42

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A FUEL CYCLE ECONOMIC ANALYSIS OF OXIDE FUELED POWER AND PROCESS HEAT PWR's FOR SEAWATER DESALINATION

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CONTENTS

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ABSTRACT

Economic studies were conducted to determine minimum equilibrium fuel cycle costs for two oxide fueled PWR concepts. Each reactor is to be used to generate steam for a single-purpose desalination plant. The two reactor concepts studied were a commercial "product line" power reactor and a lower temperature process heat reactor. Fuel cycle costs were based on economic ground rules believed to be representative for reactors going "on-line" in the 1980's.

The study indicated that, for a publicly owned reactor utilizing a privately owned 75,000 Mwth capacity fabrication plant, equilibrium fuel cycle costs of 0.348 mills/kwhr(t) and 0.324 mills/kwhr(t) could be expected from commercial power and process heat reactors, respectively. These costs are based on an ore cost of \$8.00/lb U_3O_8, a separative work charge of \$26/kg U and a tails of 0.20 w/o ^{235}U. For a privately owned reactor using the same fabrication-reprocessing complex, corresponding fuel cycle costs are .385 and .367 mills/kwhr(t). If the reactor is publicly owned and the complex is publicly owned with a 15,000 Mwth industry capacity, equilibrium fuel cycle costs are 0.402 and 0.381 mills/kwhr(t), respectively.

INTRODUCTION AND SUMMARY

Economic studies were conducted to determine minimum equilibrium fuel cycle costs for two oxide fueled PWR concepts. The two reactor concepts studied were a commercial "product line" power reactor and a lower temperature process heat reactor. Each reactor is to be used to generate steam for a single-purpose desalination plant. The fuel cycle costs generated in this study for the commercial power reactor are to be used in an overall economic evaluation of current PWR concepts. This evaluation will become a reference for comparison with advanced reactor concepts. The lower temperature process heat reactor was investigated to determine the extent of fuel cycle cost savings that can be realized by taking advantage of the decreased temperature and Doppler reactivity effects inherent in the concept. The reactors were sized to generate prime steam for a water plant capable of producing approximately 550 MGD of fresh water. The fresh water production was identical for each concept, although the reactor rating in thermal megawatts is higher for the process heat reactor. Fuel cycle costs were based on ground rules believed to be representative of reactors going on-line in the 1980's.

The Westinghouse Diablo Canyon fuel element design was chosen as the reference configuration for both reactors. Variation of the water-to-fuel ratio and enrichment for the power reactor concept indicated that the minimum fuel cycle cost was achieved for a design identical to Westinghouse's proposed Diablo Canyon reactor. The reactor develops 3250 Mwth at a system pressure of 2250 psia and an average coolant temperature of 575°F. Fuel rods consist of 0.3669-in. diameter pellets, with a clad thickness of 0.0243-in. and are set on a square pitch of 0.563-in. The equilibrium feed enrichment of 3.3 w/o ^{235}U produces 33,100 Mwd/Tonne burnup. For a publicly financed reactor and privately financed high capacity (75,000 Mwth) fabrication plant and a 10 Tonnes/day multipurpose reprocessing plant, the power reactor has fuel cycle costs of 0.360 and 0.348 mills/kwhr(t) (10.55 and 10.20 ¢/10^6 BTU) for the old and recently revised AEC separative work charges, respectively.

A similar parametric analysis was conducted for the process heat reactor concept. The process heat reactor develops 4307 Mwth at a system pressure of 500 psia and an average coolant temperature of 355°F. Fuel rods consist of 0.48-in. diameter pellets, with a 0.024-in. clad thickness and are set on a square pitch of 0.632-in. The equilibrium feed enrichment of 2.8 w/o ^{235}U produces 28,900 Mwd/Tonne burnup. For a publicly owned reactor and privately owned fabrication and processing plants, the process heat reactor has fuel cycle costs of 0.335 and 0.324 mills/kwhr(t) (9.82 and 9.50 ¢/10^6 BTU) for the old and recently revised separative work charges, respectively.

Two other economic conditions were investigated. These were:

(1) A privately financed reactor with privately financed fabrication and reprocessing plants. For both concepts, fuel cycle costs

were about 12% higher than for the publicly owned reactor plant using the same fabrication and reprocessing plants.

(2) A publicly financed reactor with publicly financed, low capacity (15,000 Mwth) fabrication and reprocessing plants. Fuel cycle costs were 18% higher than those for the publicly financed reactor using the high capacity privately financed processing plants.

Fuel cycle costs were calculated for all economic conditions using both old and recently revised AEC separative work charges.

ECONOMIC GROUND RULES

The fuel cycle cost minimization for both power and process heat reactor concepts was based on ground rules which are believed to be representative of economic conditions in the 1980's. Three different sets of economic conditions were investigated for each concept. These conditions are:

Condition I

A publicly financed reactor plant utilizing an off-site, privately financed fabrication-reprocessing plant complex. The fabrication and reprocessing plants are at the same site and are centrally located. The fabrication plant is capable of supporting a 75,000 Mwth industry of the same reactor type as studied. The reprocessing plant is multi-purpose and rated at 10 tonnes/day of heavy metal.

Condition II

A privately financed reactor plant utilizing the same fabrication and reprocessing plant complex used in Condition I.

Condition III

A publicly financed reactor plant utilizing an on-site publicly financed fabrication-reprocessing plant complex. The fabrication and reprocessing plants are both located at the reactor site. The fabrication plant is capable of supporting a 15,000 Mwth industry of the same reactor type as studied. The reprocessing plant is rated at 0.6 tonnes/day of heavy metal.

The publicly owned reactor is characterized by a 7% fixed charge rate on depreciating capital and a 5% fixed charged rate on non-depreciating capital investment. The present-worth discount factor is 4%. A privately owned reactor is assumed to have a 12% fixed charge rate on depreciating capital, a 10% fixed charge rate on non-depreciating capital investment, and a 6% present-worth discount factor. Publicly owned central processing and fabrication plants are characterized by a 7.7% fixed charge rate on capital investment while privately owned plants are assumed to have a 22% fixed-charge rate.

A reactor plant factor of 0.90 was assumed for all conditions. The fuel cycle cost minimization for both reactor concepts was based only on Condition I. The fuel cycle costs for the other two conditions were calculated for the minimized lattices which were selected using Condition I.

The reactors are assumed to begin operation in the period 1980 to 1985 using unirradiated fuel. All costs are computed on an equilibrium cycle basis as if the 1985 conditions prevailed throughout the plant lifetime. Plutonium is assumed to be resold without recycle. The fuel cycle cost is resolved into the following components:

1. Makeup Uranium is the cost of the feed fuel at the feed enrichment. The cost is calculated using an assumed ore cost of \$8.00/lb U_3O_8, an assumed separative work charge of \$30/kg U, and an optimum tails concentration of 0.2594 w/o ^{235}U. Fuel cycle costs were also calculated with the recently revised separative work charge for the reference designs minimized using the old price schedule. The revised schedule assumes a separative work charge of \$26/kg U, and a tails concentration of .20 w/o ^{235}U. The cost of converting U_3O_8 to UF_6 is assumed to be \$1.35/kg U.

2. Uranium Credit is the credit for the uranium discharged from the reactor at the end of the fuel residence. The cost was calculated on the same basis described above with no penalty for ^{236}U content.

3. Plutonium Credit is the credit for fissile plutonium discharged at the end of the fuel residence. Fissile plutonium is valued at 5/6 of the value of 90% enriched uranium, i.e., \$9.76/gm Pu. The plutonium value under the new AEC separative work charge and tails

enrichment is \$9.08/gm Pu. The sum of the first three components is called the "net fissile burnup cost" for the cycle.

4. Processing is the cost of reprocessing spent fuel. Uranium is discharged from the reprocessing plant in the form of UF_6 and the assumed cost of converting uranyl nitrate to the fluoride is \$1.35/kg. Losses are assumed to be 0.25% per pass. Plutonium is sold in the nitrate form. Interest on working capital invested in processing is considered negligible.

5. Fabrication is the cost of fabricating feed fuel. The cost of converting UF_6 to UO_2 powder is included in the fabrication cost. Unit fabrication costs are calculated using the FABCOST[1] computer code. The price of fabricated fuel is assumed to remain constant throughout the plant life. Uranium losses are assumed to be 0.2% per pass.

6. Interest on Fabrication is charged on capital invested in the fabrication of the fuel elements. The interest is calculated in the same manner as the inventory charge on fuel. The fuel elements are assumed to depreciate linearly with time over the period of irradiation.

7., 8., 9. Fabrication, Core, and Processing Inventory Charges are interest charges on capital invested in the fissile materials required in the fabrication, irradiation, and processing of the fuel. Ownership of fissile and fertile materials during fabrication and processing as well as when on-site at the reactor, is considered to be vested in the reactor plant. For core inventory charges, changes from initial to final values are assumed to occur linearly with time during irradiation. Charges are calculated on a simple interest basis and assumed holdup times are presented in Table 1.

10. Shipping is the cost of shipping both fresh and spent fuel to and from the reactor plant. Interest on working capital invested in shipping is considered negligible. The unit shipping costs are assumed to be the same regardless of the fresh fuel enrichment or irradiation of the spent fuel.

A condensed list of pertinent economic ground rules is presented in Table 1.

Table 1. A Condensation of the "1985 Desalination Ground Rules" for Three Economic Conditions

	Condition I	Condition II	Condition III
<u>Fuel Materials</u>			
Cost of Natural U_3O_8, \$/lb, U_3O_8	8.00	8.00	8.00
Cost of Separative Work, \$/kg U	30.00, 26.00	30.00, 26.00	30.00, 26.00
Value of Fissile Plutonium \$/gm fissile Pu	9.76, 9.08	9.76, 9.08	9.76, 9.08
Cost of Conversion, $U_3O_8 \rightarrow UF_6$, \$/kg U	1.35	1.35	1.35
Cost of Reconversion, UNH $\rightarrow UF_6$, \$kg U	1.35	1.35	1.35
Tails Concentration, w/o ^{235}U	0.2594, 0.20	0.2594, 0.20	0.2594, 0.20
<u>Reactor Plant</u>			
Reactor Plant Capacity Factor, %	90	90	90
Preirradiation Holdup Time, days	108	108	100
Postirradiation Holdup Time, days	168	168	160
Fixed Charge Rate on Depreciating Capital, %/yr	7	12	7
Fixed Charge Rate on Non-Depreciating Capital, %/yr	5	10	5
Average Cost of Money, %/yr	4	6	4
<u>Fuel Fabrication Plant</u>			
Industry Served by Plant, Mwth	75,000	75,000	15,000
Cost of Fuel Preparation, $UF_6 \rightarrow UO_2$, \$/kgU	3.94	3.94	10.00
Fresh Fuel Shipping Charge, \$/kg U	0.50	0.50	--
Fixed Charge Rate on Capital Investment, %/yr	22	22	7.7
Uranium Losses per Pass, w/o U	0.2	0.2	0.2
Operating Days per Year	260	260	260

Table 1 (continued)

	Condition I	Condition II	Condition III
Reprocessing Plant			
Plant Capacity per Operating Day, Tonnes/day	10	10	0.6
Operating Days per Year	260	260	260
Unit Reprocessing Cost (including reconversion), $/kg heavy metal	10.20	10.20	34.50
Uranium Losses per Pass, w/o heavy metal	0.25	0.25	0.25
Spent Fuel Shipping Charge, $/kg heavy metal	3.37	3.37	--

DESIGN BASIS

Reference Configuration

Both the power and process heat reactor concepts were based on the current "product line" 1,000 Mwe Westinghouse PWR core configuration.[2] The core is roughly cylindrical in shape and consists of identical fuel assemblies controlled by rod cluster control (RCC) assemblies. In addition, a soluble neutron poison (boric acid) is employed for long term reactivity control. The RCC assemblies are used for power balancing and to control shutdown and reactivity changes associated with operating transients. The chemical shim is used for control of hot-to-cold shutdown, buildup of xenon and samarium, and reactivity changes associated with the depletion of fissile material and buildup of fission product poisons.

A typical fuel assembly cross section is shown in Fig. 1 and Fig. 2 is an isometric view of the assembly. The fuel assembly consists of a 15 by 15 array with 204 fuel rods, 20 RCC guide thimbles, and a centrally located instrument tube. The rods are located on a square pitch. A fuel rod consists of slightly enriched sintered UO_2 pellets, clad with cold-worked Zircaloy-4 tubing. The RCC guide thimbles and the instrument tube are of stainless steel. The fuel assembly is canless and structural rigidity is achieved by welding the guide thimbles to the top and bottom nozzles, and to nine axially spaced Inconel egg crate grids. At the grid locations, each fuel rod is supported in two perpendicular directions by formed spring clips.

The RCC assemblies are inserted into the fuel assembly guide thimbles. In fuel assemblies where RCC assemblies will not be used, the flow through the unused thimbles is restricted by a plug in the upper nozzle. The control rods are silver-indium-cadmium alloy sealed in stainless steel tubes.

Initially, the core will be loaded with three fuel batches of different enrichments. The central region will contain two batches arranged in a checker-board array and will be surrounded by an outer region containing the third batch. Generally, an inward loading schedule is used for refueling one-third of the core at approximately

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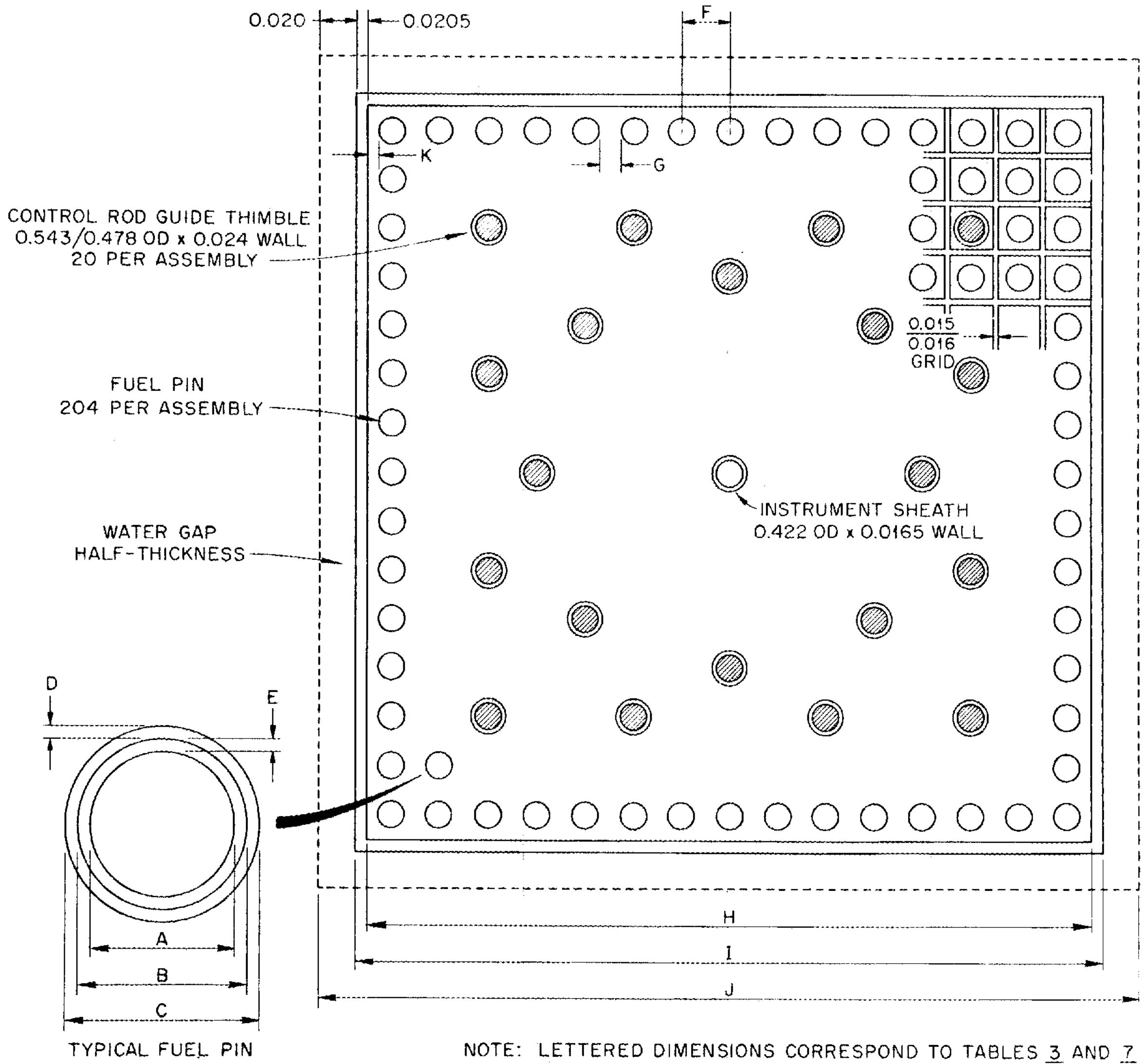

Fig. 1. Reference Configuration of the PWR Fuel Assembly

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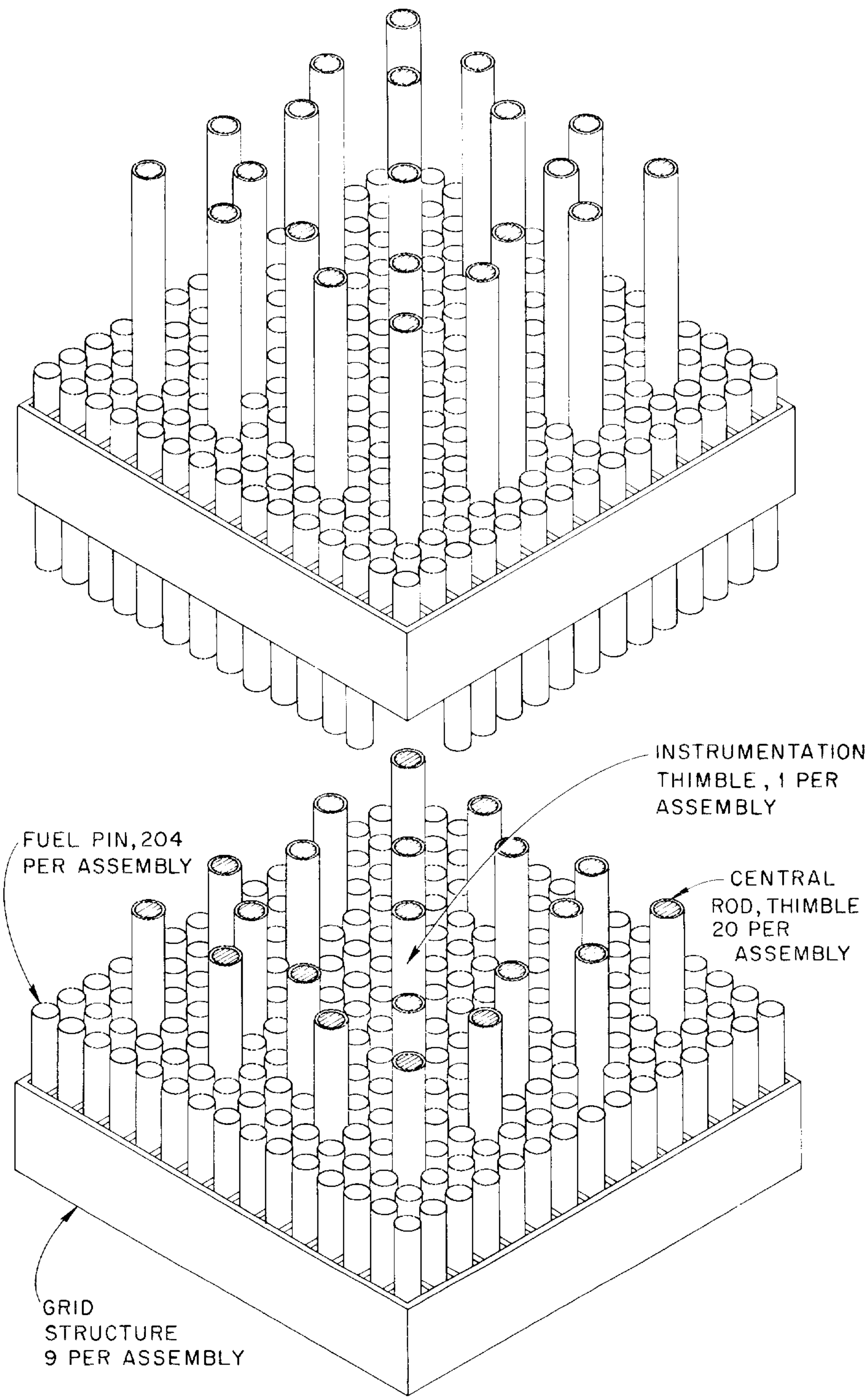

Fig. 2. An Isometric View of the Reference PWR Fuel Assembly

one year intervals. In the equilibrium cycle, all of the feed fuel rods will be of identical enrichment. Fuel pellets will be 93% of theoretical density. The ground rules of the study specify that the equilibrium cycle average fuel burnup cannot exceed the present day design assumption of 33,000 megawatt days per tonne (Mwd/tonne). It has been assumed, for purposes of comparison with other studies, that fuel will be scatter-reloaded uniformly over the whole core.

During the course of the parametric study, the thermal-hydraulic conditions were set such that they were consistent with current design practice for reactors scheduled to go on-line in the period 1970-75. In the following sections, specific mechanical, nuclear, and thermal characteristics are presented for the selected reference cores of the power and process heat reactor concepts.

Power Reactor Reference Core

The selected reference design for the oxide fueled PWR power reactor is identical to Westinghouse's Diablo Canyon reactor in every respect.[3] Variation of both enrichment and water-to-fuel ratio for the reference configuration described above showed that the minimum fuel cycle cost under 1985 desalination ground rules was achieved with the Diablo Canyon core. Tables 2 and 3 give a concise summary of pertinent thermal, hydraulic, and mechanical design parameters. Predicted burnup data are presented in Table 4 and equilibrium fuel cycle costs are given in Table 5 for three sets of economic ground rules. The core layout is shown in Fig. 3.

The reference core develops 3250 Mwth at 2250 psia with coolant inlet and outlet temperatures of 539°F and 608°F, respectively. The equivalent core diameter is 132.7 in. and the active core height is 12 ft. The full power maximum centerline fuel temperature and minimum DNBR at 112% power are estimated by Westinghouse to be 4100°F and 1.30, respectively. The core pressure drop is 28.8 psi. These values are consistent with current PWR technology and are considered acceptable from a safety standpoint. Each fuel rod in the bundle has UO_2 pellets of 3.3 w/o ^{235}U equilibrium enrichment, with a 0.3669 in. pellet diameter, and a 0.420 in. outside rod diameter. The rods are set on a square pitch of 0.563 in. Each core region will have an average equilibrium cycle

Table 2. Thermal-Hydraulic Characteristics of the Power Reactor Reference Design

Thermal Output, Mw	3250
Nominal System Pressure, psia	2250
Average Specific Power, kw/kg UO_2	32.55
Average Heat Flux, Btu/hr/ft^2	207,000
Average Linear Heat Rate, kw/ft	6.7
Hot Channel Factors	
Heat Flux	2.82
Enthalpy Rise	1.70
DNB Ratio at Nominal Conditions	1.81
DNB Ratio at 112% Power	1.30
Average Mass Flow Rate, lbs/hr/ft^2	2.564×10^6
Average Coolant Velocity, ft/sec	15.7
Core Pressure Drop, psi	28.8
Nominal Coolant Inlet Temp., °F	539
Nominal Coolant Outlet Temp., °F	608
Average Core Temp. Rise, °F	69
Nominal Outlet Temp. in Hot Channel, °F	646
Maximum Fuel Centerline Temp., °F	~4100
Maximum Clad Surface Temp., °F	657

Table 3. Mechanical Design Characteristics of the Power Reactor Reference Design

Core	
Equivalent Core Diameter, in.	132.7
Active Core Height, in.	144
Total No. of Fuel Assemblies	193
Total Uranium Loading, kg U	88233
Average Moderator Temperature, °F	575
Overall Water-to-Fuel Volume Ratio, H_2O/UO_2	1.968
Fuel Assemblies	
No. of Fuel Rods	204
No. of Guide Thimbles	20
No. of Instrument Tubes	1
No. of Inconel Grids	9
Bundle Type	RCC-Canless
Pitch (dim. F)[a], in.	.563
Bundle Dimension (dim. G), in.	.141
Bundle Dimension (dim. H), in.	8.425
Bundle Dimension (dim. I), in.	8.466
Bundle Dimension (dim. J), in.	8.506
Bundle Dimension (dim. K), in.	.0605
Fuel Rod	
Pellet Diameter, in.	.3669
Inside Clad Diameter, inc.	.3734
Outside Rod Diameter, in.	.422
Clad Thickness, in.	.0243
Diametral Gap Clearance, in.	.0065
Pellet Fraction of Theoretical Density, %	93
Pellet Material	UO_2-Sintered
Clad Material	Zircaloy 4
No. of Rods in Core	39372

[a]Lettered dimensions shown in Fig. 1.

Table 4. LTM-Predicted Burnup Characteristics of the Power Reactor Reference Design

Initial Enrichment, w/o ^{235}U	3.3
Discharge Enrichment, w/o ^{235}U	.81
Average Fuel Burnup, Mwd/Tonne	33109
Full Power Days per Region[a], days	900
Uranium Charged per Region[a], kg	29411
Uranium Discharged per Region[a], kg	28105
Fraction of ^{235}U Discharged, w/o U	.808
Fraction of ^{236}U Discharged, w/o U	.476
Fraction of ^{238}U Discharged, w/o U	98.716
Fissile Plutonium Produced per Region[a], kg	182.4
Discharge Plutonium Concentration, gm Pu/kgU	6.21
Fraction of ^{239}Pu Discharged, w/o Pu	54.3
Fraction of ^{240}Pu Discharged, w/o Pu	24.2
Fraction of ^{241}Pu Discharged, w/o Pu	15.9
Fraction of ^{242}Pu Discharged, w/o Pu	5.6
Equilibrium Conversion Ratio	.563

[a]A region consists of one-third of the core.

Table 5. Power Reactor Equilibrium Fuel Cycle Costs for Three Sets of Economic Conditions and Two AEC Price Schedules

Cost Component[a]	Condition I[b]		Condition II[c]		Condition III[d]	
	Old[e] Schedule	New[f] Schedule	Old[e] Schedule	New[f] Schedule	Old[e] Schedule	New[f] Schedule
Makeup Uranium	.351	.332	.351	.332	.351	.332
U Credit	−.035	−.035	−.035	−.035	−.035	−.035
Pu Credit	−.076	−.071	−.076	−.071	−.076	−.071
Processing	.014	.014	.014	.014	.044	.044
Fabrication	.064	.064	.064	.064	.091	.091
Interest on Fabrication	.004	.004	.008	.008	.006	.006
Fabrication Inventory	.005	.005	.010	.010	.005	.005
Core Inventory	.027	.027	.055	.053	.027	.027
Processing Inventory	.003	.003	.005	.005	.003	.003
Shipping	.005	.005	.005	.005		
Total, mills/kwhr(t)[g]	.360	.348	.400	.385	.415	.402
Total, ¢/MBtu	10.55	10.20	11.72	11.28	12.16	11.78

[a] All costs are in units of mills/kwhr(t).

[b] Publicly owned reactor with fixed charge rate on non-depreciating capital of 5%. Privately owned central processing and fabrication plants with fixed charge rate of 22% on capital investment. Processing plant is sized for 10 MT/day and fabrication plant serves a 75,000 Mwth industry.

[c] Same as Condition I except reactor is privately owned with 10% fixed charge rate on non-depreciating capital.

[d] Same as Condition I except processing and fabrication plants are on-site and publicly owned (7.7% fixed charge rate on capital investment). Processing and fabrication plants serve a nuclear installation of 15,000 Mwth).

[e] Costs are based on an ore cost of \$8.00/lb U_3O_8, conversion charge of \$1.35/kg, separative work charge of \$30/kg, and optimum tails of 0.2594 w/o ^{235}U.

[f] Costs are based on an ore cost of \$8.00/lb U_3O_8, conversion charge of \$1.35/kg, separative work charge of \$26/kg, and tails of 0.20 w/o ^{235}U.

[g] Total does not necessarily equal sum of components due to roundoff error.

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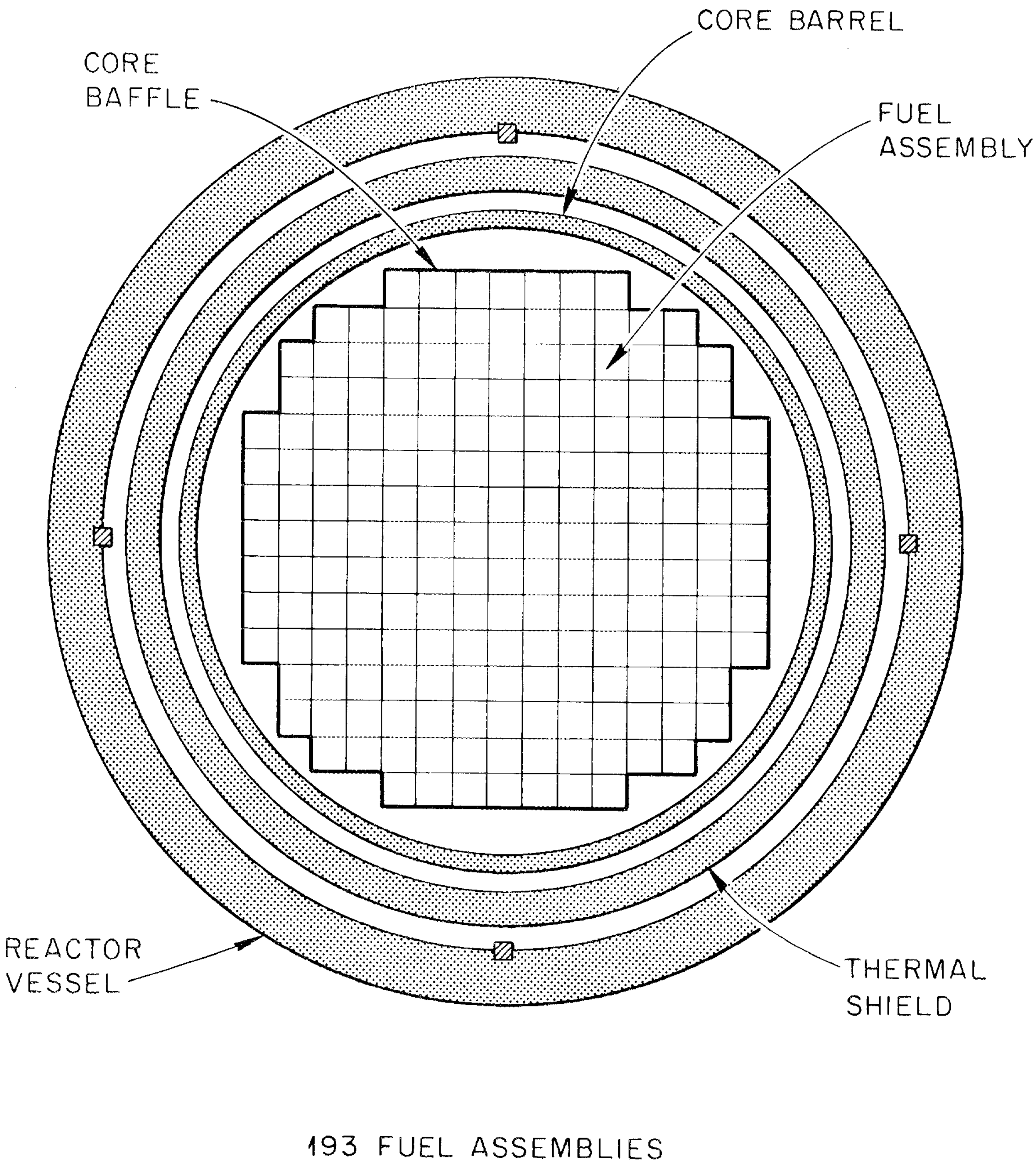

Fig. 3. Core Layout of the Power Reactor Reference Design

burnup of 33,100 Mwd/Tonne and a residence time of 900 full power days. The core has an equilibrium fuel cycle cost of 0.360 mills/kwhr(t) for ground rules described as Condition I. The net fissile burnup cost is 66% of the total cycle cost. Processing and fabrication charges are 23% of the total, while inventory and shipping charges account for the remaining 11%. When the core inventory interest rate is doubled (Condition II) for private financing, the total cycle cost rises to 0.400 mills/kwhr(t). The use of an on-site, publicly financed fabrication-reprocessing complex (Condition III) raises the total cycle cost to 0.415 mills/kwhr(t). This increase is due solely to the lower plant capacities of the on-site complex. The corresponding fuel cycle costs using the recently revised AEC separative work charge and tails concentration are 0.348, 0.385, and 0.402 mills/kwhr(t) for Conditions I, II, and III, respectively.

Although a complete systems analysis was not a part of this particular study, a brief discussion of the water plant is in order. Steam from the reactor steam generators go to back-pressure turbines coupled to a vapor compression-vertical tube evaporator process (VC-VTE). The VTE is assumed to have 15 effects and a performance ratio of 13.0. Electrical generation is limited to on-site power requirements. The additional turbine shaft horse-power from the back-pressure turbine is used by a vapor compressor, which pumps steam from the discharge of Effect 15 (110°F) up to the turbine exhaust temperature (266°F). From this point, the steam combines with the turbine exhaust steam and goes to the brine heater and first effect of the water plant. The plant is capable of producing about 550 MGD of fresh water.

A description of analytical techniques and an analysis of near-optimum lattices are presented in subsequent sections.

Process Heat Reactor Reference Core

Thermal, hydraulic and mechanical design characteristics of the process heat reference reactor are described in Tables 6 and 7. The minimum fuel cycle cost for the specified ground rules was achieved for a core with 2.8 w/o ^{235}U equilibrium enrichment and a water-to-fuel volume ratio of 1.5. Predicted burnup data are described in Table 8 while equilibrium fuel cycle costs for the three sets of ground rules are presented in Table 9.

Table 6. Thermal-Hydraulic Characteristics of the Process Heat Reactor Reference Design

Thermal Output, Mw	4307
Nominal System Pressure, psia	500
Average Specific Power, kw/kg UO_2	22.58
Average Heat Flux, Btu/hr/ft^2	188830
Average Linear Heat Rate, kw/ft	7.2
Hot Channel Factors	
Heat Flux	2.82
Enthalpy Rise	1.70
DNB Ratio at Nominal Conditions	3.93
Average Mass Flow Rate, lbs/hr/ft^2	3.369×10^6
Average Coolant Velocity, ft/sec	16.6
Core Pressure Drop, psi	40.2
Nominal Coolant Inlet Temp., °F	325
Nominal Coolant Outlet Temp., °F	383
Average Core Temp. Rise, °F	58
Nominal Outlet Temp. in Hot Channel, °F	465
Maximum Fuel Centerline Temp., °F	~4100
Maximum Clad Surface Temp., °F	496

Table 7. Mechanical Design Characteristics of the Process Heat Reactor Reference Design

Core	
Equivalent Core Diameter, in.	168.9
Active Core Height, in.	144
Total No. of Fuel Assemblies	245
Total Uranium Loading, kg U	168477
Average Moderator Temp., °F	355
Overall Water-to-Fuel Ratio, H_2O/UO_2	1.539
Fuel Assembly	
No. of Fuel Rods	204
No. of Guide Thimbles	20
No. of Instrument Tubes	1
No. of Inconel Grids	9
Bundle Type	RCC-Canless
Pitch (dim. F)[a], in.	.632
Bundle Dimension (dim. G), in.	.1275
Bundle Dimension (dim. H), in.	9.46
Bundle Dimension (dim. I), in.	9.501
Bundle Dimension (dim. J), in.	9.541
Bundle Dimension (dim. K), in.	.0538
Fuel Rod	
Pellet Diameter, in.	.450
Inside Clad Diameter, in.	.4565
Outside Rod Diameter, in.	.5045
Clad Thickness, in.	.024
Diametral Gap Clearance, in.	.0065
Pellet Fraction of Theoretical Density, %	93
Pellet Material	UO_2-Sintered
Clad Material	Zircaloy 4
No. of Rods in Core	49980

[a] Lettered dimensions shown in Fig. 1.

Table 8. LTM-Predicted Burnup Characteristics of the Process Heat Reactor Reference Design

Initial Enrichment, w/o ^{235}U	2.8
Discharge Enrichment, w/o ^{235}U	.67
Average Fuel Burnup, Mwd/Tonne	28887
Full Power Days per Region[a], days	1131
Uranium Charged per Region[a], kg	56159
Uranium Discharged per Region[a], kg	53939
Fraction of ^{235}U Discharged, w/o U	.675
Fraction of ^{236}U Discharged, w/o U	.395
Fraction of ^{238}U Discharged, w/o U	98.930
Fissile Plutonium Produced per Region[a], kg	351.3
Discharge Plutonium Concentration, gm Pu/kg U	6.27
Fraction of ^{239}Pu Discharged, w/o Pu	58.3
Fraction of ^{240}Pu Discharged, w/o Pu	22.4
Fraction of ^{241}Pu Discharged, w/o Pu	14.6
Fraction of ^{242}Pu Discharged, w/o Pu	4.7
Equilibrium Conversion Ratio	.594

[a]A region consists of one-third of the core.

Table 9. Process Heat Reactor Equilibrium Fuel Cycle Costs for Three Sets of Economic Conditions and Two AEC Price Schedules

Cost Component[a]	Condition I[b]		Condition II[c]		Condition III[d]	
	Old[e] Schedule	New[f] Schedule	Old[e] Schedule	New[f] Schedule	Old[e] Schedule	New[f] Schedule
Makeup Uranium	.325	.308	.325	.308	.325	.308
U Credit	-.027	-.027	-.027	-.027	-.027	-.027
Pu Credit	-.088	-.082	-.088	-.082	-.088	-.082
Proessing	.016	.016	.016	.016	.050	.050
Fabrication	.059	.059	.059	.059	.086	.086
Interest on Fabrication	.005	.005	.009	.009	.007	.005
Fabrication Inventory	.005	.005	.010	.010	.005	.005
Core Inventory	.033	.032	.066	.064	.033	.032
Processing Inventory	.003	.003	.005	.005	.003	.003
Shipping	.005	.005	.005	.005		
Total, mills/kwhr(t)[g]	.335	.324	.380	.367	.394	.381
Total, ¢/MBtu	9.82	9.50	11.14	10.76	11.54	11.16

[a]All costs are in units of mills/kwhr(t).

[b]Publicly owned reactor with fixed charge rate on non-depreciating capital of 5%. Privately owned central processing and fabrication plants with fixed charge rate of 22% on capital investment. Processing plant is sized for 10 MT/day and fabrication plant serves a 75,000 Mwth industry.

[c]Same as Condition I except reactor privately owned with 10% fixed charge rate on non-depreciating capital.

[d]Same as Condition I except processing and fabrication plants are on-site and publicly owned (7.7% fixed charge rate on capital investment). Processing and fabrication plants serve a nuclear installation of 15,000 Mwth.

[e]Costs are based on an ore cost of \$8.00/lb U_3O_8, conversion charge of \$1.35/kg, separative work charge of \$30/kg, and optimum tails of 0.2594 w/o ^{235}U.

[f]Costs are based on an ore cost of \$8.00/lb U_3O_8, conversion charge of \$1.35/kg, separative work charge of \$26/kg, and tails of 0.20 w/o ^{235}U.

[g]Total does not necessarily equal sum of components due to roundoff error.

The reference core produces 4307 Mwth at 500 psia, with coolant inlet and outlet temperatures of 325°F and 383°F, respectively. The reference core configuration is shown in Fig. 4 for a core with an equivalent diameter of 187.1 in. and an active core height of 12 ft. The full power maximum centerline temperature and minimum DNBR are estimated by ORNL to be 4100°F and 3.93, respectively. The limiting thermal-hydraulic characteristic for the process heat reactor design is maximum centerline fuel temperature. The temperature was selected because it is representative of the "standard" Westinghouse design temperature. A pressure drop of 40.2 psi is developed across the core. As in the power reactor reference design, these values are consistent with current PWR technology and safety limitations.

The 2.8 w/o ^{235}U pellets have a 0.45 in. diameter and the fuel rod outside diameter is 0.5045 in. The rods are set on a square pitch of 0.632 in. Each core region will have an average equilibrium fuel cycle burnup of 28,900 Mwd/Tonne for 1130 full power days. The fuel cycle cost is 0.335 mills/kwhr(t) under economic Condition I. Of the total cost, 62% is due to the net fissile burnup cost, 24% to the fabrication and processing charges, and 14% is attributable to fuel inventory charges and shipping. When the non-depreciating fixed charge rate is doubled for private financing (Condition II) the total fuel cycle cost rises to 0.380 mills/kwhr(t). The use of an on-site publicly financed fabrication-reprocessing complex serving a 15,000 Mwth industry (Condition III) raises the total fuel cycle cost to 0.394 mills/kwhr(t). As in the power reactor study, this increase is due solely to the lower plant capacities of the on-site complex. The corresponding fuel cycle costs using the recently revised AEC price schedule are 0.324, 0.367, and 0.381 mills/kwhr(t) for Conditions I, II, and III, respectively.

The 4307 Mwth process heat reactor produces essentially the same quantity of low temperature (266°F) steam as the 3250 Mwth high temperature reactor combined with its vapor compressor. The process heat reactor design provides for the same full duty water production of 550 MGD and generation of on-site pumping power as does the high temperature reactor. A short back-pressure turbine is used to generate the estimated 110 Mwe on-site pumping and auxiliary power. The turbine

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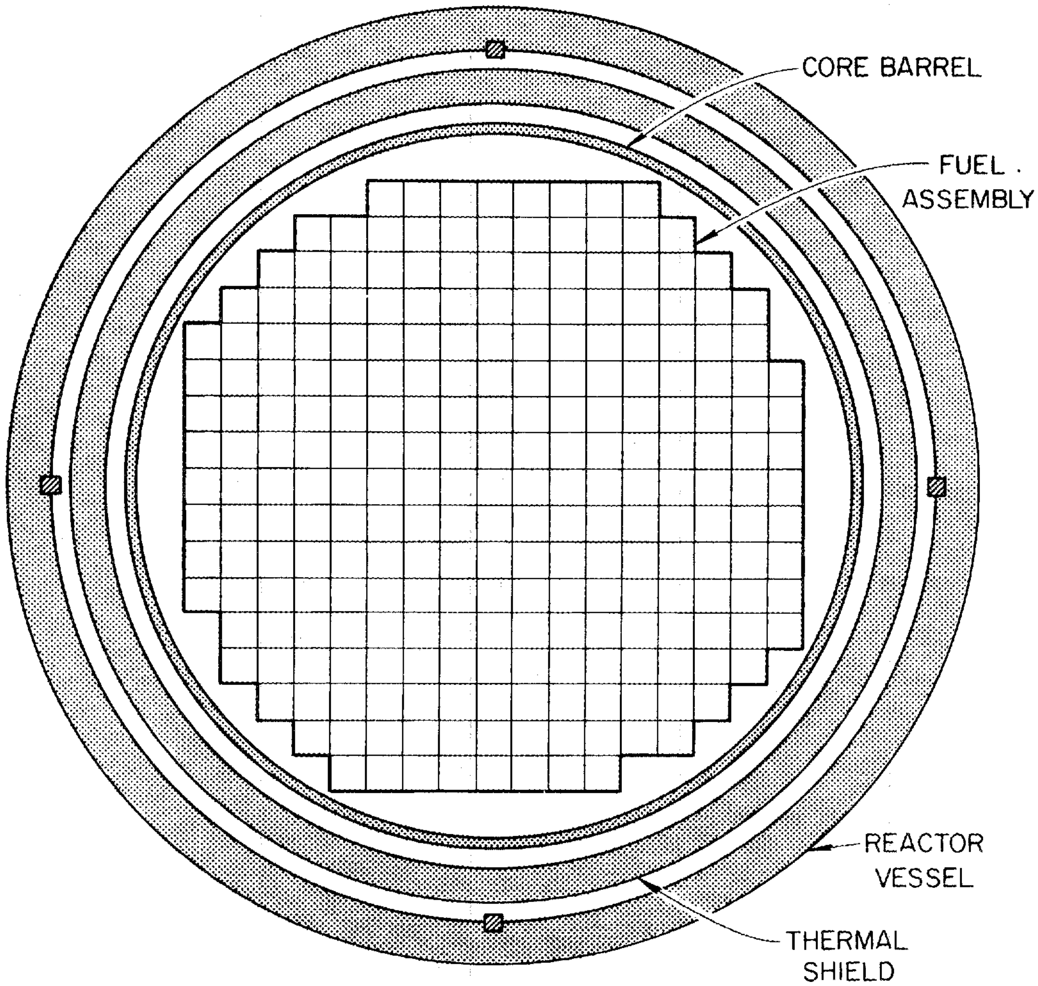

245 FUEL ASSEMBLIES

Fig. 4. Core Layout of the Process Heat Reactor Reference Design.

requires steam at 290°F inlet temperature and exhausts steam to the VTE water plant at approximately 266°F. The VTE is assumed to have a reactor inlet temperature of 325°F was selected as the minimum reasonable temperature for adequate steam generator Δt. The 383°F reactor outlet temperature provides a 58°F temperature rise across the reactor.

A description of the analytical techniques and an analysis of near-optimum lattices are presented in subsequent sections.

CALCULATIONAL METHODS

Reactor Physics

The calculational method selected for both the power and process heat reactor studies consisted of the use of GAM-I[3] and THERMOS[4] to compute a set of self-shielded cross-sections for use in LTM[5], a multi-group, zero-dimensional, depletion code for the equilibrium fuel cycle. Fast group cross-sections were prepared using the GAM-I code. GAM-I is a multi-group code that solves the Boltzmann equation for the spatially-averaged, energy-dependent fluxes in either the P_1 or B_1 approximations. Within the resolved resonance region, rod geometry effects are estimated by the NR or NRIA approximations, according to the methods developed by Adler, Hinman and Nordheim.[6] Eleven energy groups were employed, with a lower cut-off of 1.86 ev. The group boundaries are defined in Table 10. The Dancoff correction for the fuel rods was estimated by Sauer's method,[7] using the equation

$$C = \frac{e^{-\tau\Sigma\ell}}{1 + (1-\tau)\Sigma\ell}$$

where

C = Dancoff correction factor

Σ = macroscopic scattering cross-section of the moderator

D = pellet diameter

v_m = moderator-to-fuel volume ratio

v_c = clad-to-fuel volume ratio

$\ell = D\, v_m$ = mean chord length of moderator

Table 10. Energy Group Boundaries for the Calculational Model

Group	Lower Energy Boundary, ev
GAM-I	
1	1000000
2	80000
3	9120
4	215
5	78.9
6	29.0
7	13.7
8	8.32
9	5.04
10	3.06
11	1.86
THERMOS	
12	1.44
13	1.125
14	1.00
15	.55
16	.30
17	.25
18	.18
19	.10
20	.05
21	.005

$$\tau = \left[\sqrt{\frac{\pi}{4}\left(1 + \frac{v_m}{1 + v_c}\right)} - 1\right] \Bigg/ \left[\sqrt{v_m}\sqrt{\frac{v_m}{1 + v_c}}\right] - .08\left[1 + \frac{1}{2}\sqrt{\frac{v_c}{1 + v_c}}\right]$$

The effective mean chord length of the fuel is given by the equation

$$\bar{\ell}_f = \frac{D}{1 - C}$$

The thermal group cross-sections were preapred by the THERMOS code. THERMOS solves the one-dimensional Boltzmann equation for energy and space dependent fluxes by integral transport methods. The Nelkin scattering kernel was employed for hydrogen scattering, while a free gas model (Brown-St. John) was used for all other scatters. The thermal energy range was defined with ten energy groups. Cross-sections from GAM and THERMOS were input to the LTM code. LTM calculates the fuel composition and associated residence time for a reactor operating on a graded exposure equilibrium fuel cycle. The calculation is space-independent and neutron leakage is accounted for by the inclusion of a buckling term. The fuel residence time calculated is that time at which the time integral of neutron productions divided by the time integral of neutron losses equals one, or some other specified k_{eff} value. It is assumed that control poisons are constant with time. LTM also performs the simple-interest fuel cycle cost calculation for a given set of economic ground rules.

The basic data employed in the calculation were representative of the entire fuel assembly and the surrounding water gap between assemblies. Volume fractions were calculated for this assembly and equivalent pin cell dimensions were found such that the H_2O/UO_2 and H_2O/Zr volume ratios for a simplified, cylindrical pin cell were identical to the overall ratios for the fuel assembly. Structural material (exclusive of the fuel clad) was homogeneously included in the water surrounding the fuel rod. The THERMOS model therefore consisted of the fuel pellet, the radial pellet gap, the cladding thickness and a surrounding of homogeneously mixed water and structure.

Because LTM is a graded exposure code it is necessary to insert a time-constant control poison to account for the fact that fuel is loaded discretely rather than continuously. The depleting and non-depleting poisons were inserted into LTM by specifying a fractional control absorption. The code will then iterate on boron concentration in order to find the concentration that gives the specified absorption. Poison was added until the LTM-predicted burnup equalled the Diablo Canyon design burnup of 33,000 Mwd/Tonne. Burnup parameters such as final enrichment, residence time, and plutonium concentrations were compared to Westinghouse predictions to check the validity of the method. An average poison control fraction of 8.13% provided the best agreement to Westinghouse predictions. This value was then used in the parametric studies of both the power and process heat reactors.

Table 11 presents a comparison between the Westinghouse design and LTM predicted burnup parameters. Westinghouse predictions for the Diablo Canyon reactor were published in Ref. 8 for the first three cores. Equilibrium is reached during the fourth core but reasonable extrapolations of third core burnup data can easily be made. A minor difference exists between the predicted values of final enrichment and fissile plutonium production. The LTM values of both parameters are lower than values predicted by Westinghouse. This may be attributed to differences in resonance treatment, differences in cross-sections, and to the constant poison approximation. Due to these differences, the uranium credit predicted by LTM will be .010 mills/kwhr(t) lower than would be predicted using Westinghouse design values, the plutonium credit will be .004 mills/kwhr(t) lower, and the core inventory will be .008 mills/kwhr(t) lower. The net effect is that LTM will predict fuel cycle costs .006 mills/kwhr(t) higher than would be predicted using Westinghouse design information. This disagreement is less than 2% of the total fuel cycle cost and is therefore negligible. For purposes of comparison with other ORNL studies, equilibrium fuel cycle costs for the selected reference designs were calculated using results of the computer code TONG. The results are presented in Appendix A. TONG is a point depletion code capable of calculating reactor core histories of multibatch cores.

Table 11. Comparison of Equilibrium Cycle Burnup Data Predicted by Westinghouse and ORNL

Parameter	ORNL Results Using LTM Code	Westinghouse Design Predictions
Uranium Charged per Region,[a] kg	29411	29070[b]
Uranium Discharged per Region, kg	28111	27794[b]
Uranium Burned During Residence, kg	1300	1276[b]
Initial ^{235}U Enrichment, w/o	3.30	3.30[b]
Final ^{235}U Enrichment, w/o	.81	.92[b]
Fissile Plutonium Discharged per Region, kg	182.4	190.5[b]
Final Fissile Pu Concentration, gm Pu/kg U	6.21	6.55[b]
Full Power Days per Region, days	898	886[b]
Average Fuel Burnup, Mwd/Tonne	33000	33000[b]
Discharge Fraction of ^{239}Pu, w/o	54.3	56.0[c]
Discharge Fraction of ^{240}Pu, w/o	24.2	23.7[c]
Discharge Fraction of ^{241}Pu, w/o	15.9	15.0[c]
Discharge Fraction of ^{242}Pu, w/o	5.6	5.3[c]

[a]A region comprises one-third of the core.

[b]Equilibrium cycle data was extrapolated from information published in Ref. 8.

[c]Reference 9.

Thermal Hydraulics

The thermal-hydraulic characteristics of the power and process heat reactors were analyzed using the CAT-II[10] code. In its original form CAT-II, developed by Westinghouse, is valid within the pressure range of 1,000 psia to 2,300 psia. The principal outputs of the code are the axial variations of the DNB ratio, the core pressure drop, and the temperature distribution in both the hot and normal channels. For regions of subcooled and bulk boiling in the hot channel, CAT-II varies the hot channel flow rate until the pressure drops in the hot and normal channels are equalized. Physically, this represents a cross-flow between the hot channel and its neighbors.

In the power reactor thermal-hydraulic study, the results of the CAT-II analysis of the Diablo Canyon reference core were compared and normalized to Westinghouse's predicted results for the core. The normalization factors for the minimum DNBR, core pressure drop, and maximum fuel centerline temperature were then applied to CAT-II predicted results for the off-design cases. This procedure was necessary for several reasons. First, the calculational procedures available at ORNL were not the same as employed by Westinghouse for the Diablo Canyon design. Also, significant input information such as Westinghouse's assumed hot channel factors and axial power distribution were not available and ORNL assumptions were required. In light of these differences, the ORNL calculations for the Diablo Canyon core should not be expected to produce answers in full agreement with reported design values. The prediction of relative changes, however, is expected to be accurate. Table 12 presents a comparison between Westinghouse and ORNL predicted thermal-hydraulic characteristics.

The agreement between pressure drop and clad surface temperature is good. However, the calculated value for the centerline temperature is higher than that reported by Westinghouse. No explanation has been found for this difference. Since the conditions for the Diablo Canyon reactor are acceptable, ORNL calculations of temperatures less than 4762°F will indicate designs that are also acceptable, relative to Diablo Canyon. The DNB ratios are also not in agreement. The primary

Table 12. Comparison of Westinghouse Thermal-Hydraulic Design Values With ORNL Estimates

	Westinghouse	ORNL
Pressure Drop, psi	28.8	28.8
Maximum Clad Surface Temperature, °F	657.0	656.2
Maximum Centerline Temperature, °F	~4100	4762
Minimum DNB Ratio	1.81	1.42

reason is that the DNB correlation used by ORNL was different from that used in the Westinghouse design. CAT-II employs the W-2 correlation while Diablo Canyon was based on the W-3 correlation. In addition, the axial heat flux profile was not the same as used by Westinghouse.

The maximum fuel centerline temperature normalization factor developed in the power reactor study was also used in the low temperature study. The heat flux was adjusted to keep the normalized maximum channel temperature to within $\pm 50^{\circ}$F of the power reactor core's maximum centerline temperature of 4100°F. The code then searched for a coolant flow rate that precluded void formation at the hot channel exit. Because the original version of CAT-II is valid for the pressure range of 1000 psia to 2300 psia, it was necessary to modify the burnout, pressure drop and heat transfer correlations in the code to account for the 500 psia system pressure of the process heat reactor.

Burnout Correlation

The correlation used to calculate the burnout heat flux was obtained by Macbeth in 1962.[11] This correlation consists of seven equations each of which predicts the burnout flux at seven corresponding pressures ranging from 15 to 2700 psia. For a pressure between any two of the given pressures, linear interpolation is recommended.

The general burnout equation is in the form

$$\left(\frac{q''\ max}{10^6}\right) = A_i - \frac{1}{4} C_i\ D \left(\frac{G}{10^6}\right) \left[H - H_f\right]$$

where

D is the equivalent diameter in inches

H_f is the saturation enthalpy at P_i, Btu/lb

P is the pressure in psia

i is the pressure equation index

$$A_i = y_0^i\ D^{y_1^i} \left(\frac{G}{10^6}\right)^{y_2^i}$$

$$C_i = y_3^i\ D^{y_4^i} \left(\frac{G}{10^6}\right)^{y_5^i}$$

and y_0^i, y_1^i, y_2^i, y_3^i, y_4^i, y_5^i are correlation constants given in Ref. 11. This correlation was based on uniformly heated round tubes. In the present applications, the equivalent diameter will be based on the heated perimeter.

The DNB ratio is defined as the ratio of the burnout heat flux to some heat flux that is characteristic of the system and location of interest. The previously described equation was used to predict the burnout heat flux. For the system heat flux, two possibilities were considered in CAT-II. The first possibility is an equivalent average heat flux up to the location in question and the second is the local heat flux. The reason for using two procedures is the uncertainty in the effect of the non-uniform axial heat flux in the reactor. The lowest DNB ratio calculated by these procedures was used for design purposes.

Pressure Drop Correlation

The CAT-II pressure drop correlation for single phase flow was not changed. For subcooled boiling, however, the pressure drop due to friction was calculated as suggested by Mendler, et al.[12] The friction factor is calculated as follows:

$$\frac{f}{f_{iso}} = 1 + \frac{T_B - T_{LB}}{T_{sat} - T_{LB}} \left[\left(\frac{f}{f_{iso}} \right)_{sat} - 1 \right]$$

where

T_B is the bulk temperature

T_{sat} is the saturation temperature

f is the friction factor

f_{iso} is the isothermal friction factor

and

$$T_{LB} = T_{sat} + 60(q''/10^6)^{1/4}\ e^{-P/900} - q''/h$$

where

P is the system pressure, psi

h is the single phase heat transfer coefficient.

Although the above equation is strictly applicable to pressures above 800 psia, the correlation is adequate for pressures as low as 400 psia.[14]

For bulk boiling at overpower conditions, the homogeneous method of calculating pressure drops was used. This method assumes that the slip ratio is 1.0 and that the properties required in calculating the pressure drop are determined by averaging the properties according to the weight fractions of the two phases. Dinos[14] tested this model for water between 400 and 1000 psia and found the predictions to be adequate.

Heat Transfer Coefficient

The heat transfer coefficient was calculated by an equation suggested on page 678 of Ref. 15.

$$h(\mathrm{Btu/hr/ft^2}) = 170(1 + 10^{-2}\ t - 10^{-5}\ t^2)\ \frac{V^{0.8}}{D^{0.2}}$$

where

t is the bulk temperature in °F

V is the velocity in ft/sec

D is the equivalent diameter in inches

POWER REACTOR PARAMETRIC STUDY

Fuel Cycle Economics

Results of the power reactor parametric study are presented in Fig. 5 and in Tables 13 and 14 for economic Condition I. The water-to-UO_2 volume ratio was varied from 1.4 to 2.3 by changing the pellet diameter while holding lattice pitch constant. Enrichments between 2.8 and 3.8 w/o ^{235}U were investigated.

From Fig. 5, it is obvious that the cost minimum is broad with respect to both enrichment and water-to-fuel ratio. Minimum cycle costs vary by only 2-3% within a range of ±20% from the optimum water-to-fuel ratio and also by 1-2% within the range of ±0.5 w/o enrichment for a given water-to-fuel ratio. Although the parametric variation provided wide differences in individual cycle cost components, these differences tended to offset each other and resulted in little variation of the total cycle cost. The lack of variation in the fuel cycle cost made it difficult to determine the trend of minimum cost enrichment with the

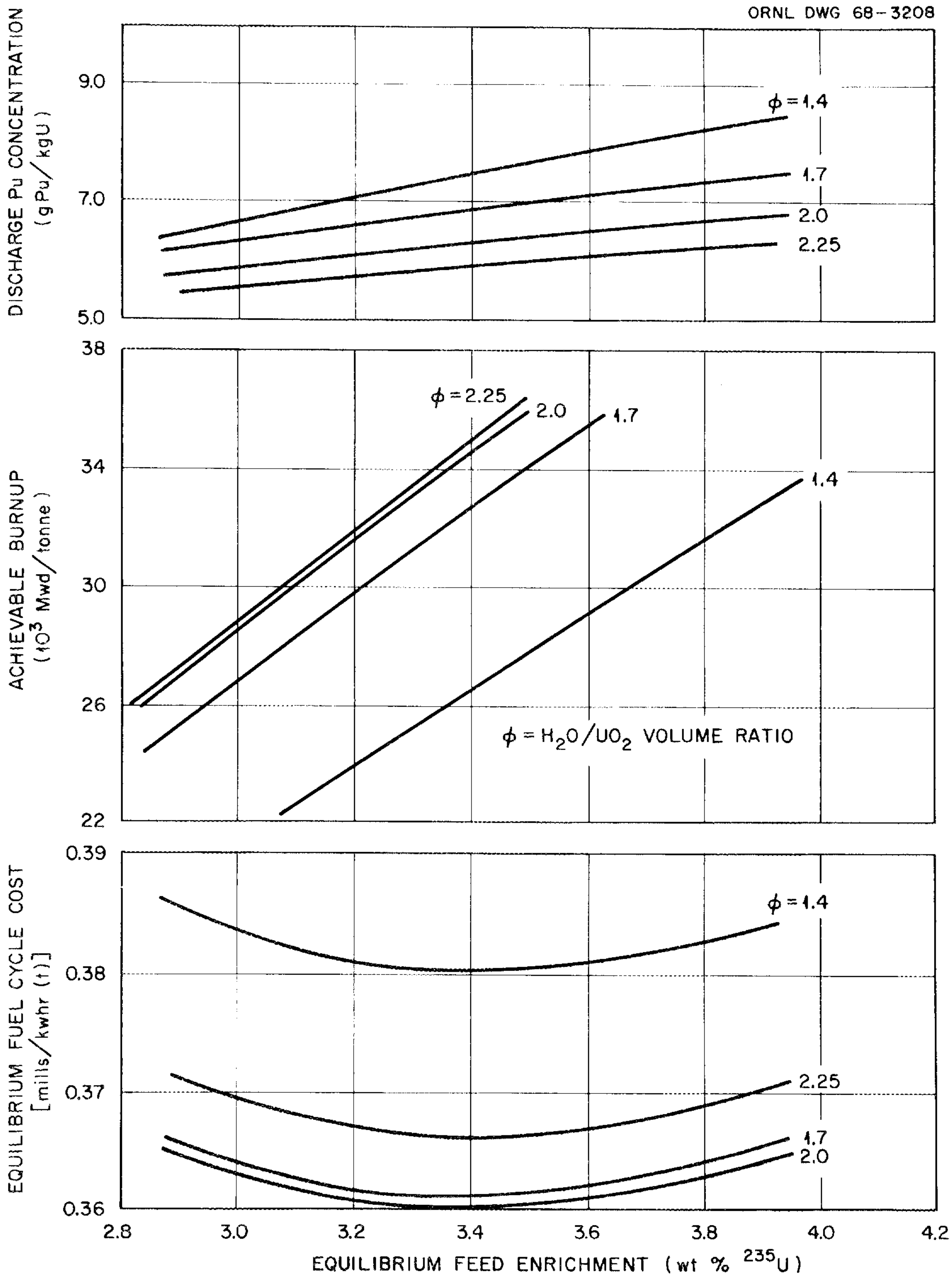

Fig. 5. Fuel Cycle Cost, Achievable Burnup, and Discharge Plutonium Concentration vs. Enrichment for Four Power Reactor Lattices.

Table 13. Equilibrium Fuel Cycle Cost Data for Four Power Reactor Lattices

	Case 1	Case 2[c]	Case 3	Case 4
Pellet Diameter, in.	0.3516	0.3669	0.3845	0.4047
Nominal (Actual) Overall H_2O/UO_2 volume Ratio	2.25 (2.263)	2.0 (1.968)	1.7 (1.673)	1.4 (1.378)
Cost Components, mills/kwhr(t)				
Makeup Uranium	0.345	0.351	0.374	0.459
Uranium Credit	-0.028	-0.035	-0.054	-0.116
Plutonium Credit	-0.068	-0.076	-0.090	-0.117
Processing	0.013	0.014	0.016	0.019
Fabrication	0.064	0.064	0.066	0.072
Interest on Fabrication	0.004	0.004	0.004	0.004
Fabrication Inventory	0.005	0.005	0.006	0.007
Core Inventory	0.025	0.027	0.032	0.042
Processing Inventory	0.002	0.003	0.003	0.005
Shipping	0.004	0.005	0.005	0.006
Total Fuel Cycle Cost,[a,b] mills/kwhr(t)	0.366	0.360	0.361	0.380
Total Fuel Cycle Cost, ¢/10^6 BTU	10.73	10.55	10.58	11.14

[a]Fuel cycle costs are based on a separative charge of \$30/kg U, optimum tails of .2594 w/o ^{235}U, conversion charge of \$1.35/kg U, and an ore cost of \$8.00/lb U_3O_8.

[b]Publicly owned reactor with fixed charge rate on non-depreciating assets of 5% and a discount rate of 4%. Privately owned central processing and fabrication plants with fixed charge rate of 22% on capital investment. Processing plant is sized for 10 MT/day and fabrication plant serves a 75,000 Mwth industry.

[c]Case 2 is typical of the Diablo Canyon Lattice Configuration.

Table 14. Mechanical and Burnup Data for Four Power Reactor Lattices

	Case 1	Case 2*	Case 3	Case 4
Pitch, in.	0.563	0.563	0.563	0.563
Pellet Diameter, in.	0.3516	0.3669	0.3845	0.4047
Clad Thickness, in.	0.0243	0.0243	0.0243	0.0243
Outside Diameter of Rod, in.	0.4067	0.4220	0.4396	0.4598
Bundle Cross-Section Dimension, in.	8.466	8.466	8.466	8.466
Nominal (Actural) Overall H_2O/UO_2 Ratio	2.25 (2.263)	2.0 (1.968)	1.7 (1.673	1.4 (1.378)
Number of Bundles	193	193	193	193
Number of Fuel Rods	39372	39372	39372	39372
Active Core Height, in.	144	144	144	144
Equivalent Core Diameter, in.	132.7	132.7	132.7	132.7
Initial Uranium Loading, kg	81024	88233	96893	107341
Final Uranium Loading, kg	77277	84315	92909	103419
Initial Enrichment, w/o ^{235}U	3.4	3.3	3.2	3.3
Final Enrichment, w/o ^{235}U	0.74	0.81	0.94	1.31
Burnup, Mwd/Tonne	35009	33109	29850	25309
Fuel Residence Time, full power days	874	900	891	837
Final Fissile Pu Concentration, gm Pu/kg U	5.90	6.21	6.59	7.30
Equilibrium Conversion Ratio	0.5447	0.5629	0.5841	0.6062
Fabrication Plant Throughput, Tonnes/yr	30.56	32.31	35.84	42.27
Processing Plant Throughput, Tonnes/yr	29.35	31.10	34.59	41.01
Fabrication Unit Cost, $/kg	53.54	50.58	47.24	43.59

*Case 2 is typical of the Diablo Canyon Lattice Configuration.

water-to-fuel ratio. For all water-to-fuel ratios studied, fuel cycle costs tended to minimize around 3.3 w/o ^{235}U.

Achievable burnup and discharge plutonium concentration followed predictable trends with respect to changes in enrichment and water-to-fuel ratio. Achievable burnup increased almost linearly with enrichment and decreased with decreasing water-to-fuel ratios. Discharge plutonium concentrations increased with decreasing water-to-fuel ratios. As the water-to-fuel ratio decreases, the neutron spectrum hardens, and the fast effect, thermal utilization, and resonance absorption in ^{238}U increase. All of these tend to increase the conversion ratio, however the overall reactivity decreases. The net result of these effects is to decrease the burnup for a given enrichment.

An analysis of the effect of these trends on the fuel cycle cost components follows. For the same enrichment, the following changes occur as the water-to-fuel ratio is decreased.

1. The net fissile burnup cost (U makeup + U credit + Pu credit) decreases. While the uranium makeup component of the net fuel cost increases, due to a higher uranium throughput, the plutonium and uranium credits increase. The increased fissile material credit is caused by the harder spectrum and an increase in resonance absorption and thermal utilization.

2. Fabrication costs generally increase because the cost increase due to the higher throughput tends to over-ride the lower unit cost of the larger diameter pellets. The unit fabrication cost is a power function of plant throughput, but the range of throughputs of interest in the study are below the "knee" of the cost versus throughput curve. Consequently, an increase in throughput does not produce a significantly lower unit cost.

3. Fuel inventory charges increase due to the larger core uranium loading and lower specific power. Also, more fissile plutonium is produced from the harder spectrum system.

For practical purposes, the fuel cycle costs for the 1.97 H_2O/UO_2 lattice (Case 2) and the 1.67 H_2O/UO_2 lattice are identical. The lower net fissile cost of the 1.67 H_2O/UO_2 lattice (Case 3) is offset by higher inventory charges associated with a longer residence time and higher fissile inventory. Fabrication costs were identical for both lattices. The 1.97 H_2O/UO_2 lattice was selected as the reference design because the thermal-hydraulic characteristics were more consistent with present design practice. This design is identical to Westinghouse's proposed Diablo Canyon reactor. The cost minimization showed that the Diablo Canyon reactor has a fuel cycle cost of 0.360 mills/kwhr(t) (10.55 ¢/10^6 BTU) for a publicly financed reactor plant and privately financed processing plants (Condition I). The reactor has fuel rods containing 0.3669-in. diameter pellets of 3.3 w/o ^{235}U, a clad thickness of 0.0243-in., and a pitch of 0.563-in. The average fuel burnup is 33,100 Mwd/Tonne for a fuel residence time of 900 full-power days.

The economic minimization was based on ground rules previously described as Condition I. The fuel cycle costs for all three sets of ground rules are shown in Table 5 for the selected reference design. Condition II is defined as a privately financed reactor plant and the same fabrication-processing complex used in the minimization study. The only difference in energy cost between Conditions I and II are the interest charges. The fuel cycle cost for the privately financed reactor plant is 0.400 mills/kwhr(t) (11.72 ¢/10^6 BTU). The publicly financed reactor plant using the on-site publicly financed processing plant (Condition III) has a significantly higher energy cost than the other two cases. This is due solely to the smaller industry size. The fabrication unit cost is \$72.33/kg compared to \$50.58/kg for the 75,000 Mwth capacity, privately financed plants. The UF_6 to UO_2 preparation charge, which is included in the fabrication cost, rises from \$4/kg to about \$10/kg due to the smaller industry size and smaller plant throughput. The unit reprocessing cost rises from \$11.55/kg to \$34.50/kg when the plant size is decreased. For Condition III, the fuel cycle cost is 0.420 mills/kwhr(t) (12.31 ¢/10^6 BTU).

Fuel cycle costs in Table 5 are based on the ^{235}U price schedule used for the minimization study. The schedule assumes a separative work charge of \$30/kg and an optimum tails concentration of 0.2594 w/o ^{235}U. Shortly after the study was completed, a revised AEC price schedule was published, based on a separative charge of \$26/kg U and a 0.20 w/o ^{235}U tails. The reference design fuel cycle costs for the three economic conditions were re-evaluated to reflect the new separative work charge and tails concentration, and are also presented in Table 5. The cycle costs obtained by using the new values are 3% to 4% lower than those obtained from the old values.

Thermal-Hydraulics

The results of thermal-hydraulic studies for near-optimum power reactor lattices are presented in Table 15. The linear heat rate was held constant for all cases. The near-optimum lattices are the same as those described in the previous section. With the exception of the core pressure drop, the thermal-hydraulic characteristics do not vary significantly between the three lattices at either 100% or 112% of full power. Calculations indicate that the maximum centerline fuel temperature varies by only $\pm 50^{\circ}$F from the reference design value, while the water-to-fuel ratio is varied by $\pm 15\%$. For the same element pitch, the fuel temperature increases as the pellet diameter decreases. This is due to the slightly higher heat flux of the smaller diameter rod, causing larger temperature drops across the clad and coolant film. At 112% power the selected reference design has a maximum centerline temperature of 4450°F. The minimum DNB ratio also fails to differ between lattices at both power conditions. The 0.3516 in. pellet diameter lattice (Case 1) has a slightly lower DNB ratio due to its higher heat flux. The reference design has a minimum DNBR of 1.30 at 112% power. Both the maximum centerline fuel temperature and minimum DNBR are consistent with currently accepted design practice. The selected reference design has a maximum linear heat rate of 18.9 kw/ft. For all designs, coolant water enters the core at 539°F and is discharged in the normal channel at 608°F. The hot channel exit temperature is 646°F. In the hot channel at 112% power, the coolant leaves the core with approximately 5.55% quality for all near-optimum design cases. All cases were run with an assumed radial power peaking factor of 1.75 and an axial peak-to-average of 1.61.

The only substantially different characteristic between design cases is the core pressure drop. No other characteristic represents a significant variation in the thermal-hydraulic design. As the pellet

Table 15. Thermal-Hydraulic Data for Three Power Reactor Lattices

	Case 1	Case 2	Case 3
Pitch, in.	0.563	0.563	0.563
Pellet Diameter, in.	0.3516	0.3669	0.3845
Clad Thickness, in.	0.0243	0.0243	0.0243
Outside Rod Diameter, in.	0.4067	0.4220	0.4396
Overall H_2O/UO_2 Ratio	2.263	1.968	1.673
Thermal Output, Mw	3250	3250	3250
Nominal System Pressure, psia	2250	2250	2250
Average Specific Power, kw/kg UO_2	35.74	32.55	29.89
Average Heat Flux, Btu/hr/ft^2	2.148×10^5	2.070×10^5	1.987×10^5
Maximum Linear Heat Rate, kw/ft	18.9	18.9	18.9
Peak-to-Average Power Ratio	2.82	2.82	2.82
DNB Ratio at Nominal Conditions	1.79	1.81	1.83
DNB Ratio at 112% Power	1.27	1.30	1.33
Average Mass Flow Rate, lbs/hr/ft^2	2.426×10^6	2.564×10^6	2.751×10^6
Average Coolant Velocity, ft/sec	15.0	15.85	17.0
Core Pressure Drop, psi	25.8	28.8	33.2
Nominal Coolant Inlet Temp., °F	539	539	539
Nominal Coolant Outlet Temp., °F	608	608	608
Average Core Temp. Rise, °F	69	69	69
Nominal Outlet Temp. in Hot Channel, °F	646	646	646
Maximum Fuel Centerline Temp., °F	~4150	~4100	~4050
Maximum Clad Surface Temp., °F	657	657	657

diameter is increased in order to decrease the water-to-fuel ratio, the core pressure drop increases. The pressure drop rises by almost 25% as the water-to-fuel ratio is decreased by 15%. The rise is primarily influenced by two factors. When the pellet diameter is increased without an increase in the pitch, the flow velocity must increase to maintain the same coolant flow rate. Since the pressure drop varies as the square of the velocity, a small increase in velocity can produce a substantial increase in pressure drop. Secondly, the increased pellet diameter results in a larger rod contact area, with respect to the volume of the coolant. That is, the hydraulic diameter of the channel decreases. The total system pressure drop should increase by almost 10% if the larger diameter pellet is used. Since the fuel cycle costs are identical for the reference design and the Case 3 design, the Diablo Canyon design was selected as the reference design on the basis of a lower pumping cost.

PROCESS HEAT REACTOR PARAMETRIC STUDY

Fuel Cycle Economics

Results of the process heat reactor parametric study are presented in Fig. 6 and in Table 16 and 17. The water-to-fuel ratio was varied from 1.2 to 2.0 and the enrichment from 2.3 to 3.3 w/o ^{235}U during the course of the study. Allowable pellet diameters for a given water-to-fuel ratio were determined from the thermal-hydraulic analysis. From Fig. 6 it can be seen that, as in the power reactor study, the cost minimum is broad with respect to both enrichment and water-to-fuel ratio. Minimum cycle costs vary by only 3% between the optimum water-to-fuel ratio and a ratio of 2.0. Cycle costs for a given water-to-fuel ratio generally vary by 3% within the range of 2.3 to 3.3 w/o ^{235}U. Individual fuel cycle cost components varied significantly, within the range of water-to-fuel ratios and enrichments studied. However, the variations tended to offset each other and resulted in little variation in the total cycle costs.

The higher water density in the process heat reactor resulting from the lower temperature tends to lower the optimum H_2O/UO_2 volume ratio in order to preserve approximately the same H to U atom ratio.

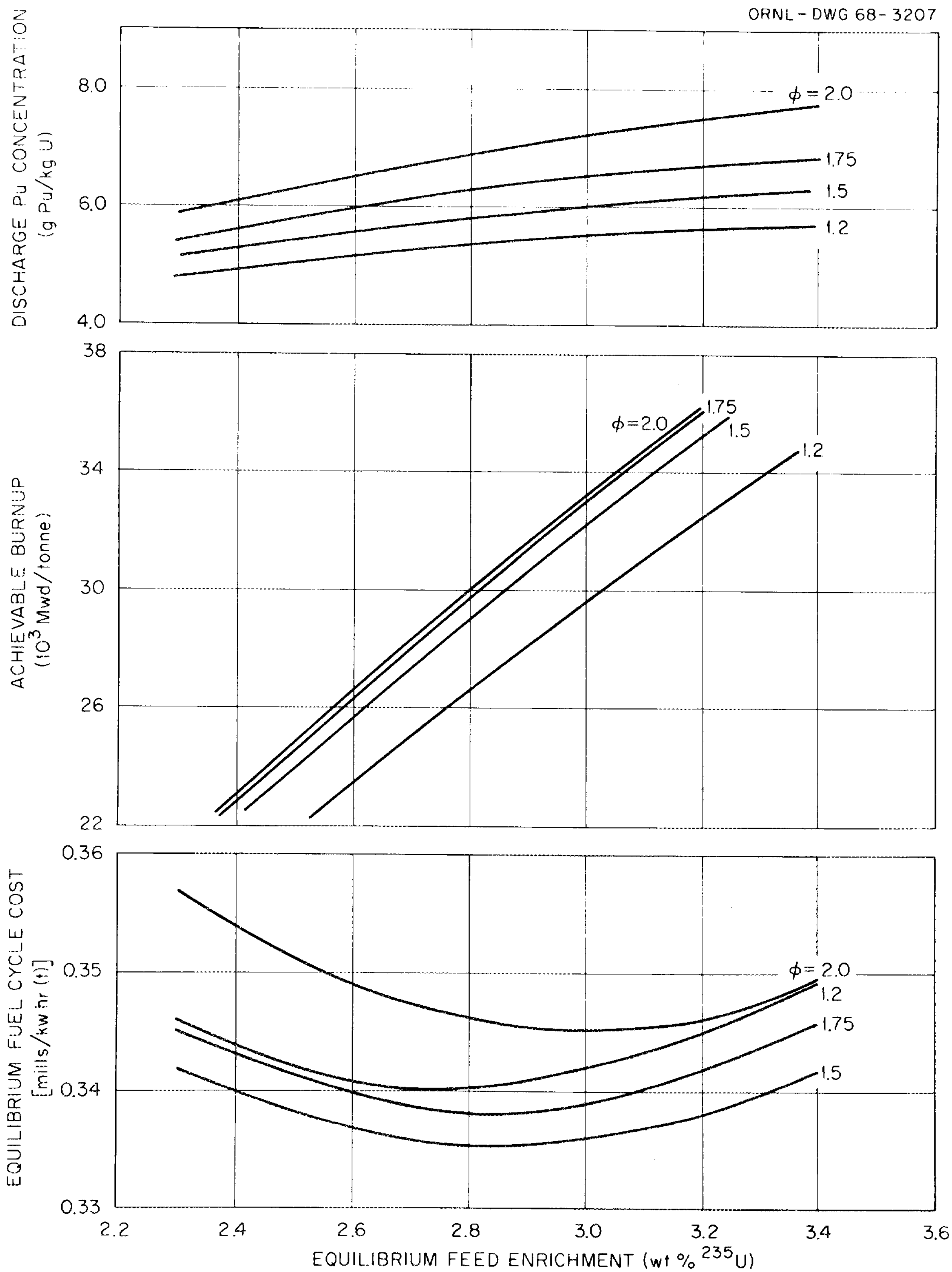

Fig. 6. Fuel Cycle Cost, Achievable Burnup, and Discharge Plutonium Concentration vs. Enrichment for Four Process Heat Reactor Lattices.

Table 16. Equilibrium Fuel Cycle Cost Data for Five Process Heat Reactor Lattices

	Case 1	Case 2	Case 3	Case 4	Case 5
Pellet Diameter, in.	0.45	0.45	0.50	0.50	0.50
Nominal (Actual) Overall H_2O/UO_2 Ratio	2.0 (2.046)	1.75 (1.792)	1.5 (1.539)	1.5 (1.537)	1.2 (1.237)
Cost Components, mills/kwhr(t)					
Makeup Uranium	0.311	0.313	0.325	0.317	0.359
Uranium Credit	-0.011	-0.016	-0.027	-0.023	-0.052
Plutonium Credit	-0.068	-0.076	-0.088	-0.085	-0.109
Processing	0.014	0.015	0.016	0.016	0.019
Fabrication	0.053	0.055	0.059	0.053	0.060
Interest on Fabrication	0.005	0.005	0.005	0.005	0.005
Fabrication Inventory	0.005	0.005	0.005	0.005	0.005
Core Inventory	0.030	0.031	0.033	0.040	0.044
Processing Inventory	0.002	0.002	0.003	0.002	0.004
Shipping	0.005	0.005	0.005	0.005	0.006
Total Fuel Cycle Cost,[a,b] mills/kwhr(t)	0.345	0.338	0.335	0.336	0.340
Total Fuel Cycle Cost, ¢/10^6 Btu	10.11	9.91	9.82	9.83	9.96

[a]Fuel cycle costs are based on a separative charge of \$30/kg U, optimum tails of .2594 w/o ^{235}U, conversion charge of \$1.35/kg U, and an ore cost of \$8.00/lb U_3O_8.

[b]Publicly owned reactor with fixed charge rate on non-depreciating assets of 5% and a discount rate of 4%. Privately owned central processing and fabrication plants with fixed charge rate of 22% on capital investment. Processing plant is sized for 10 MT/day and fabrication plant serves a 75,000 Mwth industry.

Table 17. Mechanical and Burnup Data for Five Process Heat Reactor Lattices

	Case 1	Case 2	Case 3	Case 4	Case 5
Pitch, in.	0.687	0.660	0.632	0.701	0.662
Pellet Diameter, in.	0.45	0.45	0.45	0.50	0.50
Clad Thickness, in.	0.024	0.024	0.024	0.026	0.026
Outside Diameter of Rod, in.	0.5045	0.5045	0.5045	0.5585	0.5585
Bundle Cross-Section Dim., in.	10.366	9.961	9.541	10.576	9.991
Nominal (Actual) Overall H_2O/UO_2 Ratio	2.00 (2.046)	1.75 (1.792)	1.50 (1.539)	1.50 (1.537)	1.20 (1.237)
Number of Bundles	245	245	245	241	241
Number of Fuel Rods	49980	49980	49980	49164	49164
Active Core Height, in.	144	144	144	144	144
Equivalent Core Diameter, in.	183.1	175.9	168.5	185.3	175.0
Initial Uranium Loading, kg	168477	168477	168477	204600	204600
Final Uranium Loading, kg	161168	161412	161817	196356	197345
Initial Enrichment, w/o ^{235}U	3.0	2.9	2.8	2.8	2.7
Final Enrichment, w/o ^{235}U	0.52	0.58	0.68	0.64	0.85
Burnup, Mwd/Tonne	33045	31352	28887	29570	24914
Fuel Residence Time, full power days	1294	1227	1131	1429	1204
Final Fissile Pu Concentration, gm Pu/kg U	5.43	5.88	6.27	6.18	6.66
Equilibrium Conversion Ratio	0.5465	0.5705	0.5944	0.5936	0.6235
Fabrication Plant Throughput, Tonnes/yr	44.97	45.19	49.10	47.95	56.91
Processing Plant Throughput, Tonnes/yr	41.30	43.61	47.46	46.33	55.27
Fabrication Unit Cost, $/kg U	41.47	41.43	40.70	37.16	35.73

The variation of individual cost components with water-to-fuel ratio is similar to that described previously for the power reactor cost study. As the water-to-fuel ratio decreases, the net fuel cost decreases, fissile inventory charges increase, and the fabrication cost increases slightly. These variations tend to produce a minimum cycle cost for a water-to-fuel ratio of 1.5 The selected reference design has a water-to-fuel ratio of 1.5, a pellet diameter of 0.45-in., a clad thickness of 0.024-in., and a pitch of 0.632-in. The Condition I minimum fuel cycle of 0.335 mills/kwhr(t) (9.82 ¢/10^6 BTU) occurs at 2.8 w/o ^{235}U enrichment. The reactor has an average fuel burnup of 28,900 Mwd/Tonne with a fuel residence time of 1131 days.

The results of surveys performed on two pellet diameters at the optimum water-to-fuel ratio of 1.5 are presented as Cases 3 and 4 in Tables 16 and 17. To remain within the allowable core pressure drop limits the pellet size can be varied from 0.45-in. to 0.52-in. diameter. Results presented for diameters of 0.45-in. and 0.50-in. indicate that the pellet size is not a significant factor in determining the minimum fuel cycle cost for the optimum water-to-fuel ratio. The larger pellet produces a slightly higher initial k_{eff} for the same enrichment and water-to-fuel ratio and consequently greater burnup. This is due to the decrease in the volume fraction of the structural material required when a larger pellet is used. The decrease in structural absorption produces a slightly more thermalized spectrum. The slight decrease in ^{238}U resonance absorption of the larger pellet lattice also increases reactivity. Net fuel costs for the two lattices are essentially identical. Variation of individual cost components between the two pellet sizes tend to cancel and both lattices optimize at the same enrichment. The larger pellet diameter lattice has a core pressure drop of 29 psi compared to 40 psi for the 0.45-in. pellet diameter lattice. The resulting difference in pumping cost is estimated to be equal to the difference in fuel cycle cost between the two lattices. Therefore, the 0.45-in. pellet diameter lattice was chosen as the reference design because it more nearly represents the pellet size and clad thickness most suitable to present-day fabrication capability.

As previously mentioned, the economic optimization was based on ground rules described as Condition I. Fuel cycle costs were determined for Conditions II and III for the lattice selected under Condition I ground rules. The fuel cycle costs for all three sets of ground rules are shown in Table 9 for both the old and recently revised AEC separative work charges. Condition II is defined as a privately financed reactor plant using the same fabrication-reprocessing complex used in the optimization study. The only difference in energy cost between Conditions I and II are interest charges. The fuel cycle cost for the privately financed reactor plant is 0.380 mills/kwhr(t) (11.14 ¢/10^6 BTU). As in the power reactor study, the publicly financed reactor plant using the on-site publicly financed processing and fabrication plants (Condition III) has a significantly higher cycle cost than the other two cases. This is due to the small industry size. The unit fabrication cost is $59.73/kg compared to $40.70/kg for the 75,000 Mwth capacity privately financed plant. Changes in the reprocessing unit cost and in the UF_6 to UO_2 fuel-preparation charge for the smaller industry size are identical to those reported for the power reactor study.

Fuel cycle costs utilizing the recently revised AEC separative work and tails enrichment values are between 3 and 4% lower than corresponding costs utilizing the older $30/kg U and optimum tails ground rules.

Thermal-Hydraulics

The thermal hydraulic studies provided design curves which limited the number of lattices that could be investigated for the process heat reactor. The design curves are based on a core pressure drop range of 25-40 psi and a maximum fuel centerline temperature equal to that used in current PWR technology (~4100°F). The curves are presented in Fig. 7. Any combination of pellet diameter and overall water-to-fuel ratio above curve A will result in a core pressure drop less than 25 psi. Similarly, any combination below curve B will result in a pressure drop greater than 40 psi. Consequently, the only combinations that can be considered are those between the two curves.

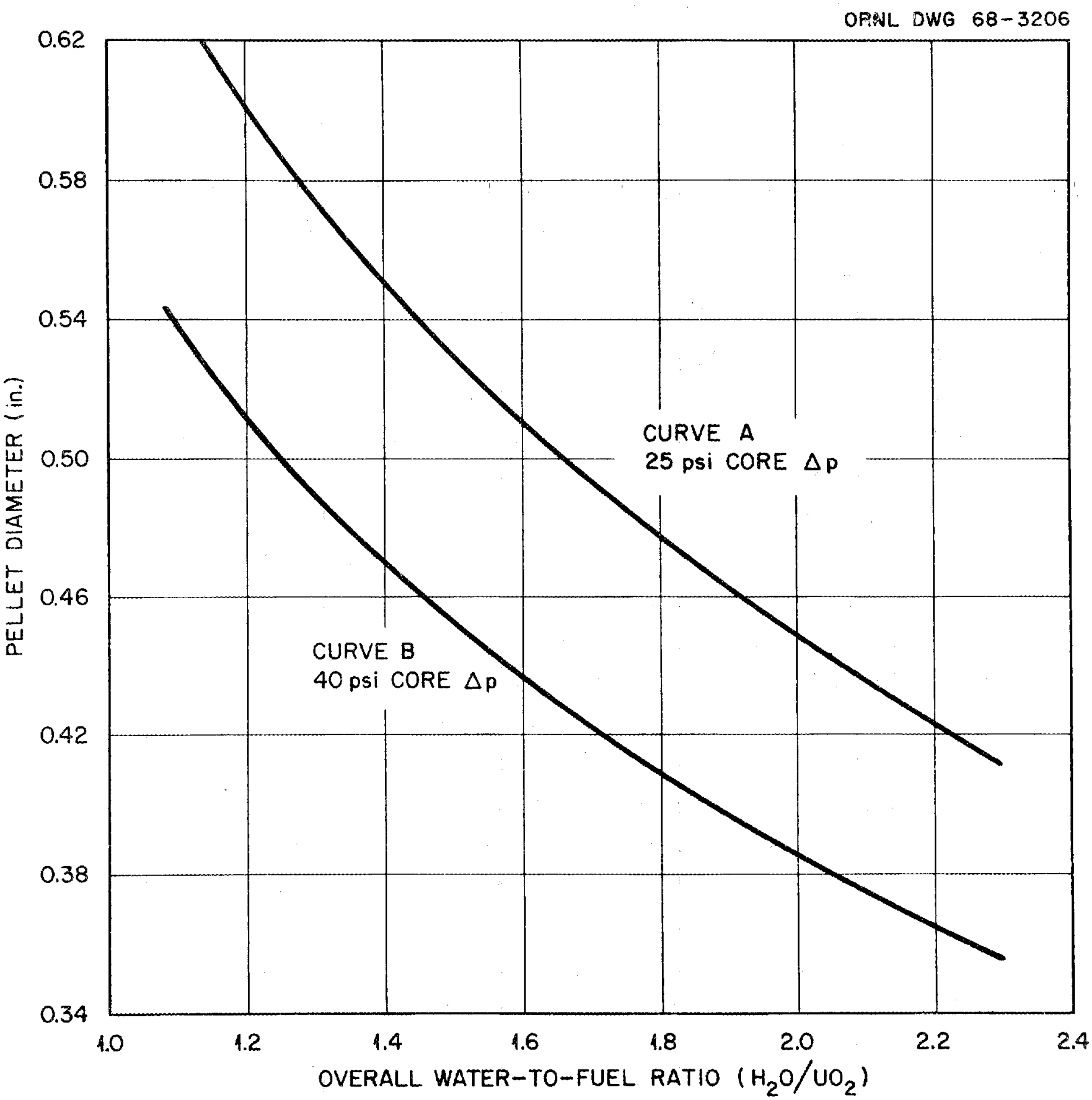

Fig. 7. Thermal-Hydraulic Design Curves for Process Heat Reactor Lattices.

For the basic Westinghouse fuel bundle, the lattice pitch required to obtain a specified core water-to-fuel ratio for a given pellet and rod diameter may be calculated from

$$P = K(\Phi\ D_p^2 + D_r^2)$$

where

P = pitch, in.

K = a constant dependent on the number of fuel rods and the volume of water displaced by the guide thimbles (K = .71605 for all cases considered)

Φ = desired volume ratio of water-to-fuel

D_p = pellet diameter, in.

D_r = fuel rod outside diameter, in.

The equation was derived from available mechanical configuration data and is an approximation accurate to ±2% of the calculated water-to-fuel ratio. Therefore, with the use of this equation and Fig. 7, lattices can be easily chosen for physics investigation.

The thermal-hydraulic characteristics of near-optimum lattices described in the previous section are presented in Table 18. The DNB ratios for all cases are between 4.0 and 4.5 and departure from nucleate boiling is therefore not considered to be a controlling thermal-hydraulic design criterion at either 100% or 112% of full power. As described in a previous section the linear heat rate and flow rate were adjusted for all cases to hold the maximum centerline fuel temperature to a value consistent with power reactor design technology, i.e., 4100°F. It was assumed that the same peak-to-average power ratio and hot channel factors used in the power reactor design were applicable to the process heat reactor design. The process heat reactor core can be designed to a higher maximum linear heat rate than used in the power reactor design because the coolant temperature is lower. The selected reference design requires a maximum linear heat rate of 20.3 kw/ft to achieve a centerline temperature of 4100°F while the power reactor is designed for a linear heat rate of 18.9 kw/ft to achieve the same temperature. For all near-optimum cases, coolant water enters the core at 325°F and exits the normal channel at 383°F. Coolant in the hot channel exits at 465°F, two degrees below the saturation temperature.

Table 18. Thermal-Hydraulic Data for Five Process Heat Reactor Lattices

	Case 1	Case 2	Case 3	Case 4	Case 5
Pitch, in.	0.687	0.660	0.632	0.701	0.662
Pellet Diameter, in.	0.45	0.45	0.45	0.50	0.50
Clad Thickness, in.	0.024	0.024	0.024	0.026	0.026
Outside Rod Diameter, in.	0.5045	0.5045	0.5045	0.5585	0.5585
Overall H_2O/UO_2 Ratio	2.0	1.75	1.5	1.5	1.2
Thermal Output, Mw	4307	4307	4307	4307	4307
Nominal System Pressure, psia	500	500	500	500	500
Average Specific Power, kw/kg UO_2	22.6	22.6	22.6	18.6	18.6
Average Heat Flux, Btu/hr/ft^2	1.888×10^5	1.888×10^5	1.888×10^5	1.741×10^5	1.741×10^5
Maximum Linear Heat Rate, kw/ft	20.3	20.3	20.3	20.6	20.6
Peak-to-Average Power Ratio	2.82	2.82	2.82	2.82	2.82
DNB Ratio at Nominal Conditions	3.56	3.73	3.93	4.20	4.43
Average Mass Flow Rate, lbs/hr/ft^2	2.610×10^6	2.923×10^6	3.369×10^6	2.813×10^6	3.352×10^6
Average Coolant Velocity, ft/sec	12.8	14.4	16.6	13.8	16.5
Core Pressure Drop, psi	24.8	30.6	40.2	29.0	40.6
Nominal Coolant Inlet Temp., $^\circ$F	325	325	325	325	325
Nominal Coolant Outlet Temp., $^\circ$F	383	383	383	383	383
Average Core Temp., Rise, $^\circ$F	58	58	58	58	58
Nominal Outlet Temp. in Hot Channel, $^\circ$F	465	465	465	465	465
Maximum Fuel Centerline Temp., $^\circ$F	~4100	~4100	~4100	~4100	~4100

As in the power reactor study, the only substantial difference between the near-optimum cases exists in the core pressure drop. Cases 3 and 5 have a pressure drop of about 40 psi while cases 2 and 4 have a core Δp of 30 psi. Higher pressure drops are caused by a smaller flow area, which increases the fluid velocity, and the core Δp is a function of the square of the velocity. In addition, the ratio of the flow area to the frictional contact surface, as characterized by the hydraulic diameter, is smaller for cases 3 and 5. This serves to increase the friction factor and results in a higher pressure drop.

Since the difference in fuel cycle cost between cases 3 and 4 offset the pumping cost difference, the 0.45-in. diameter lattice was selected, because the pellet size more nearly represents present-day fabrication plant capability.

CONCLUSIONS

The oxide fueled PWR study indicated that, for a publicly owned reactor utilizing a privately owned 75,000 Mwth capacity fabrication plant, equilibrium fuel cycle costs of 0.360 mills/kwhr(t) and 0.335 mills/kwhr(t) could be expected from commercial power and process heat reactors, respectively. For a privately owned reactor using the same fabrication-reprocessing complex, corresponding fuel cycle costs are 0.400 mills/kwhr(t) and 0.380 mills/kwhr(t). If the reactor is publicly owned and the on-site fabrication-reprocessing complex is publicly owned with a 15,000 Mwth industry capacity, equilibrium fuel cycle costs are 0.415 mills/kwhr(t) and 0.394 mills/kwhr(t), respectively. For comparative purposes, vendor-predicted equilibrium cycle costs are 0.38-0.42 mills/kwhr(t) and 0.44-0.48 mills/kwhr(t) for publicly and privately owned power reactors, respectively. These cost ranges are based on reactors reaching their equilibrium cycle in the early 1980's. Costs generated by this study are for reactors going on-line in the early 1980's, and reaching their equilibrium cycle in the late 80's or early 90's. Vendor-predicted costs for this time period are not available. Other differences between the generated costs and vendor-predicted costs are attributable to differences in the assumed economic ground rules. This study assumed relatively large established fabrication and reprocessing industries. All costs quoted above were based on a separative work charge of \$30/kg U and an optimum tails of 0.2594 w/o ^{235}U. Using the recently revised separative work charge of \$26/kg U and tails of 0.20 w/o ^{235}U, a fuel cycle cost saving of 3-4% will be realized for all economic conditions.

A comparison of the fuel cycle costs for both reactor concepts indicates that a saving of 7% can be achieved in the fuel cost component of the prime steam cost by using the process heat reactor rather than the commercial power reactor for the production of fresh water. For Condition I, the net fuel cost represents 66% of the total cycle cost for the power reactor but only 62% for the process heat reactor. Fabrication and reprocessing charges account for 23% and 24%, respectively, while shipping and inventory charges are responsible for the remaining 11% and 14%.

A comparison of the design and cost parameters between both concepts indicates that the cost optimization followed predictable trends. For example, the increase in initial reactivity that is experienced by designing to lower moderator and fuel temperatures can result in cost savings primarily reflected in the net fissile burnup cost (feed cost + uranium credit + plutonium credit). The lower temperature process heat reactor requires a lower water-to-fuel volume ratio and enrichment to achieve a reasonably high burnup. The reactivity gained by the moderator and Doppler effects results in a lower net fuel cost and fuel cycle cost. Fabrication cost advantages achieved by using a larger pellet and a higher uranium throughput are offset by the increase in core inventory charges, caused by the necessarily lower specific power.

It should be noted that, for both concepts, the cost minimum is broad with respect to enrichment and water-to-fuel ratio. For a given enrichment and reactor concept, cycle costs vary by 3%, within $\pm$20% of the optimum water-to-fuel ratio. For a given water-to-fuel ratio and concept, cycle costs vary by only 3% within a range of $\pm$0.5 w/o ^{235}U from the optimum enrichment.

For both concepts, the fuel cycle cost for a privately owned reactor plant is 12% higher than the cost for a publicly owned plant using the same privately financed fabrication-reprocessing complex.

The cost difference is due solely to the doubled interest charges. For the publicly owned reactor plant using an on-site publicly financed fabrication-reprocessing plant, the fuel cycle cost is 18% higher. This is due to the smaller capacity of the fabrication-reprocessing complex. Fabrication plant capacities for the complex capable of supporting the 15,000 Mwth industry are one-fifth of the capacity of the 75,000 Mwth industry plants. The lower throughputs are reflected through a 45% increase in the unit fabrication cost. The on-site processing plant has only 6% of the capacity of the centrally located larger industry plant, resulting in a 30% increase in the unit reprocessing cost.

Appendix A

RESULTS OF TONG CALCULATIONS FOR THE SELECTED REFERENCE DESIGNS

For purposes of comparison with other ORNL studies, equilibrium fuel cycle costs for the selected reference designs were calculated using results of the computer code TONG.[16] TONG is a point depletion code capable of calculating reactor core histories of multi-batch cores. GAM-I and THERMOS were used to prepare a set of multigroup microscopic cross-sections. For the point depletion calculation, it is assumed that the exposure of a sample of material representative of the core average to the flux necessary to develop the average power density will give a good approximation of the spatially averaged cycle time behavior of the core. Such a calculation is reliable only when the core is large and reflected, as are the reference cores.

In a typical depletion calculation with the TONG code, initial nuclide concentrations are specified in each of the several fuel batches. These concentrations are averaged, and the point eigenvalue problem is solved to establish the fluxes. Depletion history is followed for each fuel batch exposed to the single set of fluxes, which are recalculated at specified time intervals.

To begin a cycle, the fuel loading in a newly loaded batch may be specified or a desired multiplication factor, k, may be satisfied (usually without control rods) by adjustment of one or more nuclide concentrations. At the start of each depletion step, a required k (near unity) may be achieved by adjustment of control rod poison. The end of a cycle is established by extrapolation to zero poison concentration at a specified final reactivity.

At the end of a cycle, material in one zone is discharged and reprocessed, and when desired, fuel nuclides are returned to the core at some later cycle. If the end of a cycle occurs at a time that exceeds a specified total accumulated time, the reactor history is ended.[16]

Another option available in the code was used to perform the calculations described in this appendix. The method consisted of specifying the burnup and cycle time and allowing the code to adjust (by iteration) the beginning of cycle ^{235}U concentration in order to meet the desired burnup and cycle time. In this manner, the code will achieve the equilibrium cycle after 8 to 9 cycle histories.

A comparison of burnup parameters predicted by TONG, Westinghouse, and LTM for the equilibrium cycle is presented in Table 19. To achieve a given burnup, TONG consistently predicts a feed enrichment 0.5 to 0.6 w/o ^{235}U below that predicted by LTM and Westinghouse. Discharge uranium and plutonium concentrations predicted by TONG are also lower than those predicted by LTM and Westinghouse. As previously described in this report, the LTM predictions of enrichment and burnup for the power case were normalized to Westinghouse predictions at the Diablo Canyon design point. The process heat reactor calculations are also normalized to the same design point through the use of the same fractional control absorption.

The disagreement between TONG predicted values and LTM-Westinghouse predicted values may be attributed to two causes. First, it must be realized that Westinghouse predictions (and therefore LTM predictions) are conservative for the enrichment required to meet a specific burnup. Fuel burnups are warranted and enrichments are necessarily predicted higher than the actual required enrichment. From recent unpublished studies performed by ORNL, it is estimated that the design conservatism is on the order of .2 w/o ^{235}U. The remaining .3 to .4 w/o ^{235}U appears to be caused by a combination of different fission product treatment and the neglect of non-depleting control rod poison. TONG predicts a more thermal spectrum than either LTM or Westinghouse and therefore predicts a lower ^{235}U discharge enrichment and lower plutonium production.

TONG has historically predicted enrichments 0.5 to 0.6 w/o ^{235}U below Westinghouse predictions. In Ref. 17 TONG calculations indicated that, for a Westinghouse design similar to that used in this study, an enrichment of 2.4 w/o ^{235}U was required to produce 24,000 Mwd/Tonne, while Westinghouse predicted an enrichment of 3.0 w/o ^{235}U. TONG predictions of the discharge uranium and plutonium concentrations were also considerably lower than Westinghouse predictions.

Fuel cycle costs calculated on the basis of TONG results are presented in Table 20 for the economic condition previously described in Condition I. This condition assumes public financing of the reactor

Table 19. Comparison of TONG, Westinghouse, and LTM Predicted Burnup Parameters for the Selected Power and Process Heat Reactor Reference Designs

Equilibrium Cycle Parameters	Power Reactor Concept			Process Heat Reactor Concept	
	TONG Results	LTM Results	Westinghouse Results	TONG Results	LTM Results
Uranium charged per region, kg	29411	29411	29070	56159	56159
Uranium discharged per region, kg	28048	28111	27794	53863	53939
Uranium burned during residence, kg	1363	1300	1276	2296	2220
Initial ^{235}U enrichment, w/o	2.78	3.30	3.30	2.31	2.80
Final ^{235}U enrichment, w/o	.40	.81	.92	.31	.68
Fissile plutonium discharged per region, kg	156.8	182.4	190.5	297.1	351.3
Final fissile Pu concentration, gm Pu/kg U	5.33	6.21	6.55	5.29	6.27
Full power days per region, days	898	898	886	1131	1131
Average fuel burnup, Mwd/Tonne	33109	33109	33000	28887	28887
Discharge Fraction of ^{239}Pu, w/o	47.7	54.3	56.0	51.6	58.3
Discharge Fraction of ^{240}Pu, w/o	30.8	24.2	23.7	28.7	22.4
Discharge Fraction of ^{241}Pu, w/o	14.1	15.9	15.0	13.3	14.6
Discharge Fraction of ^{242}Pu, w/o	7.4	5.6	5.3	6.4	4.7

Table 20. TONG Predicted Equilibrium Fuel Cycle Costs for Selected Power and Process Heat Reactor Concepts

Cost Component	Reference Core	
	Power Reactor	Process Heat Reactor
Makeup uranium	.266	.238
Uranium credit	-.004	-.000
Plutonium credit	-.061	-0.69
Processing	.014	.016
Fabrication	0.64	.059
Interest on fabrication	.010	.011
Fabrication inventory	.002	.003
Core inventory	.019	.022
Processing inventory	.002	.002
Shipping	.005	.005
Total Fuel Cycle Cost[a,b,c] mills/kwhr(t)	.316	.286
Total Fuel Cycle Cost, ¢/10^6 BTU	9.26	8.38

[a]Fuel cycle costs are based on a separative work charge of \$26/kg U, tails concentration of .20 w/o ^{235}U, conversion charge of \$1.35/kg U and an ore cost of \$8.00/lb U_3O_8.

[b]Total does not necessarily equal sum of components due to roundoff error.

[c]Publicly owned reactor with fixed charge rate on non-depreciating assets of 5% and a discount rate of 4%. Privately owned central processing and fabrication plants with fixed charge rate of 22% on capital investment. Processing plant is sized for 10 MT/day and fabrication plant serves a 75,000 Mw(th) industry.

plant and private financing of a fabrication plant capable of supporting a 75,000 Mw(th) industry and a 10 Tonne/day reprocessing plant. The cost calculation uses the discounted-worth method based on a 4%/yr average cost of money and a 5% fixed charge rate on non-depreciating capital. Fuel cycle costs are consistently lower than those predicted by LTM for the same cases. This is due solely to the lower equilibrium feed enrichments, therefore decreasing the net burnup and inventory cost components of the total cycle cost.

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A FUEL CYCLE ECONOMIC ANALYSIS OF OXIDE FUELED POWER AND PROCESS HEAT PWR'S FOR SEAWATER DESALINATION

Oak Ridge National Laboratory, Tenn.

ORNL-TM-2046 (Jan.1969), 59 p, 7 fig, 20 tables, 17 ref

Economic studies were conducted to determine minimum equilibrium fuel cycle costs for two oxide fueled PWR concepts. Each reactor is to be used to generate steam for a single-purpose desalination plant. The two reactor concepts studied were a commercial "product line" power reactor and a lower temperature process heat reactor. Fuel cycle costs were based on economic ground rules believed to be representative for reactors going "on-line" in the 1980's.

The study indicated that, for a publicly owned reactor utilizing a privately owned 75,000 Mwth capacity fabrication plant, equilibrium fuel cycle costs of 0.348 mills/kwhr(t) and 0.324 mills/kwhr(t) could be expected from commercial power and process heat reactors, respectively. These costs are based on an ore cost of \$8.00/lb U_3O_8, a separative work charge of \$26/kg U and a tails of 0.20 w/o ^{235}U. For a privately owned reactor using the same fabrication-reprocessing complex, corresponding fuel cycle costs are .385 and .367 mills/kwhr(t). If the reactor is publicly owned and the complex is publicly owned with a 15,000 Mwth industry capacity, equilibrium fuel cycle costs are 0.402 and 0.381 mills/kwhr(t), respectively.

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