP 10E6\$	1.099	1.082

PRIMARY PIPING	10F6	1.072	1.056
INTERMED PIPING	10F6	.683	.678
REACTOR VESSEL	10F6	2.158	2.108
CAPITAL INVEST.	\$/KW	140.15	139.17
REACTOR POWER	MWT	2640.0	2630.0
NET ELECTRICAL OUT. MWF		1051.9	1051.9
NET TURBINE PLANT W.R.		8385.6	8362.1
PLANT EFFICIENCY		.3984	.3999
REACTOR PRESSURE DROP		104.42	105.59
FUEL ASSEMBLY HEIGHT		8.38	8.49
PRIMARY HOT LEG TEMP F		969.0	982.0
PRIMARY COLD LEG TEMP F		730.6	731.1
INTER. HOT LEG TEMP F		946.0	951.0
INTER. COLD LEG TEMP F		608.0	608.0
STEAM TEMP. F		905.0	913.0
FINAL FEED TEMP. F		402.0	394.0
STEAM PRESSURE PSIG		2545.0	2585.0
STEAM GENERATOR			
H.T. AREA	10E3 SQ-FT	68.37	69.85
TUBE LENGTH	FT	161.45	167.35
TUBE O.D.	IN	.533	.543
NUMBER OF TUBES		3034.6	2937.2
H2O M.V. 10F6LR/FT2-HR		1.6800	1.6700
NA M.V. 10F6LR/FT2-HR		.7300	.7350
H2O PRESSURE DROP PSI		315.95	315.26
NA PRESSURE DROP PSI		16.80	17.62
IXX			
H.T. AREA	10E3 SQ-FT	52.77	47.12
TUBE LENGTH	FT	32.81	31.96
TUBE O.D.	IN	.7092	.7224
NUMBER OF TUBES		8661	7796
TUBE M.V. 10F6LR/SQFT -HR		2.4250	2.5500
SHELL M.V. 10F6LR/SQFT -HR		1.1875	1.2312
TUBE PRESSURE DROP PSI		16.800	17.620
SHELL PRESSURE DROP PSI		10.259	9.669
PRIMARY PUMPS			
POWER	10E3 HP	12.07	11.40
SPECIFIC SPEED		3490.0	3565.0
SHAFT SPEED	RPM	711.8	744.9
COVER GAS PRESSURE PSIA		49.96	49.98
FLOW RATE	10E3 GPM	144.58	136.95
HEAD	FT-NA	330.70	329.44
INTERMEDIATE PUMPS			
POWER	10E3 W.P.	2.921	2.894
SPECIFIC SPEED		7470.0	7500.0
SHAFT SPEED	RPM	805.0	821.2
COVER GAS PRESSURE PSIA		39.63	39.92
FLOW RATE	10E3 GPM	99.45	97.65
HEAD	FT-NA	110.09	111.08
PIPING			
PRIMARY FLOW VEL FT/SEC		25.350	24.413
PRIMARY PIPE O.D. IN.		48.760	48.382
INTER. FLOW VEL. FT/SEC		29.212	28.900
INTER. PIPE O.D. IN		37.81	37.67
STEAM FLOW VEL. FPS		300.00	300.00
STEAM PIPE O.D. IN		27.894	27.814
WALL THICKNESS IN		3.887	3.943

4 MODULE CORE STEAM CONDITIONS

	3500/ 850	3500 / 908	3500 / 948	3500/ 960	3500/ 990
FUEL CYCLE COSTS M/KW-HR	.7508	.7318	.7808	.7775	.7720
CAPITAL COSTS M/KW-HR	2.5578	2.5671	2.5001	2.5022	2.5177
TOTAL COSTS M/KW-HR	3.3085	3.2989	3.2809	3.2797	3.2897
STEAM GENERATORS 10E6 \$	8.349	8.453	7.599	7.664	8.510
IXXS 10E6 \$	3.076	3.767	3.031	3.170	2.913
PRIMARY PUMPS 10E6 \$	2.419	2.464	2.901	2.935	3.166
INTERMEDIATE PUMP 10E6\$	1.026	1.082	1.071	1.068	1.049
PRIMARY PIPING 10E6 \$	.929	.951	1.074	1.085	1.171
INTERMED PIPING 10E6 \$	.617	.574	.554	.550	.546
REACTOR VESSEL 10E6 \$	2.186	2.190	2.047	2.078	2.165
CAPITAL INVEST. \$/KW	138.75	139.26	135.62	135.73	136.58
REACTOR POWER MWT	2715.0	2600.0	2627.5	2620.0	2592.5
NET ELECTRICAL OUT.MWE	1051.4	1050.1	1051.6	1051.8	1051.4
NET TURBINE PLANT H.R.	8638.9	8268.2	8334.9	8303.2	8207.8
PLANT EFFICIENCY	.3873	.4039	.4002	.4015	.4055
REACTOR PRESSURE DROP	111.72	110.11	96.03	99.10	104.12
FUEL ASSEMBLY HEIGHT	9.50	9.24	8.30	8.32	8.31
PRIMARY HOT LEG TEMP F	976.0	988.0	1014.0	1016.0	1028.0
PRIMARY COLD LEG TEMP F	690.4	719.4	784.7	789.6	819.3
INTER. HOT LEG TEMP F	944.0	970.0	994.0	1000.0	1007.0
INTER. COLD LEG TEMP F	563.0	615.0	632.0	635.0	642.0
STEAM TEMP. F	850.0	908.0	948.0	960.0	990.0
FINAL FEED TEMP. F	300.0	383.0	304.0	303.0	308.0
STEAM PRESSURE PSIG	3500.0	3500.0	3500.0	3500.0	3500.0
STEAM GENERATOR					
H.T AREA 10E3 SQ-FT	62.18	60.19	52.56	53.08	63.78
TUBE LENGTH FT	161.06	151.76	157.00	158.73	192.74
TUBE O.D. IN	.510	.500	.529	.527	.526
NUMBER OF TUBES	2892.3	3027.4	2417.6	2423.9	2400.9
H2O M.V. 10E6LB/FT2-HR	2.3000	2.2450	2.2850	2.2700	2.2750
NA M.V. 10E6LB/FT2-HR	.7100	.7050	.8570	.8470	.8470
H2O PRESSURE DROP PSI	95.68	87.07	86.21	85.98	98.68
NA.PRESSURE DROP PSI	25.43	35.57	29.84	31.68	25.45
IXX					
H.T. AREA 10E3 SQ-FT	43.50	54.54	43.83	45.43	35.57
TURE LENGTH FT	32.56	37.16	34.39	34.61	25.34
TURE OD IN	.6555	.5923	.6634	.6366	.5900
NUMBER OF TUBES	7784	9465	7337	7875	9086
TUBE M.V.10E6LB/SQFT -HR	2.8750	2.9875	3.0500	3.0531	3.0500
SHEL M.V.10E6LB/SQFT -HR	1.2050	1.0925	1.5350	1.4912	1.4725
TURE PRESSURE DROP PSI	25.429	35.566	29.837	31.676	25.447
SHELL PRESSURE DROP PSI	10.034	9.895	11.962	11.820	11.149
PRIMARY PUMPS					
POWER 10E3 HP	10.83	10.94	11.97	12.39	13.85
SPECIFIC SPEED	3365.0	3410.0	3455.0	3432.5	3395.0
SHAFT SPEED RPM	770.2	765.4	665.1	669.9	656.2
COVER GAS PRESSURE PSIA	50.00	49.96	49.54	49.99	49.94
FLOW RATE 10E3 GPM	123.17	126.21	151.45	153.07	165.36
HEAD FT NA	346.57	343.19	315.84	323.93	336.67
INTERMEDIATE PUMPS					
POWER 10E3 H.P.	3.229	4.439	4.192	4.270	3.850
SPECIFIC SPEED	7500.0	7500.0	7500.0	7485.0	7500.0
SHAFT SPEED RPM	983.3	1196.0	1154.7	1183.8	1110.7
COVER GAS PRESSURE PSIA	48.63	67.67	66.01	67.57	62.47
FLOW RATE 10E3 GPM	89.92	93.49	93.06	92.11	91.29
HEAD FT-NA.	133.68	178.13	169.44	174.45	158.85

PIPING					
PRIMARY FLOW VEL FT/SEC	25.000	25.000	26.500	26.500	26.500
PRIMARY PIPE O.D. IN.	45.398	45.928	48.800	49.855	50.954
INTER. FLOW VEL. FT/SEC	35.000	32.750	33.650	33.650	33.650
INTER. PIPE O.D. IN	35.88	34.64	34.11	33.94	33.79
STEAM FLOW VEL. FPS	295.00	292.50	297.50	300.00	300.00
STEAM PIPE O.D. IN	24.260	26.129	25.805	25.873	26.346
WALL THICKNESS IN	4.221	4.696	4.745	4.791	4.966

	IMX H.E. 17 F	IMX H.E. 31 F	SG H.E. 22 F	SG H.E. 58 F
FUEL CYCLE COSTS M/KW-HR	.7750	.7844	.7488	.7667
CAPITAL COSTS M/KW-HR	2.5382	2.5229	2.5551	2.5318
TOTAL COSTS M/KW-HR	3.3132	3.3073	3.3040	3.2985
STEAM GENERATORS 10E6 \$	8.161	7.483	9.309	8.217
IMXS 10E6 \$	3.655	2.848	3.032	3.147
PRIMARY PUMPS 10E6 \$	2.483	2.734	2.637	2.717
INTERMEDIATE PUMP 10E6 \$	1.009	1.017	1.078	1.016
PRIMARY PIPING 10E6 \$	.833	1.117	1.037	.993
INTERMED PIPING 10E6 \$	.596	.569	.560	.538
REACTOR VESSEL 10E6 \$	1.903	2.188	2.188	2.084
CAPITAL INVEST. \$/KW	137.69	136.86	138.61	137.34
REACTOR POWER MWT	2642.5	2750.0	2625.0	2627.5
NET ELECTRICAL OUT. MWE	1051.8	1051.9	1051.8	1051.8
NET TURBINE PLANT H.R.	8427.7	8737.6	8336.8	8348.3
PLANT EFFICIENCY	.3980	.3825	.4007	.4003
REACTOR PRESSURE DROP	81.25	108.56	108.56	101.40
FUEL ASSEMBLY HEIGHT	8.45	8.99	8.99	8.59
PRIMARY HOT LEG TEMP F	987.0	999.0	999.0	1003.0
PRIMARY COLD LEG TEMP F	719.3	746.5	746.5	757.2
INTER. HOT LEG TEMP F	970.0	963.0	964.0	982.0
INTER. COLD LEG TEMP F	590.0	573.0	616.0	604.0
STEAM TEMP. F	911.0	922.0	942.0	924.0
FINAL FEED TEMP. F	387.0	316.0	364.0	376.0
STEAM PRESSURE PSIG	2460.0	2010.0	2720.0	2740.0
STEAM GENERATOR				
H.T. AREA 10E3 SQ-FT	62.70	55.08	73.61	61.64
TUBE LENGTH FT	160.61	147.75	174.38	157.47
TUBE O.D. IN	.566	.529	.526	.568
NUMBER OF TUBES	2634.5	2689.9	3066.4	2633.0
H2O M.V. 10E6 LB/FT2-HR	1.6400	1.6150	1.6675	1.7025
NA M.V. 10E6 LB/FT2-HR	.7300	.7450	.7025	.7300
H2O PRESSURE DROP PSI	281.07	338.63	339.62	269.49
NA PRESSURE DROP PSI	20.35	12.97	16.11	18.72
IMX				
H.T. AREA 10E3 SQ-FT	54.41	36.50	44.80	46.55
TUBE LENGTH FT	36.03	24.40	32.00	33.99
TUBE OD IN	.6658	.6879	.7603	.7127
NUMBER OF TUBES	8663	8304	7034	7341
TUBE M.V. 10E6 LB/SQFT -HR	2.4500	2.4250	2.5125	2.5250
SHEL M.V. 10E6 LB/SQFT -HR	1.1125	1.2500	1.3000	1.3500
TUBE PRESSURE DROP PSI	20.351	12.966	16.115	18.717
SHELL PRESSURE DROP PSI	13.028	9.106	10.042	11.565
PRIMARY PUMPS				
POWER 10E3 HP	9.22	12.08	11.66	11.59
SPECIFIC SPEED	3520.0	3565.0	3445.0	3385.0
SHAFT SPEED RPM	677.4	740.0	738.5	697.3
COVER GAS PRESSURE PSIA	49.83	49.87	49.81	49.99
FLOW RATE 10E3 GPM	128.66	142.78	136.29	140.44
HEAD FT NA	283.17	335.76	339.78	328.69

INTERMEDIATE PUMPS

POWER 10E3 H.P.	2.921	2.695	3.508	3.234
SPECIFIC SPEED	7500.0	7470.0	7470.0	7500.0
SHAFT SPEED RPM	935.4	864.5	962.6	1007.5
COVER GAS PRESSURE PSIA	45.54	43.48	55.15	53.87
FLOW RATE 10E3 GPM	88.33	89.24	96.28	88.58
HEAD FT-NA.	123.58	112.62	136.73	136.71

PIPING

PRIMARY FLOW VEL FT/SEC	29.100	24.062	24.725	26.600
PRIMARY PIPE O.D. IN.	42.980	49.765	47.965	46.930
INTER. FLOW VEL. FT/SEC	29.837	31.562	34.525	33.125
INTER. PIPE O.D. IN	35.31	34.52	34.23	33.56
STEAM FLOW VEL. FPS	240.00	300.00	230.00	280.00
STEAM PIPE O.D. IN	31.324	29.364	31.329	28.243
WALL THICKNESS IN	4.264	3.429	4.704	4.220

Figure 1 Optimized Reference Plant Design Parameters with Moisture Separation Only

Figure 2 Reactor Bulk Temperature Rise as a Function of Reactor Bulk Outlet Temperature

Figure 3 Effect of Plutonium Cost on Power Cost for One- and Four-Module Core Plant

Figure 4 Effect of Fabrication Cost on Power Cost for One- and Four-Module Reactor Plant

3160-2

Figure 5 Effect of Maximum Sodium Velocity on Power Cost for one- and four-Module Reactor Plant

3160-1

Figure 6 Effect of Average Burnup on Power Cost for One- and Four-Module Reactor Plant

Figure 7 Effect of Fuel Swelling Rate on Power Cost for One- and Four-Module Reactor Plant

Figure 8 Effect of Maximum Fuel Centerline Temperature on Power Cost for One- and Four-Module Reactor Plant

Figure 9 Effect of Fuel Thermal Conductivity on Power Cost for One- and Four-Module Reactor Plant

Figure 10 Effect of Maximum Cladding Temperature on Power Cost for One- and Four-Module Reactor Plants

Figure 11 Effect of Steam Pressure and Temperature on Power Cost for Four-Module Reactor Plant

3160-15

Figure 12 Effect of Reactor Bulk Sodium Outlet Temperature on Power Cost, Plant Capital Cost, and Fuel Cycle Cost for One- and Four-Module Reactors with and without Variable Feedwater Temperature

Figure 13 Steam Generator Temperature ~ Enthalpy Relations for Various Reactor Bulk Sodium Outlet Temperatures, Four-Module Core, Constant Feedwater Temperature.

3160-20

Figure 14 Steam Generator Temperature ~ Enthalpy Relations for Various Reactor Bulk Sodium Outlet Temperatures, Single-Module Core Constant Feedwater Temperature

Figure 15 Steam Generator Temperature ~ Enthalpy Relations for Various Reactor Bulk Sodium Outlet Temperatures Four-Module Core Variable Feedwater Temperature

Figure 16 Steam Generator Temperature ~Enthalpy Relations for Various Reactor Bulk Sodium Outlet Temperatures, Single-Module Core, Variable Feedwater Temperature

Figure 17 System Temperatures vs. Bulk Sodium Outlet Temperature, Constant Feedwater Temperature, Single and Four-Module Cores

3160-22

Figure 18 System Temperatures vs. Bulk Sodium Outlet Temperature, Variable Feedwater Temperature, Four-Module Core

Figure 19 System Temperatures vs Bulk Sodium Outlet Temperature. Variable Feedwater Temperature. Single-Module Core

Figure 20 Effect of Bulk Reactor Outlet Temperature on Steam Pressure, Four-Module Core Plant

3160-10

Figure 21 Effect of Bulk Reactor Outlet Temperature on Component Costs, Four-Module Reactor Plant

3160-35

Figure 22 Effect of Bulk Reactor Outlet Temperature on Component Costs, One-Module Reactor Plant

Figure 23 Effect of Blanket Thickness on Power Cost, Single-Module Reactor Plant

Figure 24 Effect of Doubling Time Associated with Blanket Thickness on Power Cost for One-Module Reactor Plant

3160-8

Figure 25 Effect of Fuel Dwell Time on Power Cost for One- and Four-Module Reactor Plant

Figure 26 Effect of Steam Generator Hot-End Temperature Difference Constraint on Power Cost for Four-Module Core Plant

3160-6

Figure 27 Effect of Intermediate Heat Exchanger Hot-End Temperature Difference Constraint on Power Cost for Four-Module Core Plant

3160-5

Figure 28 Fuel Cycle Cost as a Function of Fuel Rod Diameter

Figure 29 Fuel Rod Diameter as a Function of Fuel Residence Time

3160-16

Figure 30a

Four-Module Core -- Reference Case

Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 30b

Four-Module core -- Reference Case

Core Pressure Drop vs. Bulk Sodium Outlet Temperature with minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 30c

Four- Module Core -- Reference Case

Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Fuel Rod Spacing Constant at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 30d

Four-Module Core -- Reference Case

Reactor inlet temperature vs. bulk sodium outlet temperature at core heights of 3, 3½, 4, 4½, and 5 feet.

Figure 31a

Single-Module Core -- Reference Case

Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 31b

Single-Module Core -- Reference Case

Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 31c

Single-Module Core -- Reference Case

Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Fuel Rod Spacing Constant at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 3Id

Single-Module Core -- Reference Case

Reactor inlet temperature vs. bulk sodium outlet temperature at core heights of 3, 3½, 4, 4½, and 5 feet.

Figure 32a

Single-Module Core -- \$5000/kg Fissile Plutonium

Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 32b

Single-Module Core -- \$5,000/kg Fissile Plutonium

Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3 1/2, 4, 4 1/2, and 5 Feet.

Figure 32c

Single-Module Core -- \$5000/kg Fissile Plutonium

Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Fuel Rod Spacing Constant at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 32d

Single-Module Core -- \$5,000/kg Fissile Plutonium

Reactor inlet temperature vs. bulk sodium outlet temperature at core heights of 3, 3½, 4, 4½, and 5 feet.

Figure 33a

Single-Module Core -- \$20,000/kg Fissile Plutonium

Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 33b

Single-Module Core -- \$20,000/kg Fissile Plutonium

Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 33c

Single-Module Core -- \$20,000/kg Fissile Plutonium

Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Fuel Rod Spacing Constant at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 33d

Single-Module Core -- \$20,000/kg Fissile Plutonium

Reactor inlet temperature vs. bulk sodium outlet temperature at core heights of 3, 3½, 4, 4½, and 5 feet.

Figure 34a

Single-Module Core -- Thermal Conductivity = 7 Btu/ft-°F-hr

Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 34b

Single-Module Core -- Thermal Conductivity = 7 Btu/ft-°F-hr

Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 34c

Single-Module Core -- Thermal Conductivity = 7 Btu/ft-°F-hr

Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Fuel Rod Spacing Constant at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 34d

Single-Module Core -- Thermal Conductivity = 7 Btu/ft-°F-hr

Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 35a

Single-Module Core -- Thermal Conductivity = 12 Btu/ft-°F-hr

Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 35b

Single-Module Core -- Thermal Conductivity = 12 Btu/ft-°F-hr

Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 35c

Single-Module Core -- Thermal Conductivity = 12 Btu/ft-°F-hr
 Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Fuel Rod
 Spacing Constant at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 35d

Single-Module Core -- Thermal Conductivity = 12 Btu/ft-°F-hr
 Reactor inlet temperature vs. bulk sodium outlet temperature at core heights of 3, 3½, 4, 4½, and 5 feet.

Figure 36a

Single-Module Core -- Fuel Centerline Temperature = 2,136 °F

Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 36b

Single-Module Core -- Fuel Centerline Temperature = 2,136 °F

Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 36c

Single-Module Core -- Fuel Centerline Temperature = 2,136 °F

Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Fuel Rod Spacing Constant at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 36d

Single-Module Core -- Fuel Centerline Temperature = 2,136 °F

Reactor inlet temperature vs. bulk sodium outlet temperature at core heights of 3, 3½, 4, 4½, and 5 feet.

Figure 37a

Single-Module Core -- Fuel Centerline Temperature = 2,545 °F

Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 37b

Single-Module Core -- Fuel Centerline Temperature = 2,545 °F

Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 37c

Single-Module Core -- Fuel Centerline Temperature = 2,545 °F

Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Fuel Rod Spacing Constant at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 37d

Single-Module Core -- Fuel Centerline Temperature = 2,545 °F

Reactor inlet temperature vs. bulk sodium outlet temperature at core heights of 3, 3½, 4, 4½, and 5 feet.

Figure 38a

Single-Module Core -- Cladding Surface Temperature = 1,189 °F

Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 38b

Single-Module Core -- Cladding Surface Temperature = 1,189 °F
 Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod
 Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core
 Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 38c

Single-Module Core -- Cladding Surface Temperature = 1,189 °F

Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Fuel Rod Spacing Constant at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 38d

Single-Module Core -- Cladding Surface Temperature = 1,189 °F

Reactor inlet temperature vs. bulk sodium outlet temperature at core heights of 3, 3½, 4, 4½, and 5 feet.

Figure 39a

Single-Module Core -- Cladding Surface Temperature = 1,284 °F

Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 39b

Single-Module Core -- Cladding Surface Temperature = 1,284 °F
 Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 39c

Single-Module Core -- Cladding Surface Temperature = 1,284 °F

Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Fuel Rod Spacing Constant at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 39d

Single-Module Core -- Cladding Surface Temperature = 1,284 °F
Reactor inlet temperature vs. bulk sodium outlet temperature at core heights of 3, 3½, 4, 4½, and 5 feet.

Figure 40a

Single-Module Core -- Burnup = 50,000 MWD

Fuel Cycle Cost vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 40b

Single-Module Core -- Burnup = 50,000 MWD

Core Pressure Drop vs. Bulk Sodium Outlet Temperature with Minimum Fuel Rod Spacing Constant and Sodium Velocity Constant at 30 ft/sec; both at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 40c

Single-Module Core -- Burnup = 50,000 MWD

Sodium Coolant Velocity vs. Bulk Sodium Outlet Temperature with Fuel Rod Spacing Constant at Core Heights of 3, 3½, 4, 4½, and 5 Feet.

Figure 41 Cross-Sectional View of Alternate Reactor Concept

3160-17

Figure 42 Radial Power Distribution

Figure 43 Simplified Flow Diagram of Executive Program OPT

Figure 44 Schematic Showing Components of Plant Model

Figure 45 Simplified Flow Diagram of Subroutine CALC

(1) No.	(2) STEAM COND.	(3) WLTD H.R.	(4) RANKINE H.R.	(5) WLTD H.R. RANKINE HR.	(6) CORRELATION TO COL 5
1	3515/1050	7702	7645	1.0074	1.0055
2	3515/1000	7815	7731	1.0109	1.0120
3	3615/900	8095	7927	1.0212	1.0217
4	2415/1000	8011	7841	1.0216	1.0215
5	2415/900	8208	8008	1.0249	1.0318
6	2415/850	8429	8100	1.0407	1.0349
7	1815/1000	8247	7968	1.0350	1.0353
8	1815/900	8515	8128	1.0475	1.0449
9	1015/D&S	9702	9087	1.0676	1.0684

Figure 46 Rankine Cycle

Figure 47 Triangular Pitch Tube Geometry

REFERENCES

1. J. Weisman, et al., "Optimal III - A Digital Computer Code for the Optimization of Pressurized Water Reactor Systems," WCAP-2895.
2. "Large Sodium Pump Design Study" WARD-3762-1.
3. A. A. Bishop, et al., "High Temperature Supercritical Water Loop", WCAP-2056.