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CIVILIAN POWER REACTOR PROGRAM

PART III

TID-8518
Addendum

Core-parameter Studies for Selected Reactor Types

UNITED STATES ATOMIC ENERGY COMMISSION

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PART III

Core-parameter Studies for Selected Reactor Types

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PREFACE

On June 1, 1959, the Atomic Energy Commission's Division of Reactor Development undertook the task of establishing a long-range program for the development of civilian power reactors. The results of the studies performed in the course of this task were published by the Atomic Energy Commission in the following series of reports, under the general title *Civilian Power Reactor Program*; these reports are available from the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C., at the indicated prices.

TID-8516—Part I—Summary of Technical and Economic Status as of 1959, Price \$1.

TID-8517—Part II—Economic Potential and Development Program as of 1959, Price \$0.70.

TID-8518—Part III—Technical Status Reports:

Book 1, "Status Report on Fast Reactors as of 1959," Price \$1.

Book 2, "Status Report on Pressurized Water Reactors as of 1959," Price \$1.25.

Book 3, "Status Report on Aqueous Homogeneous Reactors as of 1959," Price \$1.25.

Book 4, "Status Report on Heavy Water Moderated Reactors as of 1959," Price \$1.25.

Book 5, "Status Report on Boiling Water Reactor Technology as of 1959," Price \$0.60.

Book 6, "Status Report on Sodium Graphite Reactors as of 1959," Price \$1.

Book 7, "Status Report on Organic-Cooled Power Reactors as of 1959," Price \$2.25.

Book 8, "Status Report on Gas Cooled Reactors as of 1959," Price \$0.55.

TID 8519, Part IV—Plans for Development as of February, 1960. Also published by the Atomic Energy Commission was Report SL-1674, "Power Cost Normalization Studies—Civilian Power Reactor Program, 1959," which presents backup information on the normalized cost estimates incorporated in Part I of this series.

In conjunction with the evaluation studies summarized in the referenced series of reports, a series of preliminary studies was undertaken under Atomic Energy Commission sponsorship to provide data concerning the effects of perturbations of significant reactor-core parameters on power cost. The present report summarizes the results of these preliminary studies, for five selected reactor types.

The reactor-plant reference designs on which the core-parameter studies are based have been made consistent with information published in the following reports as indicated:

TID-8518 (Part III, Individual Status Reports)—The reactor-plant type, the type of fuel, and the limits of technology are consistent with the information contained in the individual status reports.

SL-1674 (Power Cost Normalization Studies)—The plant-capital cost, the fuel cycle data and fuel-fabrication cost were made consistent wherever practical with the information contained in the report on normalization studies.

The technical and economic status has obviously changed since the referenced technical and economic status reports were published. However, since core parameters are shown as variables in the present report and are plotted against a change in cost, they show the relative economic trends as the parameters are varied. In addition, the effects of a change in cost data (for example, fuel-fabrication cost) are shown where applicable.

In addition to the information contained in the individual sections on the various core-parameter studies, the appendices provide related reference information.

Appendix I includes cost data for the various reactor concepts. Appendix II gives the assumptions and ground rules used in the core-parameter studies. Appendix III lists the key contractors who assisted in preparing the core parameter information on which this report is based. Appendix IV summarizes the reference material used in preparing this report.

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I. INTRODUCTION

The ultimate objective in the design of a nuclear power plant is to develop a complete system that will produce power at the lowest possible cost. The technology of nuclear power reactors is in an early stage of development, and it is therefore highly desirable to determine the reactor-core and plant-design parameters that have a significant effect on power cost. The information will be useful in design optimization and can also be used as a guide for determining the technical areas that merit the greatest efforts.

The total power cost of a nuclear reactor plant is closely associated with such composite parameters as plant efficiency, core power density, fuel specific power, fuel exposure, fuel-enrichment level, and the conversion ratio. These parameters are interrelated and form the basis for determining fuel-cycle cost and plant-capital cost for a given reactor type.

Each of the composite parameters noted is affected by other design variables. For example:

(a) Core power density, which defines the amount of thermal energy produced per unit of reactor core volume (kw/liter of core), is affected by such items as moderator-fuel spacing, peak-to-average power, and fuel specific power. Core power density itself affects plant-capital cost and fuel-cycle cost.

(b) Fuel specific power, which defines the amount of thermal energy that can be removed per unit weight of fuel material, is affected as follows: The upper limit of fuel specific power is generally determined by either burnout, central-fuel melting and fission-gas release, or relative fabrication costs. A low fuel specific power means a high fuel inventory and a correspondingly higher fuel-use charge. Specific-

power capability within these limitations is affected by the peak-to-average power characteristics of the reactor. Peak-to-average power is determined by the following factors: axial peak-to-average power, radial peak-to-average power, water-gap peaking, enrichment mismatch, fuel-density mismatch, transient-power overshoot, and control-rod perturbation. Specific-power capability, in conjunction with fuel enrichment, determines the fuel-inventory charges.

(c) Fuel exposure most directly affects the fabrication costs of the fuel elements and is limited physically by fission-gas release, volumetric changes, and structural integrity as related to clad integrity. Because of power-distribution, control, and criticality effects, it is not possible to obtain relatively uniform maximum burnup for all elements without a fuel management program. It is beyond the scope of this report to justify the optimum fuel management program for a given reactor type. Fuel management programs have been assumed for each reactor type and are described in subsequent pages of this report.

(d) The fuel-enrichment level and the conversion ratio are determined by the core composition, the fuel exposure, and the core and reflector size.

It is important to know the individual effects of each significant reactor parameter on power cost, as well as the composite effect of several parameters, since a change in one parameter may adversely affect other parameters.

Core-parameter variations fall into two categories: those that can be realized within existing technology and those that require research and development to eliminate uncertainties or to improve core performance. The results of

the core-parameter studies will show the potential economic gains to be obtained from changing the various parameters, and should aid in determining when research and development may be justified.

Future trends will also have a significant effect on the optimum design parameters for a particular reactor type. For example, the optimum average fuel exposure is interrelated with fabrication cost. Also, the optimum power density (fuel loading) is a function of the base price of UF_6 . The future trends in those items must be considered in any core-parameter study.

In the present status of reactor technology, it is necessary to make simplifying assumptions in order to conduct studies of the type under discussion. These assumptions will probably introduce some degree of error in the results; however, these errors should not materially distort the trends indicated by the results of the studies.

The primary purpose of this report is to provide a tool for readily evaluating the relative economic incentives for changing reactor-core parameters. The cost relationships are therefore shown in terms of "differential cost" (that is, change in cost) in lieu of total cost.

A total cost for each reactor described is shown in appendix 1 so that total power cost for a given set of parameters can be obtained, if desired.

It should be noted that while the information given in this report can be used for conceptual-design purposes, considerably more detail would obviously be required for the final detail design of a reactor core.

A description of the five different reactor types considered and a discussion of the effects on power costs of varying the significant core parameters are provided in the subsequent sections of this report. The reactor-core and plant-design conditions used for the reference design of the reactor concepts described are based on the technical status reports published by the AEC as Books 1 through 8 of Part III (TID-8518) of the series of reports on the "Civilian Power Reactor Program" (see Preface). The effects of changing the reactor-core parameters on power cost are based on information provided to the AEC in support of the Commission's long-range program for civilian power reactors that was commenced in 1959. A list of these documents and other reference data are provided in appendix 4.

II. PRESSURIZED-WATER REACTORS

A. Description of Reactor Plant

The pressurized-water reactor is a heterogeneous, UO_2 -fueled, thermal reactor that uses light water (H_2O) as the moderator and the coolant. The system utilizes an intermediate coolant loop between the reactor and the turbine. The water in the primary coolant loop

is maintained under high pressure in order to keep the bulk temperature of the coolant leaving the reactor below the saturation temperature during normal operating conditions. The significant reference-design characteristics for the pressurized-water reactor plant are given in table II-1.

TABLE II-1.—SUMMARY OF THE REFERENCE-DESIGN CHARACTERISTICS FOR THE PRESSURIZED WATER REACTOR PLANT

A. Plant Data:		B. Reactor Description—Continued	
1. Plant size (net) Mw(e)-----	300	5. Material inventory:	
2. Turbine output (gross), Mw(e)-----	320	a. Fuel, metric tons of U-----	63.8
3. Reactor power, Mw(t)-----	1,065	6. Reactor control:	
4. Plant efficiency (net), %-----	28.2	a. Method of control-----	rods
B. Reactor Description:		b. Number of control elements-----	46
1. Reactor vessel:		C. Plant-Performance Data:	
a. Inside diameter, ft-----	13.0	1. Primary-coolant outlet tempera-	574
b. Over-all height, ft-----	36	ture, °F.	
c. Wall thickness, in-----	7.9	2. Primary-coolant inlet tempera-	533
d. Material-----	SS clad CS	ture, °F.	
e. Design pressure, psi-----	2,500	3. Reactor Δt , °F-----	41
2. Reactor core:		4. Primary-system operating pres-	2,150
a. Active diameter, ft-----	9.34	sure, psi.	
b. Active height, ft-----	9.66	5. Primary-coolant flow rate, lb/hr--	69.5 x 10 ⁶
c. Active core volume, cu ft-----	661	6. Average core heat flux, Btu/hr/sq	107,500
d. Lattice arrangement-----	square	ft.	
3. Reflector:		7. Maximum core heat flux, Btu/hr/	398,000
a. Material-----	H ₂ O	sq ft.	
b. Radial thickness, ft-----	1.5	8. Maximum fuel temperature, °F--	4,500
4. Fuel elements:		9. Core-coolant velocity, ft/sec-----	14.1
a. Fuel material-----	UO ₂	10. Hot-channel factor-----	3.7
b. Clad material-----	SS	11. Core power density, kw/liter of	56.2
c. Fuel enrichment, %-----	3.45	core.	
d. Discharge enrichment, %-----	2.3	12. Core specific power, kw(t)/kg of	16.7
e. Pu production, gm/kg of U-----	7.4	U.	
f. Fuel-element geometry-----	rods	13. Fuel exposure, Mwd/metric ton of	14,700
g. Cladding, thickness, in-----	0.029	U (average).	

B. Fuel Management Program

The fuel management program selected as the reference design for the pressurized-water reactor, utilizes a three-cycle fuel-loading procedure in which the core is divided into three concentric regions. Refueling is accomplished by removing one region at a time. In this procedure, new fuel is introduced into the outer third of the core at each cycle. The previous outer region is moved to an intermediate third of the core. The fuel in the intermediate third (now burned through two cycles) is moved to the central third of the core. The completely burned fuel is removed from the central third and processed to recover its uranium and plutonium.

C. Core Power Density and Fuel Specific Power

The reactor-core power density affects both the capital cost of the plant and the fuel-cycle cost. An increase in the reactor-core power density will reduce the size and cost of the reactor pressure vessel, the vapor-containment structure, the plant shielding, the control-rod drive mechanisms, and the buildings and structures for this equipment. The principal effects of the reactor-core power density on fuel-cycle cost are on the fuel loading, which affects the fuel-use charge; on the moderator-fuel spacing, which affects fuel-enrichment levels and burnup cost; and on the fuel specific power, which affects both the aforementioned variables and also the fuel-fabrication cost.

While an increase in core power density will reduce the capital cost of the reactor components, it may have an adverse effect on the fuel-cycle cost. The objective of analyzing the core power density for a given reactor type is to consider its effects on plant-capital cost and fuel-cycle cost and to determine the point where the combined effect of these two variables results in the lowest power cost. It is important to note that this optimum point will be affected by such items as the base cost

of UF_6 and fabrication cost, in addition to the technical limitations of such items as fuel performance, moderator-fuel spacing, and reactive lifetime.

There are several means of obtaining an increase in the average power density in a reactor core. First, the fuel-rod diameter can be reduced and the total number of fuel rods per unit volume increased. This procedure maintains the same total fuel rod length for a given power output and holds the thermal output per unit length (kw/ft) at a constant value. While this approach can be accomplished with no advancements in technology, it will increase the fuel-fabrication cost. A second means of increasing core power density is to operate the hottest rod at a higher power density, thus raising the average power density of the core. To carry this approach beyond current limitations would require experimental work in order to develop an improved fuel element or to verify that higher outputs are permissible. A third means of achieving higher power density is to reduce the peak-to-average power in the reactor core; this will permit a higher average value without increasing the design point. Each of these methods involves a different type of change in the core and plant, and has been analyzed separately to determine its effect on power cost.

The effects of core power density on plant-equipment cost are shown on figure II-1. This data reflects the relative economic incentive in plant-equipment cost as the power density is changed, but does not reflect the change in fuel-cycle cost that is necessary to obtain the power density. The cost variation shown is a composite cost and is based on the following plant equipment varying with the power density: reactor pressure vessel, vapor-containment structure, primary shielding, control-rod drive mechanisms, and supporting buildings and structures. The relatively small change in plant cost that occurs over a wide spread of core power density indicates that the other parameters that must be changed in order to achieve a different power density will have a

FIG. II-1—Effects of the core power density on the plant-equipment cost, for a pressurized-water reactor.

significant effect on the selected power density.

The effects of core power density on total energy cost for four different values of fuel exposure are shown on figure II-2. The fuel-rod size corresponding to the power density is also shown on figure II-2. The rod size can be directly related to fuel specific power. It was assumed, for the purpose of showing this relationship, that the power density is changed by varying the fuel-rod size. For example, to obtain a higher power density, the center-line temperature of the UO_2 fuel was held constant (at approximately $4,500^\circ\text{F}$) and the rod size was reduced. This increased the rod heat flux, and resulted in more power per unit of fuel weight. The thermal power was held constant and the core size was reduced appropriately as power density was increased. The moderator-fuel spacing, the materials volume fraction, and the hot-channel factors were held constant.

Two opposing factors are dominant in creating the variations shown in figure II-2. First,

the fabrication cost increases as the rod size decreases. (The relationship between rod size and fabrication cost is shown by figure 2-1, appendix 2.) Second, the fuel loading is reduced as rod size is reduced, resulting in lower fuel-use charges at higher power densities. At lower values of fuel exposure, fuel fabrication is by far the dominant criterion. At higher values of fuel exposure, the fuel-use and burn-up charges become the most dominant criteria.

The differential total energy cost shown in figure II-2 reflects the changes in plant cost and the change in fuel-cycle cost as power density is changed. The change in fabrication cost and the effects of adding fuel enrichment for the longer fuel exposures were included in the fuel-cost component.

The most significant point shown in figure II-2 is the shift in optimum power density as the fuel exposure is changed. This curve indicates that the optimum power density for a fuel exposure of 14,000 Mwd/metric ton of U

FIG. II-2—Effects of the core power density on the total energy cost for selected values of fuel exposure, for a pressurized-water reactor.

(average) is approximately 56 kw/liter of active core volume, whereas the optimum power density for a fuel exposure of 22,000 Mwd/metric ton of U is approximately 82 kw/liter of core.

An arbitrary zero reference design point was selected to show four values of fuel exposure on one figure. Curves for each exposure level are plotted through this zero reference. In actual fact, the reference point (zero) would be at a different cost level for each exposure; however, the change in cost shown in figure II-2 adequately reflects the effects of power density on cost without the cost component due to changes in exposure level alone. The total cost continues to decrease as fuel exposure is increased.

Increased fuel exposure primarily affects fuel-fabrication cost. It is therefore axiomatic that one of the primary reasons for seeking higher fuel exposures is the fact that within the current status of technology the fuel-fabrication-cost component of the total fuel-cycle cost is high. The data presented in figure II-2 indicate that long fuel exposures will reduce the effects of relatively high fabrication cost to the extent that higher power densities are desirable (at the higher fuel exposures) even though the relative fabrication cost of fuel rods compatible with these exposures increases at the higher power densities.

Present trends indicate that the cost of fabricating UO_2 fuel will decrease with additional experience and larger-order volumes. A pro-

jection of fuel-fabrication costs over a period of years is shown in figure 2-1 of appendix 2.

An illustration of the effects of fuel-fabrication cost on the optimum power density is given by figure II-3. The fuel-exposure level is held constant at 14,700 Mwd/metric ton of U (average). This curve indicates that reductions in fabrication cost will also provide a strong incentive for a higher power density core or, under the assumption that the technology will limit the power density, may be a significant factor in determining the optimum fuel-exposure level.

There is no appreciable difference in the effect on energy cost between increasing power density by reducing the fuel-rod diameter or by increasing the thermal limits on the hottest fuel rod. The same relationship exists between average coolant temperature and the coolant temperature at the outlet of the hot channel. One of the ground rules on which present re-

actor designs is based is that no bulk boiling is allowed at the exit of the core. In the reference design, the hottest temperature at the core outlet is below the saturation temperature at 2,150 psia (646°F). A margin is allowed for small pressure and temperature variations during operation and to account for instrument errors.

A reduction in peak-to-average power in the core will have a significant effect on energy cost. This will result in an increase in the average power density of the core and a decrease in the peak-to-average coolant enthalpy rise, $F_{\Delta T}$. The advantages of a reduction in $F_{\Delta T}$ can be taken as either reduced main-coolant flow, reduced steam-generator heat-transfer surface, reduced primary-coolant pressure, increased steam pressure, or greater plant output; or as a combination of all these advantages to a lesser degree. For all these improvements, the maxi-

FIG. II-3—Effects of the fuel-fabrication cost on the optimum power density, for a pressurized-water reactor.

imum coolant-outlet temperature is still maintained below saturation.

Figure II-4 illustrates the improvement achieved by reducing the peak-to-average core power. The solid lines show the reduction in energy cost that comes about if no improvement in $F_{\Delta T}$ is accounted for, while the dotted lines illustrate the cost reduction obtained if $F_{\Delta T}$ is reduced along with F_q , the peak-to-average heat flux. The difference between the two curves reflects cost reductions due to the following factors:

- (1) Lower auxiliary power requirements due to the reduction in the primary-loop pumping power.
- (2) Reduced capital costs due to the reduced pump size in the primary loop.
- (3) Higher gross electrical output due to the higher efficiency at the increased steam pressure.

Although considering the optimization of all these improvement factors is beyond the scope

of this report, figure II-4 illustrates a reduction in power-generation costs due to a combination of these improvements that has been selected as a balance that is felt to be reasonably close to optimum.

As noted earlier in this report, all the designs discussed in the report are based on the prevention of bulk boiling at the outlet of the hot channel in the core. The difference between the solid and dotted curves in figure II-4 also gives an indication of the cost of this ground rule, since allowing bulk boiling would permit the same plant improvements that are brought about by a reduction in $F_{\Delta T}$.

Figure II-5 presents a more complete picture of energy-cost improvements resulting from a reduction in the peak-to-average power density. The table in figure II-5 illustrates values of F_q and $F_{\Delta T}$ that are associated with specific values of the power density, P_o .

Core specific power reflects the ability of the fuel to generate heat per unit weight of fuel

FIG. II-4—Effects of reducing the peak-to-average core power on the total energy cost, for a pressurized-water reactor.

FIG. II-5—Effects of the fuel-exposure level and F_Q plus $F_{\Delta T}$ on the total energy cost, for a pressurized-water reactor.

content and is generally expressed as the fractional thermal energy release per unit weight of fuel. This can also be expressed in energy per foot of fuel rod. Operation at high specific powers results in low fuel inventory, which is reflected in minimum fuel-use charges. The factors that affect the optimum selection of design specific power are also directly related to those factors that affect the optimum power density. A reactor may be designed to operate at any value of specific power within the design limitations of either burnout heat flux or fuel-central melting.

Effects of variations in specific power have been shown in the previous curves that are used to show the effects of power density on energy cost. Rod-diameter changes were made, with increases in specific power, to hold the fuel-central temperatures below the melting point. As rod sizes are reduced, the allowable specific power may be increased approximately in pro-

portion to the square of the rod radius. Alternatively, specific power may be increased by reducing the peak-to-average core power, thus permitting an increase in the thermal output per unit length (kw/ft) of the fuel rod. Effects on differential energy costs, obtained by reducing the peak-to-average core power, are shown on figure II-6. This peak-to-average power reduction can be obtained by variations in the moderator-to-fuel ratio or by use of multiple-region enrichments. In either case, increases in core fabrication charges will result. The gains realizable from "core flattening" are significant and are increased at long exposures, where higher fabrication charges tend to be less significant. Figure II-7 illustrates the effects of decreased fabrication charges on optimum specific power by changes in rod diameter in a manner similar to that discussed under power-density effects.

FIG. II-6—Effects of the fuel specific power and the fuel exposure on the total energy cost, for a pressurized-water reactor.

D. Variation of Moderator-to-Fuel Ratio

Variation of the moderator-to-fuel ratio for a pressurized-water reactor affects both the fuel-cycle and plant-capital costs. Physically, the moderator-to-fuel ratio is varied by spacing the fuel rods closer or further apart. The U^{235} loading approaches a minimum at a moderator-to-fuel ratio of approximately 1.5. Plutonium production is greater and the atom fraction of U^{235} burned is less for a tighter lattice configuration. Reactivity effects, as a function of the moderator-to-fuel ratio, are important in establishing plant operating characteristics, such as temperature coefficients.

Fuel-cycle economics and plant-capital costs tend to favor a relatively tight lattice for

intermediate-to-long exposures; however, the effect of changing the moderator-to-fuel ratio, over the range of interest, is nominal and a selection may well be based on factors other than nuclear.

Several capital cost factors are affected by changes in the moderator-to-fuel ratio. Pumping power is reduced at high moderator-to-fuel ratios because lower velocities are required to circulate the coolant through the core. Conversely, vessel-shielding, containment, core-internals, and control-element costs tend to increase at high moderator-to-fuel ratios because of adverse effects on the core power density.

Figure II-8 is a plot of the variation in differential total energy costs with the moderator-

FIG. II-7—Effects of the fuel-fabrication cost on the optimum specific power, for a pressurized-water reactor.

FIG. II-8—Effects of the moderator-to-fuel ratio on the total energy cost, for a pressurized-water reactor.

to-fuel ratio at four values of fuel exposure. Depicted effects include considerations of fuel-cycle costs, pumping energy, and capital costs.

The curves indicate that the reference design is close to optimum for a fuel exposure of 14,700 Mwd/metric ton of U (average) with a moderator-to-fuel ratio of 1.25. It is evident that the effects of the moderator-to-fuel ratio are nominal on total costs; however, at higher fuel exposure levels, plutonium production becomes significant. This tends to shift the optimum moderator-to-fuel ratio to a somewhat lower value. The variation in energy cost with changes in the moderator-to-fuel ratio is small compared with such effects as core structural volume and specific power.

E. Stainless-Steel Clad-to-Fuel Volume Ratio

Cladding design criteria for UO_2 rod-fuel systems are generally based on "free standing" characteristics, such that tubes will not collapse when exposed to primary system pressure. Alternate design approaches may be considered for fuel cladding wherein substantial reductions in metal-clad thickness might be obtained. These include provision of pressure compensation or demonstration of cladding support by UO_2 fuel, which would permit thinner metal walls.

The relative stainless-steel content of a pressurized-water reactor design directly affects enrichment-level requirements due to the parasitic effect of such high cross-section materials.

The effect of reducing clad thickness for the reference design can be demonstrated, as shown in figure II-9, by holding all design parameters constant except for clad thickness. Figure II-9 shows clearly that a reduction in stainless-steel core parasitic material results in an associated reduction in energy costs. These cost reductions reflect the lower burnup and use charges that are obtained as fuel enrichment is decreased. In addition to these cost reductions, additional savings may be expected in reduced fabrication costs due to the lower enrichment. Losses during fabrication, due to

FIG. II-9—Effects of the fuel-clad thickness on the total energy cost, for a pressurized-water reactor.

pelletizing, grinding, etc., account for increasing costs with higher fuel enrichment.

The economic incentives for minimizing highly parasitic materials are significant and represent one of the dominant effects that have been investigated in this parametric study.

F. Fuel Exposure

Effects of fuel exposure on fuel cost determine the length of residence of fuel in the reactor between refuelings. Short exposures result in relatively high fuel charges because of increased fabrication costs associated with shorter fuel lifetime. Reductions in fuel-fabrication charges for long exposures are offset by the higher burnup cost and the higher use charges associated with increased enrichments to maintain reactivity lifetimes. An optimum exposure may be determined between these limits for a given reactor design.

Present-day technology does not ensure that long exposures are attainable without an increase in element failure frequency due to combined effects of fission-gas release, fuel integrity, and clad integrity. Reactivity control

becomes more difficult for long exposures and requires the use of additional control strength or surface in the form of rods or the use of soluble or burnable poisons. The incentives to long exposures will be offset by reductions in fabrication charges and added complexities of reactivity control devices. The relative incentives for long burnup for the reference design are shown on the plot in figure II-10, which is based on holding all core parameters constant except fuel exposure. Although the optimum point was not determined for the optimum design configuration, the optimum exposure is estimated to be between 30,000 and 50,000 Mwd/metric ton of U (average). Definition of the optimum exposure depends heavily on the statistics of fuel integrity at long exposures; these statistics have not yet been demonstrated.

G. Summary Conclusions

The results of the parametric studies on the pressurized-water reactor indicate that four significant parameters affect power cost. These variables are the core power density, the fuel

specific power, the metal volume fraction, and the fuel exposure. These parameters are inter-related and the following conclusions may be drawn:

1. The optimum power density and fuel specific power are strongly dependent on the fuel-exposure level and the core-fabrication cost. If the fuel exposure is limited by technology or reactivity-control problems to values of less than 30,000 Mwd/metric ton of U (average), there is a strong economic incentive to reduce fuel-fabrication cost. However, if significant reductions in fuel-fabrication cost are achieved, then there is less incentive to achieve exceedingly higher fuel burnup.

2. Cost-reduction trends in fabrication cost must be considered in conjunction with obtainable fuel exposures before the optimum power density and fuel specific power can be determined.

3. The ability to obtain longer fuel exposures and to achieve lower fabrication cost will provide significant economic incentive for higher power-density cores.

FIG. II-10—Effects of the fuel-exposure level on the total energy cost, for a pressurized-water reactor.

4. Within the present framework of technology, higher power density is directly associated with higher fuel specific power.

5. Higher fuel specific power will result in a shorter residence time of the fuel in the core. While this should increase fuel-integrity reliability, it will result in more frequent refueling. This could have an adverse effect on the plant-availability factor. This would probably reduce the economic incentives shown in this report.

6. The effects of moderator-to-fuel ratio on power cost, within reasonable limits, is not a major economic design consideration. Other factors, such as mechanical considerations, should be considered as the dominant consideration in selecting the moderator-to-fuel ratio.

7. Reductions in clad thickness will have the most significant effect on power cost of any parameter studied in this report. Achievement of thinner fuel clad must be tempered by the fact that current design practice is based on a "free standing—non-

collapsible" design. Any change in this philosophy would result in a major deviation from current technology and would require experimental results to determine feasibility.

8. Based on current fabrication cost, there is a strong economic incentive to achieve higher fuel burnup. As fabrication cost decreases, this incentive will become less significant. The feasibility limits of reactivity control, which may become one of limiting factors in reactivity lifetime, were not considered in the fuel-burnup projections used in this report. The most obvious method of increasing average fuel exposure is to reduce peak-to-average core power.

9. There is a significant economic incentive to optimize reactor core parameters. It is apparent that optimum parameters will change as the limits of technology are advanced. For example, lower fabrication or higher fuel exposure dictates higher fuel specific power and higher power density cores.

III. BOILING-WATER REACTORS

A. Description of Reactor Plant

The reference design is a dual-cycle boiling-water reactor plant. The reactor is a heterogeneous, UO_2 -fueled, thermal reactor that uses light water (H_2O) as the moderator and the coolant. The fuel is clad with stainless steel. The primary steam generated in the reactor is supplied from two sources; the steam is separated in an external steam drum and introduced directly to the turbine throttle. In addition, water from the steam drum is

pumped through secondary steam generators (heat exchangers), where additional steam is generated and introduced in a second admission to the turbine. Hence, the term "dual-cycle." The parameter studies are based specifically on the dual-cycle boiling-water reactor and are not quantitatively applicable to other types of boiling-water reactors. The significant reference-design characteristics of the boiling-water reactor are given in table III-1.

TABLE III-1.—SUMMARY OF THE REFERENCE-DESIGN CHARACTERISTICS FOR THE BOILING-WATER REACTOR PLANT

A. Plant Data:		5. Materials inventory:	
1. Plant size (net), Mw(e)	300	a. Fuel, metric tons of U	77.2
2. Turbine output (gross), Mw(e) ..	320	6. Reactor control:	
3. Reactor power, Mw(t)	1,020	a. Method of control	rods
4. Plant efficiency (net), %	29.4	b. Number of control elements	104
B. Reactor Description:		C. Plant-Performance Data:	
1. Reactor vessel:		1. Primary-coolant outlet temperature, °F.	545.3
a. Inside diameter, ft	13.3	2. Primary-coolant inlet temperature, °F.	505
b. Over-all height, ft	46	3. Reactor Δt , °F	40.3
c. Wall thickness, in.	6.2	4. Primary-system operating pressure, psi.	1,015
d. Material	SS clad CS	5. Primary-coolant flow rate, lb/hr ..	2.15×10^6
e. Design pressure, psi	1,500	6. Average core heat flux, Btu/hr/sq ft.	97,700
2. Reactor core:		7. Maximum core heat flux, Btu/hr/sq ft.	283,000
a. Active diameter, ft	11.60	8. Maximum fuel temperature, °F ..	4,500
b. Active height, ft	11.8	9. Peak-to-average power	2.92
c. Active core volume, cu ft	1,250	10. Core voids—weight, %	8.0
d. Lattice arrangement	square	11. Core power density, kw/liter of core.	28.9
3. Reflector:		12. Core specific power, kw(t)/kg of U.	13.2
a. Material	H_2O	13. Fuel exposure, Mwd/metric ton of U (average).	15,000
b. Radial thickness, ft	1.0		
4. Fuel elements:			
a. Fuel material	UO_2		
b. Clad material	SS		
c. Fuel enrichment, %	2.90		
d. Discharge enrichment, %	1.50		
e. Fuel-element geometry	rods		
f. Cladding thickness, in.	0.025		

B. Fuel Management Program

The fuel management program selected as the reference design for the boiling-water reactor is based on a uniformly enriched core at beginning of life. Refueling is based on 20 percent batch loading. Fresh fuel is loaded on the outside periphery of the core and fuel is discharged from the central portion of the reactor. All fuel-cycle data are based on equilibrium core conditions.

C. Core Power Density and Fuel Specific Power

The reactor-core power density affects both the capital cost of the plant and the fuel-cycle cost. An increase in the reactor-core power density will reduce the size and cost of the reactor pressure vessel, the vapor-containment structure, the plant shielding, the control-rod drive mechanisms, and the buildings and structures for this equipment.

The principal effects of the reactor-core power density on fuel-cycle cost are on the fuel loading, which affects the fuel-use charge; on the moderator-fuel spacing, which affects fuel-enrichment levels and burnup cost; and on the fuel specific power, which affects both the aforementioned variables and also the fuel-fabrication cost.

While an increase in core power density will reduce the capital cost of the reactor components, it may have an adverse effect on the fuel-cycle cost. The objective of analyzing the core power density for a given reactor type is to consider its effects on plant-capital cost and fuel-cycle cost and to determine the point where the combined effect of these two variables results in the lowest power cost.

There are several means of obtaining an increase in the average power density in a reactor core. First, the fuel-rod diameter can be reduced and the total number of fuel rods per unit volume increased. This procedure maintains the same total fuel rod length for a given power output and holds the thermal

output per unit length (kw/ft) at a constant value. While this approach can be accomplished with no advancements in technology, it will increase the fuel-fabrication cost. A second means of increasing core power density is to operate the hottest rod at a higher power density, thus raising the average power density of the core. To carry this approach beyond current limitations would require experimental work in order to develop an improved fuel element or to verify that higher outputs are permissible. A third means of achieving higher power density is to reduce the peak-to-average power in the reactor core; this will permit a higher average value without increasing the design point. Each of these methods involves a different type of change in the core and plant, and has been analyzed separately to determine its effect on power cost.

The effects of core power density on reactor plant equipment cost are shown on figure III-1. This data reflects the relative economic incentive in plant-equipment cost as the power density is changed but does not reflect the change in fuel-cycle cost that is necessary to obtain the power density. The cost variation shown is a composite cost and is based on the following plant equipment varying with the power density: reactor pressure vessel, vapor-containment structure, primary shielding, and control-rod drive mechanisms. The relatively large effects of power density on plant-equipment cost shown in figure III-1 are due to the high cost of these items for a dual-cycle boiling-water reactor, and are not quantitatively representative of other types of boiling-water reactors. This is further illustrated by figure III-2, which shows the effects of core power density on containment cost. These curves indicate an optimization of power density with respect to capital costs of higher than 60 kw/liter. However, a proper balance of this gain with the effects of the higher power density on fuel-cycle cost will shift this value.

The effects of core power density on total energy cost for three different values of fuel

FIG. III-1—Effects of the core power density on the plant-equipment cost, for a boiling-water reactor.

FIG. III-2—Effects of the core power density on containment cost, for a boiling-water reactor.

exposure are shown on figure III-3. The fuel-rod size corresponding to the power density is also shown on figure III-3. The rod size can be directly related to fuel specific power. It was assumed, for the purpose of showing this relationship, that the power density is changed by varying the fuel-rod size. For example, to obtain a higher power density, the center-line temperature of the UO_2 fuel was held constant (at approximately $4,500^\circ\text{F}$) and the rod size was reduced. This increased the rod heat flux and resulted in more power per unit of fuel weight. The thermal power was held constant and the core size was reduced appropriately as power density was increased. The moderator-fuel spacing, the materials volume fraction, and the hot-channel factors were held constant.

The following assumptions were made in generating the data for figure III-3:

FIG. III-3—Effects of the core power density on the total energy cost, for a boiling-water reactor.

(1) The fabrication cost increases as the rod size decreases.

(2) The fuel loading is reduced as rod size is reduced, resulting in lower fuel-use charges at higher power densities.

(3) The void content is held constant (at 8 percent) as the power density is increased by recirculating more water through the core.

(4) The changes in fabrication cost and the effects of adding fuel enrichment for longer fuel exposures, together with the cost of extra pumping power, are included in the fuel-cost components.

The data on figure III-3 show the total differential cost effect of fuel exposure and power density; it is apparent that a principal effect is due strictly to changes in fuel exposure.

The same data are plotted on figure III-4 with all curves passing through an arbitrary zero reference point. This effectively nullifies, for comparative purposes, the effects of fuel exposure on power with the exception of how it affects the optimization of power density. These data show that the optimum power density increases as fuel exposure increases. If the void content were allowed to vary with power density, a higher value for the optimum point could be expected. However, high void contents affect the stability of boiling-water reactors; hence, experimental work would be required in order to determine feasibility.

The importance of attaining long fuel exposure is illustrated in figure III-3. Beyond the optimum point, the net burnup costs and the increased U^{235} lease charge associated with the

FIG. III-4—Effects of the core power density on the total energy cost (based on an arbitrary zero reference point), for a boiling-water reactor.

long exposures and high enrichments start to outweigh the advantages of the reductions in the fuel-fabrication-cost component.

Increased fuel exposure primarily affects fuel-fabrication cost. It is, therefore, axiomatic that one of the primary objectives in seeking higher fuel exposures is due to the fact that within the current status of technology the fuel-fabrication-cost component of the total fuel-cycle cost is high. The data presented in figure III-3 indicate that long fuel exposures are desirable primarily because of the fact that they offset relatively high fabrication costs.

Present trends indicate that the cost of fabricating UO_2 fuel will decrease with additional experience and larger-order volumes.

The effects of fuel-fabrication cost at different power densities, but constant fuel exposures, are shown on figure III-5; the curve is based on constant reactor voids and a fuel exposure of 15,000 Mwd/metric ton of U (average). This curve indicates that with high fabrication cost (100 dollars/kg or higher) the optimum power density should be approximately 45 kw/liter. Lower fabrication costs

(less than 100 dollars/kg) provide an incentive for higher power density. The conclusions obtained from figures III-3 and III-5 are that higher power densities offer incentive, provided that the fuel exposure can be increased or that fabrication cost can be reduced.

Boiling "burnout" is characterized by the rather abrupt formation of a thin insulating blanket of steam across the heat-transfer surface, with a correspondingly large increase in thermal resistance. Experiments have shown that this condition at typical reactor heat fluxes could cause excessive overheating, including melting of the fuel clad. Hence, design and operation of the boiling-water reactor must be done so that this destructive phenomenon is avoided.

The design steam quality and void fraction are selected so that the reactor operates within the limits of: (1) boiling burnout due to excessive steam formation rates at the fuel-element surfaces, and (2) nuclear and hydraulic stability. Within these limits, selection is made so that a near-optimum economic balance is achieved between fuel-cycle physics considerations, which favor a low-core steam volume

FIG. III-5—Effects of the core power density and fabrication cost on the total energy cost, for a boiling-water reactor.

fraction, and system pumping, piping, and heat-exchanger costs, which favor high-core steam volume fractions. At rated conditions, the average exit steam quality is approximately 8 percent by weight.

The minimum burnout factor is estimated to be no less than 1.5, on the basis of established boiling-burnout design data. (The minimum burnout factor is defined as the minimum ratio of heat flux to cause burnout divided by actual heat flux under the worst combination of operating conditions.) This magnitude is considered to be feasible.

A reduction in peak-to-average power in the core will have a significant effect on power cost. This will result in an increase in the aver-

age power density of the core and a decrease in the peak-to-average coolant enthalpy rise. Considering the effect of optimizing all these improvements is beyond the scope of this report.

Core specific power reflects the ability of the fuel to generate heat per unit weight of fuel content and is generally expressed as the fractional thermal energy release per unit weight of fuel. This can also be expressed in energy per foot of fuel rod. Operation at high specific powers results in low fuel inventory, which is reflected in minimum fuel-use charges. The factors that affect the optimum selection of design specific power are also directly related to those factors that affect the optimum power density. A reactor may be designed to operate

at any value of specific power within the design limitations of either burnout heat flux or fuel-central melting.

Effects of variations in specific power have been shown in the previous curves that are used to show the effects of power density on energy cost. Rod-diameter changes were made, with increases in specific power, to hold the fuel-central temperatures below the melting point. As rod sizes are reduced, the allowable specific power may be increased approximately in proportion to the square of the rod radius. Alternatively, specific power may be increased by reducing the peak-to-average core power, thus permitting an increase in the thermal output per unit length (kw/ft) of the fuel rod. Figure III-6 illustrates the effects of fabrication charges on optimum specific power by changes in rod diameter in a manner similar to that discussed under power-density effects.

D. Variation of Moderator-to-Fuel Ratio

Variation of the moderator-to-fuel ratio for a boiling-water reactor affects both the fuel-cycle and plant-capital costs. Physically, the moderator-to-fuel ratio is varied by spacing the fuel rods closer or further apart. The U^{235} loading approaches a minimum at a moderator-to-fuel ratio of approximately 2.5. Plutonium production is greater and the atom fraction of U^{235} burned is less for a tighter lattice configuration. Reactivity effects, as a function of the moderator-to-fuel ratio, are important in establishing plant operating characteristics, such as temperature coefficients.

A ratio of 2.5 was selected for the reference reactor design in order to (a) obtain greater stability of operation, because of the correspondingly reduced magnitude of the void-reactivity coefficient, (b) permit greater

FIG. III-6—Effects of the fuel specific power on the total energy cost, for a boiling-water reactor.

flexibility of fuel design, and (c) provide increased reactivity control.

Fuel-cycle economics and plant-capital costs tend to favor a relatively tight lattice for intermediate-to-long exposures; however, the effect of changing the moderator-to-fuel ratio, over the range of interest, is nominal and a selection may well be based on factors other than nuclear. Modest changes in the moderator-to-fuel volume ratio can be accomplished, without changing the lattice or core dimensions, by adjusting the fuel-rod diameter slightly.

Several capital-cost factors are affected by changes in the moderator-to-fuel ratio. Pumping power is reduced at high moderator-to-fuel ratios because lower velocities are required to circulate the coolant through the core. Conversely, vessel-shielding, containment, core-internals, and control-element costs tend to increase at high moderator-to-fuel ratios because of adverse effects on the core power density.

The effects of various moderator-to-fuel ratios are shown on figure III-7. This curve shows the composite effects of exposure level and combined cost effects of changes in fuel-cycle physics, core-pressure drop, and major capital-cost items (such as the pressure vessels, containment, shielding, and building structure) that result from variation of the moderator-to-fuel volume ratio.

It is evident that the effects of the moderator-to-fuel ratio are nominal on total costs;

however, at higher fuel exposure levels, plutonium production becomes significant. This tends to shift the optimum moderator-to-fuel ratio to a somewhat lower value. The variation in energy cost with changes in moderator-to-fuel ratio is small compared with such effects as core structural volume and specific power.

E. Stainless-Steel Clad-to-Fuel Volume Ratio

Cladding design criteria for UO_2 rod-fuel systems are generally based on "free standing" characteristics, such that tubes will not collapse when exposed to primary system pressure. Alternate design approaches may be considered for fuel cladding wherein substantial reductions in metal-clad thickness might be obtained. These include provision of pressure compensation or demonstration of cladding support by UO_2 fuel, which would permit thinner metal walls.

The relative stainless-steel content of a boiling-water reactor design directly affects enrichment-level requirements due to the parasitic effect of such high cross-section materials.

The requirements of the cladding material are that the clad must not collapse or distort as a result of yielding or creep at any time during its life, and the escape of fission products from the cladding tube must be prevented. Therefore, the stress in the cladding tube due to external reactor pressure, internal pressure due to fission gas release, or any other cause

FIG. III-7—Effects of the moderator-to-fuel ratio on the total energy cost, for a boiling-water reactor.

must not result in an excessive deformation. Sufficient volume is provided within the cladding so the fission-gas pressure will not exceed the external pressure. Therefore, the cladding is designed so that the stress due to reactor pressure on a tube of maximum ovality with zero internal pressure will cause less than 1 percent plastic strain in the life of the fuel.

The effect of reducing clad thickness for the reference design is shown on figure III-8. These curves are based on published data and appear conservative when compared with similar data generated for pressurized-water reactors. All design parameters were held constant except for clad thickness. Figure III-8 shows clearly that a reduction in stainless-steel core parasitic material results in a significant reduction in energy costs. These cost reductions reflect the lower burnup and use charges that are obtained as fuel enrichment is decreased. In addition to these cost reductions, additional

savings may be expected in reduced fabrication costs due to the lower enrichment. Losses during fabrication, due to pelletizing, grinding, etc., account for increasing costs with higher fuel enrichment.

The economic incentives for minimizing highly parasitic materials are significant and represent one of the dominant effects that have been investigated in this parametric study.

F. Reactor Pressure Level

The reactor pressure level for the reactor design concept is 1000 psia. The effect of pressure level on total power cost is shown on figure III-9. The data on which the curve is based took into account the variation in the cost of reactor equipment and installation, as well as the variation in the fuel cost resulting from changes in plant heat rate.

FIG. III-8—Effects of the fuel-clad thickness on the total energy cost, for a boiling-water reactor.

FIG. III-9—Effects of the reactor pressure on the total energy cost, for a boiling-water reactor.

G. Fuel Exposure

The effects of fuel exposure on plant cost are shown on figure III-10. The curve is based on holding the reactor parameters constant and simply increasing the average exposure level of the fuel.

The fuel exposure determines the length of residence of fuel in the reactor between refuelings. Short exposures result in relatively high fuel-cycle costs; this is due primarily to the high fabrication-cost component. Reductions in the fuel-fabrication cost component, due to long exposures, are offset by the higher burnup cost and higher use charges associated with increased enrichments to maintain reactivity lifetimes. An optimum exposure may be determined between these limits for a given reactor design.

Present-day technology does not ensure that long exposures are attainable without an increase in fuel element-failure frequency due to combined effects of fission-gas release, fuel integrity, and clad integrity. Reactivity control becomes more difficult for long exposures and requires the use of additional control strength or surface in the form of rods or the use of soluble or burnable poisons. Although the optimum point was not determined for the optimum design configuration, the optimum exposure is estimated to be between 15,000 and 25,000 Mwd/metric ton of U (average). Definition of the optimum exposure depends heavily on the statistics of fuel integrity at long

exposures; these statistics have not yet been demonstrated.

H. Summary Conclusions

The results of the parametric studies on the boiling-water reactor indicate that four significant parameters effect the power cost. These variables are the core power density, fuel specific power, the metal-volume ratio, and fuel exposure. The following conclusions may be drawn:

1. The parameters in this report are based on a "dual-cycle" boiling-water reactor. The results are not necessarily applicable to other types of boiling-water reactors.
2. The optimum power density of the boiling-water reactor will increase as the fuel exposure level increases or the fabrication cost decreases.
3. The most attractive methods of increasing power density are to reduce peak-to-average power or to increase the fuel specific power. Significant cost reductions in these areas appear feasible but require experimental verification.
4. The effects of moderator-to-fuel ratio on power cost, within reasonable limits, is not a major economic design consideration. Other factors, such as mechanical considerations, should be considered as the dominant consideration in selecting the moderator-to-fuel ratio.

FIG. III-10—Effects of the fuel-exposure level on the total energy cost, for a boiling-water reactor.

5. Reductions in clad thickness will have a significant effect on power cost. The economic incentives shown in this report are based on published physics data and appear to be conservative. Based on similar work for the pressurized-water reactor, the incentives should be considerably higher than those shown. Achievement of thinner fuel clad must be tempered by the fact that current design practice is based on a "free standing-noncollapsible" design. Any change in this philosophy would result in a major deviation from current technology and

would require experimental results to determine feasibility.

6. The effects of voids in the boiling-water reactor has an effect on the optimum power density. Increases in the void content (8 percent by weight) would probably result in larger economic incentives for higher power-density reactors.

7. The effects of primary reactor pressure on plant cost are not a significant factor.

8. Considerably more detailed analysis is required to refine the trends indicated in this report to more quantitative basis.

IV. ORGANIC-COOLED REACTORS

A. Description of Reactor Plant

The organic-cooled reactor is a heterogeneous, thermal reactor that utilizes an organic material (Santowax R) as the moderator and the coolant. The particular reactor type described in this report utilizes a plate type of fuel composed of uranium—3.5 percent molybdenum alloy, which is clad with an extended-surface aluminum. The system utilizes four (parallel) intermediate coolant loops between the reactor and the turbine. The significant reference design characteristics for the or-

ganic-cooled reactor plant as given in table IV-1.

B. Fuel Management Program

The fuel management program selected as a reference design for the organic-cooled reactor utilizes a uniformly enriched core at beginning of life. Refueling is accomplished on an annual basis, which involves removing approximately 36 percent of the core load (at 7,000 Mwd/metric ton of U average) at each refueling. All of the physics data given are based on equilibrium core conditions.

TABLE IV-1.—SUMMARY OF THE REFERENCE-DESIGN CHARACTERISTICS FOR THE ORGANIC-COOLED REACTOR PLANT

Gross electrical power, Mw(e)-----	314.4	Initial conversion ratio-----	0.6
Gross cycle efficiency, %-----	31.1	Moderator-to-fuel ratio-----	3.42
Thermal power to primary coolant, Mw(t).-----	1,010	Control-rod type-----	cruciform
Net electrical power, Mw(e)-----	291.5	Number of control elements-----	73
Net cycle efficiency, %-----	28.9	Total worth of control rods, %-----	15
Thermal power leakage from core, Mw(t).-----	10	Peaking factors:	
Total thermal power, Mw(t)-----	1,020	Over-all-----	4.08
Coolant-----	Santowax R	Axial-----	1.57
Coolant inlet temperature, °F-----	524	Radial-----	1.5
Coolant outlet temperature, °F-----	600	Element (adjacent to rod)-----	1.73
Total number of fuel elements-----	372	Hot-channel factors:	
Type of fuel element-----	finned plates	$F\phi$ -----	1.08
Fuel (aluminum clad)-----	Uranium—	$F\Delta t$ -----	1.30
	3.5% molybdenum alloy	$F\theta$ -----	1.43
Initial enrichment, atom %-----	2.1	Maximum coolant velocity, ft/sec-----	15
Total number of lattice spaces in core--	408	Average coolant velocity, ft/sec-----	10
Core diameter, in-----	164	Maximum permissible fuel temperature, °F-----	1,200
Core height, in-----	156	Maximum cladding surface temperature, °F-----	750
Core operating pressure, psi-----	90	Maximum fuel-element power, Mw(t) --	4.1
Total weight of fuel in core, kg-----	120,400	Core pressure drop, psi-----	80
Total weight of uranium in core, kg-----	115,600	Maximum heat flux, Btu/hr/sq ft-----	94,000
Average fuel exposure, Mwd/metric ton of U-----	7,000	Burnout heat flux, Btu/hr/sq ft-----	500,000
Peak fuel exposure, Mwd/metric ton of U-----	11,000	Maximum specific power, kw(t)/kg of U-----	35.7
Initial reactivity, first core, %-----	9.5	Average specific power, kw(t)/kg of U-----	8.8
Depleted enrichment, atom %-----	1.38	Core power density, kw(t)/liter-----	18.8
Plutonium in spent element, gm/kg of U-----	3.67	Mode of heat transfer-----	Forced convection
		Total coolant flow, lb/hr-----	95,000,000
		Number of primary loops-----	4
		Steam pressure, psig-----	550
		Steam temperature, °F-----	580

C. Core Power Density and Fuel Specific Power

There are distinct economic advantages in obtaining a higher power density in reactor cores. The realizable gains in moving to a higher power density are a function of the reactor type and its design limitations and the effects of higher power density on the fuel-cycle cost for the particular reactor in question.

The effects of core power density on reactor plant equipment cost are shown in figure IV-1. The data shown indicate the economic incentive in plant-equipment cost with variation in core power density but does not reflect the change in fuel-cycle cost or changes in other reactor parameters that may be necessary to achieve the higher power densities.

The plant items that are considered to vary with power density are the size of the reactor vessel, the organic cost, the containment structure, and the supporting building and structures. The organic reactor utilizes a low-pressure coolant and the relatively thin-walled vessel is not as significant a cost item as in

high-pressure coolant reactors. Variations in plant cost with core power density more directly effect fuel-cycle cost in the organic-cooled reactor.

There are a limited number of ways to achieve a higher power density in an organic-moderated reactor that utilizes finned-plate metallic fuel elements. The first and most obvious approach is to arbitrarily reduce the moderator-to-fuel ratio. However, this method has significant effects on core physics and core heat transfer. Its effects on power density were not evaluated per se in this report, but a curve is provided by figure IV-13 of section IV that shows the cost variations as the moderator-to-fuel ratio is changed.

Second, the fuel-plate thickness can be reduced while holding the moderator-to-fuel ratio constant. This is, in effect, a method of changing the power density. However, for this particular analysis, the reactor volume and thermal power were held constant and the effect of varying the plate thickness only affected the specific power of the fuel. Figure IV-2 shows the effects of changing the fuel-

FIG. IV-1—Effects of the core power density on the plant-equipment cost, for an organic-cooled reactor.

plate thickness and the specific power on energy cost.

It is apparent that a large portion of the cost differential shown on figure IV-2 is due directly to the effects of increased fuel exposure on fuel-cycle costs; that is, significant gains would be made by increasing fuel exposure with no change in plate size. In order to show more clearly the shift in optimum plate thickness, all three curves are shown to intercept at an arbitrary zero reference point in figure IV-3. This, in essence, omits the cost-level change that is due strictly to exposure level and indicates the relative economic incentives in moving to thinner plates as fuel exposures are increased.

Several competing factors contribute to the shapes of these curves. If the number of plates is kept fixed, the result of making the fuel plates thicker is a pronounced increase in the cost of pump motors and pumping power, due to the increased pressure drop through the core. This increased pressure drop also has the effect of requiring heavier fuel-element steel

walls to contain the fuel plates; this variation in steel content in the core will affect the fuel enrichment.

Decreasing the moderator-to-fuel ratio by increasing the plate thickness also increases fuel cycle costs by increasing the core fuel loading and increasing the fuel inventory charge. Increasing the moderator-to-fuel ratio by decreasing the plate thickness serves to decrease the coolant temperature rise through the core and thereby decreases the cost of the steam generators. Higher moderator-to-fuel ratios cause higher coolant make-up costs.

A third method of increasing power density is to reduce the peak-to-average power in the reactor core. This will produce a higher average value without increasing the design value.

The effects of changes in the gross axial and radial thermal flux peaking factors are shown on figures IV-4 and IV-5, respectively. These curves are based on arbitrary changes in the flux peaking factor and the resulting effects on the major plant equipment and fuel inventory.

FIG. IV-2—Effects of the fuel-plate thickness on the total energy cost, for an organic-cooled reactor.

FIG. IV-3—Effects of the fuel-plate thickness on the total energy cost (based on an arbitrary zero reference point), for an organic-cooled reactor.

FIG. IV-4—Effects of the axial peak-to-average flux ratio on the total energy cost, for an organic-cooled reactor.

FIG. IV-5—Effects of the radial peak-to-average flux ratio on the total energy cost, for an organic-cooled reactor.

Since one of the major cost components is due to an increase in fuel exposure, the three exposure curves were drawn through an arbitrary zero reference point to nullify this component of cost, as shown in figure IV-6. This plot shows how the level of fuel exposure changes the economic incentive when only the effects of a change in peak-to-average flux are considered. These curves show the economic incentive if the peak-to-average flux can be reduced; however, significant reductions over those used as the reference design would require a considerable extension in the technology.

Core power density can be increased by power flattening, which can be accomplished by changing the peak-to-average neutron flux. This factor includes the peaking due to the lumped moderator surrounding the fuel element, as well as the peaking due to adjacent

control rods and structural spacers. This parameter has a direct influence upon the power that may be removed from the hottest element and, therefore, determines the total number of elements required in the core. In addition to being reflected in the fuel costs as inventory charges, changes in this parameter affect the pumping power, the size of the reactor vessel, the shielding, the number of rods and drives required, the pump and motor size, and the surface required in the steam generators. The combination of these individual cost changes is shown on figure IV-7. The achievement of peak-to-average flux ratios significantly lower than those used for the reference design will require improvements in the technology.

A change in the core hot-channel factor will also increase the core power density. The hot-channel factors represent safety factors incorporated in the design calculations to allow for

FIG. IV-6—Effects of the axial peak-to-average flux ratio on the total energy cost (based on an arbitrary zero reference point), for an organic-cooled reactor.

uncertainties in the prediction of plant performance. These uncertainties may be due to manufacturing tolerances or accuracy limitations in calculation procedures. The effect of variations in these factors is to change the core and vessel size, as a result of a change in the required number of fuel elements. The number of control rods, the pump and motor capabilities, and the size of the heat exchangers are also affected. Fuel costs vary with the inventory charges based upon core loading. Figure IV-8 illustrates the differential costs due to assumed variations in $F_{\Delta T}$, the factor that accounts for uncertainties in the temperature rise of the coolant, while figure IV-9 illustrates the differential cost due to F_θ , the factor based upon inaccuracies in the heat-transfer correla-

tion used to compute the temperature drop through the coolant film adjacent to the fuel-element surface. These curves show that the effect of $F_{\Delta T}$ is more pronounced than that due to F_θ for each of the three fuel exposures studied.

A plot of differential cost as a function of $F_{\Delta T}$ with all curves intercepting at an arbitrary zero reference point is shown on figure IV-10. While it is of interest to see the economic incentive available, it is also apparent that significant reductions in the hot-channel factors used in the reference design will be a major departure from current practice.

Some of the effects of variations in specific power on energy cost have been indicated on the previous curves that show the effects of

FIG. IV-7—Effects of the fuel-element peak-to-average flux ratio on the total energy cost, for an organic-cooled reactor.

changes in power density. This is due to the fact that one of the significant methods of obtaining higher power densities is to increase the specific power of the fuel. The methods of achieving higher specific power include increasing the fuel-element cladding temperature, flattening the neutron-flux distribution, reducing the hot-channel factors, and increasing the surface-to-mass ratio of the fuel. The effects of variations in fuel specific power on energy cost are shown on figure IV-11.

The maximum permissible fuel-element surface temperature for the fuel elements used in the reference reactor design is 750°F. This limitation is based upon the reduced creep strength of the aluminum cladding at elevated temperatures, the temperature dependence of the dimensional stability of the U-3.5% molybdenum alloy fuel under irradiation, and the permeability of the nickel diffusion barrier that separates

the fuel and cladding. The purpose of the variation of this parameter was to determine the effects of this temperature limit on energy costs. The approach in this case was to assume that the maximum allowable surface temperature was reduced to 700°F and increased to 800°F. For the purposes of this calculation, the reactor outlet temperature was held fixed at 600°F and the steam conditions remained unchanged. The results of this calculation are given on figure IV-12. The economic importance of this surface-temperature limitation, which strongly affects the core size and all the major primary loop equipment, is evident from the curve. Increases in this value would require extensions in the technology. Reducing the maximum surface temperature from 750°F to 700°F increases the total capital cost of the plant and also increases the annual fuel costs, because of the larger core loading. These in-

FIG. IV-8—Effects of hot-channel factor $F_{\Delta T}$ on the total energy cost, for an organic-cooled reactor.

creases result in a net energy cost increase that is greater than 0.8 mill/kw-hr for all fuel exposures studies.

FIG. IV-9—Effects of the hot-channel factor F_g on the total energy cost, for an organic-cooled reactor.

D. Variations of Moderator-to-Fuel Ratio

One of the primary physics parameters in a reactor core is the moderator-to-fuel ratio (M/F). In the core concept under consideration, this parameter may be varied in a number of ways. The number of fuel plates per element may be varied, while maintaining constant plate thickness; the thickness of the fuel plates may be varied, while maintaining 10 fuel plates per element; or the lattice spacing may be varied, without any variation of the internal fuel-element geometry. For the purposes of this study, all three methods were investigated.

The curves shown on figure IV-13 illustrate the effects of changes in M/F upon power gen-

FIG. IV-10—Effects of the hot-channel factor $F_{\Delta T}$ on the total energy cost (based on an arbitrary zero reference point), for an organic-cooled reactor.

erating costs as determined by varying the number of plates. These effects are expressed as differential energy costs in mill/kw-hr for three different fuel exposures of 5,000, 7,000, and 9,000 Mwd/metric ton of U (average). The curves indicate that the effect of M/F upon power costs over the entire range investigated (2.5 to 5.0) is a fairly small one, the difference between the worst case and the optimum being less than 0.2 mill/kw-hr for

any one fuel exposure. The primary difference is due to increased fuel exposures, as shown by intercepting these curves through an arbitrary zero reference point in figure IV-14. The curves also indicate a trend toward lower costs as M/F is increased. This decrease in cost is due to several contributing factors. First, the net fuel-cycle costs are lower for the more dilute cores since they are closer to the optimum nuclear configuration and, therefore, ex-

FIG. IV-11—Effects of the average specific power on the total energy cost, for an organic-cooled reactor.

hibit better neutron economy. In addition to this the core loading and, therefore, the fuel inventory is lower at high moderator-to-fuel ratios. A secondary, out-of-reactor, cost effect that is quite significant is the cost of the steam-generator units.

Since, for a given maximum core velocity, the total coolant flow rate is greater for the higher moderator-to-fuel ratios, the temperature rise in the core for a given power level is smaller. This results in a higher coolant inlet temperature, since the reactor-outlet temperature was fixed for the study. Consequently, a lower surface area is required for the steam generators. An offsetting effect at higher moderator-to-fuel ratios is the increase in organic makeup costs, which increase as the weight fraction of organic material in the core increases. At the higher moderator-to-fuel ratios shown on figure IV-13, there is an increase in operating costs of about 0.1 mill/kw-hr due to this effect.

Figure IV-15 shows the result of varying M/F by varying the plate thickness. The variation is shown to be dependent on the fuel

exposure attained. For a fuel exposure of 5,000 Mwd/metric ton of U, the power-generation cost curve reaches a broad minimum centered around an M/F value of 4.5, while for an exposure of 9,000 Mwd/metric ton of U, the energy cost curve continually decreases for higher moderator-to-fuel ratios over the range studied.

Figure IV-16 shows the result of varying M/F by changing the lattice geometry rather than the design of the individual fuel elements. Since the magnitude of the element-flux peaking factor has an effect upon the thermal performance of the core and, therefore, upon energy costs, the reference design employed as tight a lattice as was considered to be mechanically practical. Figure IV-16 shows the effect of the variation in lattice spacing upon energy cost to be negligible, for a fuel exposure of 7,000 Mwd/metric ton of U, in spite of the increase in flux peaking with increasing lattice size. This is due largely to a compensating decrease in fuel-cycle costs for this fuel exposure at the higher moderator-to-fuel ratios.

FIG. IV-12—Effects of the maximum fuel-element surface temperature on the total energy cost, for an organic-cooled reactor.

E. Effects of Resonance Escape Probability

Resonance capture affects net fuel-cycle costs. The magnitude of the resonance escape probability has a significant effect upon the conversion ratio, as well as upon the enrichment required to sustain reactivity for a given exposure level. To evaluate this parameter, a magnitude of variation was selected to give a ± 2 percent variation in initial core reactivity. Figure IV-17 shows the effect of this variation upon power-generating costs.

Figure IV-18 shows the variation in initial enrichment with resonance escape probability. It is obvious from this figure that the initial

enrichment may vary as much as 0.25 atom percent U^{235} for each of three fuel exposures, due to a small inaccuracy in estimating resonance capture.

F. Effects of Stable-Fission-Product Poisons

Very little in the way of precise data is available to allow an accurate prediction of the amount of parasitic absorption produced by stable fission products. A value of 50 barns per fission has been widely used and was employed in the burnup calculations for this study. In order to check the importance of this parameter in determining net fuel-cycle

FIG. IV-13—Effects of the moderator-to-fuel ratio (number of plates variable) on the total energy cost, for an organic-cooled reactor.

FIG. IV-14—Effects of the moderator-to-fuel ratio (number of plates variable) on the total energy cost (based on an arbitrary zero reference point), for an organic-cooled reactor.

FIG. IV-15—Effects of the moderator-to-fuel ratio (plate thickness variable) on the total energy cost, for an organic-cooled reactor.

costs, burnup analyses were performed in which values of 40 and 60 barns per fission were assumed. The results of these calculations for a fuel exposure of 7,000 Mwd/metric ton of U are given in figure IV-19. This curve shows the total effect of about ± 0.07 mill/kw-hr over the range investigated.

G. Effects of Fuel-Element-Box Thickness

There is a mechanical problem in the design of organic forced-convection cores that be-

comes acute for large cores in which the length of the fuel elements exceeds 8 or 9 feet. This problem is associated with the bending stresses on the square fuel-element box due to the pressure drop through the element. Since these stresses determine the thickness of the steel walls of the fuel-element box, they have a pronounced effect upon fuel enrichment and, therefore, the fuel-cycle costs.

The stress problem arises due to the fact that, in order to limit the bypass flow of coolant around the outside of the fuel channels to a

FIG. IV-16—Effects of the lattice spacing on the total energy cost, for an organic-cooled reactor.

FIG. IV-17—Effects of the resonance escape probability on the total energy cost, for an organic-cooled reactor.

FIG. IV-18—Effects of the resonance escape probability on the initial fuel enrichment, for an organic-cooled reactor.

FIG. IV-19—Effects of the stable fission-product poisons on the total energy cost, for an organic-cooled reactor.

few percent, a seal must be provided. This flow seal cannot be easily provided at the upper grid, due to the necessity for providing clearances for the motion of the control rods. With the flow seal provided below the core, the pressure outside the elements will be essentially the same as the pressure in the upper plenum. If the coolant flow is upward through the core, the pressure differential will act outward against the walls of the fuel-element box. If the coolant flow is downward, the direction of this force is reversed since the upper plenum will experience the highest pressure in the vessel. In this case, the stresses are considerably reduced as a result of the support provided by the fuel plates and cladding ribs. For this reason, downflow was selected for the reference design case. The core pressure drop of 80 psi for this core, which is 13 feet in active length, was high enough to require a box wall thickness of 60 mils.

Figure IV-20 shows the results of a series of calculations at a fuel exposure of 7,000 Mwd/metric ton of U, in which the required thickness of the steel fuel-element box was assumed to vary from 40 to 80 mils. This curve indicates the importance of limiting the core pressure drop since this variation in steel content affects the parasitic volume fraction and the required fuel enrichment enough to result

in almost a 0.5 mill/kw-hr difference in energy costs over the range considered. An interesting result of this effect is discussed in a later section dealing with selection of an optimum value for the maximum coolant velocity.

H. Effect of Core Length-to-Diameter (L/D) Ratio

In establishing the design parameters for the reference design, a core L/D ratio of approximately unity was arbitrarily selected. In order to determine the effect of this parameter upon power costs, core performance calculations were undertaken for cases in which the L/D ratio varied from about 0.8 to 1.2.

The results, shown on figure IV-21, indicate that very small cost variations are experienced from a fairly significant change in this parameter, the total variation being about 0.05 mill/kw-hr for each fuel exposure studied over the L/D range investigated.

I. Effect of Coolant Velocity

A maximum coolant velocity of 15 ft/sec was selected for the reference design plant. This velocity was chosen because of the fact that at higher velocities the core pressure drop becomes excessive and at lower velocities the

FIG. IV-20—Effects of the fuel-box thickness on the total energy cost, for an organic-cooled reactor.

Fig. IV-21—Effects of the core L/D ratio on the total energy cost, for an organic-cooled reactor.

core size increases markedly. As a part of the core-parameter survey, it was decided to investigate a range of coolant velocities to determine the optimum point. As the velocity is increased, the core surface area required for heat transfer decreases, thereby reducing the number of fuel elements. The size of the reactor vessel decreases, as well as the cost of the surface-area requirements in the boilers. These advantages, however, are eventually over-ridden by the increased cost of pumps and motors and the increased pumping-power requirements. In addition to this, as the pressure drop through the core increases, the required thickness of the steel fuel-element box also

increases, with the effect upon enrichment and fuel-cycle costs just described in subsection G. These combined effects result in a minimum cost for a maximum coolant velocity of about 11.2 ft/sec, as shown on one of the curves on figure IV-22.

It is interesting to note the interplay between two separate parameters illustrated on Figure IV-22. A curve has been plotted to show the optimum coolant velocity, ignoring the effect of box thickness upon fuel costs. This curve is labeled *Minimum Without "Steel Effect"* and indicates a minimum cost at about 17.2 ft/sec. It is obvious from these curves that the effects of parameter changes upon de-

Fig. IV-22—Effects of the coolant velocity on the total energy cost, for an organic-cooled reactor.

tailed features of the core may not be ignored without distorting the ultimate results. In this case, there is almost a 50 percent difference in the predicted optimum velocities obtained by the two methods described.

J. Effect of High Boiler Content in the Coolant

Figure IV-23 shows a total cost variation of 0.1 to 0.2 mill/kw-hr for each fuel exposure

FIG. IV-23—Effects of the high boiler content on the total energy cost, for an organic-cooled reactor.

studied when the equilibrium high boiler (HB) content in the coolant varies from 20 to 40 percent. The purification systems in the reference design are sized to maintain the high boiler content conservatively at 30 percent. Stable and continuous operation, however, has been experienced at the OMRE with concentration levels of decomposition products as high as 40 percent. Although it is true that a high boiler content reduces the heat-transfer capabilities of the coolant, requiring an increase in core size and coolant flow, and also increases the viscosity and therefore the core pressure drop, the savings in organic make-up costs more than compensate for these disadvantages. The reduced make-up costs are due to the fact that the decomposition rates of organic coolants decrease with increasing high

boiler content. In this case, a reduction in annual operating expense, due to organic make-up, is experienced in going from 30 to 40 percent HB for each of the fuel exposures studied. In addition to this, and unreflected in the curve, are some very minor capital-cost savings due to the reduced capacity of the purification systems.

K. Effect of Fuel Exposure

The fuel exposure level specified for the reference design case was 7,000 Mwd/metric ton of U (average) in the spent fuel elements. This exposure level was based upon the metallurgical properties of irradiated U—3.5 percent Mo alloy. For the purposes of investigating the effect of fuel exposure upon energy costs, it was assumed that the fuel could be irradiated to as high as 9,000 Mwd/metric ton of U average or roughly 14,000 Mwd/metric ton of U peak burnup. The entire range between 5,000 and 9,000 Mwd/metric ton of U was investigated.

Figure IV-24 illustrates the effect of this parameter upon costs. The difference in costs between 5,000 Mwd/metric ton of U and the optimum of the curve at 8,500 Mwd/metric ton of U is roughly 0.5 mill/kw-hr. The fuel-exposure curve will go through a cost minimum for higher burnup periods as a result of the requirement for higher enrichments to sustain reactivity. This minimum will vary somewhat depending upon the assumption used for fuel cycle inventory.

L. Summary Conclusions

The following conclusions may be drawn from the parametric studies on the organic-cooled reactor plant:

1. Methods of increasing core power density, fuel specific power, and fuel exposure

FIG. IV-24—Effects of the fuel-exposure level on the total energy cost, for an organic-cooled reactor.

level are needed to show substantial reductions in energy cost over those shown in the reference design.

2. Any major increase in power density must result from reduction in peak-to-average power by either reducing the hot-channel factors, reducing the peak-to-average flux, or increasing the fuel-surface temperatures.

(a) Reductions in the hot-channel factors from those values used in the reference design will require a major departure from current design practice.

(b) Significant reductions in peak-to-average power over those values used in the reference design will require an extension in the technology.

(c) The fuel-surface temperature used in the reference design is based on the current limit of aluminum in the core environment. Improvement in this unit will probably require the development of a new material. Also, the maximum coolant temperature is restricted by pyrolytic decomposition of the organic material to values of approximately 800°F.

3. Fuel specific power can be increased by reducing the plate thickness. This approach

could be used as method of increasing core power density.

4. The organic-cooled reactor reference design parameters are relatively close to certain technical limits such as power density, maximum-fuel-surface temperature, and fuel-burnup limitation. These technical limitations must be resolved before significant economic incentives can be obtained.

5. The fuel-box thickness affects the parasitic content of the core. Significant reductions in the thickness will have a marked effect on fuel cost.

6. Variations in parameters such as the moderator-to-fuel ratio, lattice spacing, resonance escape probability, and the L/D ratio have little effect on energy cost.

7. The results of this study are applicable only to an organic reactor with metallic-plate fuel elements clad with aluminum. The use of UO_2 clad with higher-temperature materials will extend some of the technical limitations that currently fix the cost of the organic-cooled reactor. It will allow considerably more margin for obtaining increased power density, fuel specific power, and fuel exposure if the core optimization shows sufficient economic incentive for such changes.

V. SODIUM-GRAPHITE REACTORS

A. Description of Reference Reactor Plant

The reference reactor used for this core-parameter survey is a 300-Mw(e) sodium-graphite reactor that utilizes graphite as the moderator and liquid sodium as the coolant. The neutron energy range is thermal.

The reactor core consists of slightly enriched, uranium-molybdenum fuel elements suspended in a closely packed array of canned, hexagonal, graphite moderator elements. The moderator elements are scalloped at the corners, so that each fuel element is surrounded by three adjoining elements for a circular channel. Concentric with this channel is the process tube. One end penetrates the lower grid plate; the other end terminates at the fuel-element hanger-rod disconnect. The fuel elements are supported in these tubes.

Sodium inlet pipes enter the reactor cavity just above the top of the moderator cans and run downward to the lower part of the reactor vessel. The major portion of the sodium flows into the lower plenum below the grid plate and then flows upward through the process tubes to the sodium pool above the core.

The moderator and reflector elements are graphite prisms that are hexagonal in cross section and canned in stainless steel. The moderator can is of 0.016-inch-thick Type 304 stainless steel and has end closures or heads that are designed to compensate for the differential thermal expansion between the graphite and the stainless steel.

The fuel elements are 61-rod clusters of Type 304 stainless-steel tubing that contain the fuel slugs. The tubing has a wall thickness of 0.010 inch and is sized for a 0.010-inch radial clearance around the 0.33-inch diameter fuel slug for a sodium bond. The fuel slugs are composed of a slightly enriched U-10 percent Mo metal alloy.

The significant reference-design characteristics of the sodium-graphite reactor plant are given in Table V-1.

B. Fuel Management Program

The fuel management program used for the reference design was based on a uniformly enriched core at start of life. The fuel was rotated from outside to inside on a batch-loading principle and discharged from the center section of the core.

C. Power Density and Specific Power

A variation in lattice spacing through a change in moderator-element size varies the moderator-to-fuel ratio and power density for a fixed number of fuel assemblies. Increasing the amount of moderator in the core tends to lower the power density and increase the core reactivity in three ways:

1. It increases the probability that fission neutrons will escape resonance capture in U^{238} while slowing down.
2. It increases the average number of neutrons released per neutron capture in U^{235} . (The spectrum is more nearly thermal).
3. It decreases the neutron leakage from the core by increasing the core diameter.

Partially or completely offsetting this increase in reactivity is the additional neutron capture in the moderator. A maximum core reactivity will be reached at some moderator-to-fuel ratio. An increase or decrease in moderator-to-fuel ratio from this point will decrease reactivity. This particular moderator-to-fuel ratio does not necessarily give the lowest energy cost because of capital-cost effects. The differential capital-cost variation of all items related to power density is shown in figure V-1.

TABLE V-1.—SUMMARY OF THE REFERENCE-DESIGN CHARACTERISTICS FOR THE SODIUM-GRAPHITE REACTOR PLANT

A. Plant Data:		B. Reactor Description—Continued	
1. Plant size (net), Mw(e).....	300	e. Fuel-slug diameter, in.....	0.33
2. Turbine output (gross), Mw(e)....	320	f. Cladding thickness, in.....	0.010
3. Reactor power, Mw(t).....	884	g. Radial bond (sodium) clearance..	0.010
4. Plant efficiency (net), %.....	34.0	h. Number of elements in core.....	214
B. Reactor Description:		i. Number of rods per element.....	61
1. Reactor core:		4. Material inventory:	
a. Active diameter, ft.....	15.5	a. Fuel, metric tons of U.....	50.6
b. Active height, ft.....	15	C. Plant-Performance Data:	
c. Active core volume, cu ft.....	2,830	1. Primary-coolant outlet temperature, °F.	945
d. Lattice arrangement.....	hexagonal	2. Primary-coolant inlet temperature, °F.	607
2. Reflector and coolant:		3. Reactor Δt , °F.....	338
a. Material of reflector.....	graphite	4. Maximum fuel temperature, °F....	1,250
b. Material of coolant.....	sodium	5. Core coolant velocity, ft/sec.....	19.5
3. Fuel elements:		6. Core power density, kw/liter of core.	11.05
a. Fuel material.....	U-10% molybdenum alloy	7. Fuel exposure, Mwd/metric ton of U (average).	3,400
b. Clad material.....	SS	8. Pressure drop across core (coolant), psi.	12.9
c. Fuel enrichment, %.....	3.11		
d. Fuel-element geometry.....	rods

FIG. V-1—Effects of the core power density on the plant-capital cost, for a sodium-graphite reactor.

FIG. V-2—Effects of the moderator-element size on the core power density, for a sodium-graphite reactor.

The optimum moderator-to-fuel ratio must be determined by an economic study in which all factors, including conversion ratio and capital costs as well as fuel enrichment, are considered. For this study, the size of the moderator elements in the 300-Mw(e) sodium-graphite reactor were varied from 14 to 26 inches across “flats” on the hexagonal graphite logs. The relation between moderator-element

size and power density is shown on figure V-2.

The following relation of power density and cost were obtained as a result of this study:

1. Minimum fuel-cycle costs are achieved with a power density of approximately 9 kw/liter of core (see figs. V-2 and V-3). The optimum moderator-to-fuel ratio, considering fuel-cycle costs only, is less than the moderator-to-fuel ratio that gives maximum

FIG. V-3—Effects of the core power density on the total energy cost, for a sodium-graphite reactor.

reactivity. This is primarily due to the increased resonance capture in U^{238} and higher conversion ratios at the lower moderator-to-fuel ratios.

2. Minimum power-generating costs are achieved with a power density slightly greater than the power density ratio for minimum fuel-cycle costs. With an inexpensive moderator and with no pressurization required in the primary coolant system, the reactor-core size can be varied without significantly affecting capital costs (see fig. V-1).

3. The optimum specific power associated with these parameter variations is 14 kw/kg, as shown in figure V-4.

D. Variation in Moderator-to-Fuel Ratio

A variation in the fuel-rod diameter with fixed moderator spacing affects the moderator-

to-fuel ratio and the specific power. The aforementioned moderator-to-fuel ratio variations obtained to determine effects on power density did not account for specific-power variations. The relation between moderator-element size and moderator-to-fuel ratio is shown on figure V-5.

An increase in fuel-rod diameter with no change in moderator volume tends to increase reactivity in two ways: (a) by an increase in the fast fission of U^{238} and (b) by an increase in thermal utilization. In an undermoderated reactor such as the 300-Mw(e) sodium-graphite reactor, this increase in reactivity is offset by "hardening" of the neutron spectra. Fewer neutrons reach thermal energies because of the increased opportunity for resonance capture in U^{238} and the increased fissioning of U^{235} by intermediate energy neutrons (lower η).

In this study, the moderator-to-fuel ratio was varied as the diameter of the fuel slugs

FIG. V-4—Effects of the fuel specific power on the total energy cost, for a sodium-graphite reactor.

FIG. V-5—Effects of the moderator-element size on the moderator-to-fuel ratio, for a sodium-graphite reactor.

was varied between 0.3 and 0.4 inch. No change was made in the sodium flow area. The size of the scallops in the corners of the moderator elements was varied slightly in accordance with the variation in fuel-element diameter. The relation between the fuel-slug diameter and the moderator-to-fuel ratio is shown on figure V-6.

Fabrication cost is assumed to be relatively independent of fuel-slug diameter. Therefore, for equivalent burnups, the fuel-fabrication costs in mills/kw-hr tend to decrease with an increase in the fuel-slug diameter.

The variation in fuel-burnup charges with fuel-rod diameter is quite small.

The change in fuel-rod diameter requires no significant change in capital costs. The variation in power-generating costs is therefore equal to the variation in fuel-cycle costs.

The optimum moderator-to-fuel ratio as determined by the fuel-slug diameter (minimum power-generation costs) will depend upon the average fuel exposure that can be obtained. Lower average fuel exposures favor larger slug diameters; for example, with an average fuel exposure of 3,400 Mwd/metric ton of U, the

FIG. V-6—Effects of the fuel-slug diameter on the moderator-to-fuel ratio, for a sodium-graphite reactor.

FIG. V-7—Effects of the moderator-to-fuel ratio on the fuel cost, for a sodium-graphite reactor.

optimum slug diameter is approximately 0.36 inch, while with an average fuel exposure of 16,800 Mwd/metric ton of U, the optimum slug diameter is approximately 0.30 inch. The relation between fuel cost and the moderator-to-fuel ratio, as determined by the fuel-slug diameter, is shown in figure V-7 for various levels of fuel exposure.

E. Variation in Core Parasitic Materials

In the reference design established for this reactor-core parameter study, the fuel cladding is 0.010-inch-thick stainless-steel tubing with an 0.35 inch inside diameter. An increase in this cladding thickness increases the amount of nuclear "poison" or parasitic materials in the core and therefore decreases core reactivity. The variation in core reactivity with fuel-cladding thickness is indicated in figure V-8. The increase in fuel-cycle costs with increase in fuel-cladding thickness is primarily due to the increase in fuel enrichment. If there were no corresponding increase in fuel-fabrication cost, a decrease in fuel-cladding thickness to 0.005 inch from the 0.010-inch value used in the reference design would decrease fuel-cycle costs slightly (approximately 0.1 mill/kw-hr).

F. Variation in Moderator-Can Thickness and Material

The reference sodium-graphite reactor requires the use of a large amount of stainless-steel structural material, introduced into the core by the moderator-element canning. Zirconium and zirconium alloys have frequently been considered for this application. Reactor designs are now under way that will eliminate a large portion of this structural material.

To indicate the significance of the moderator-can thickness on power-generator costs, a study was made of the effects of varying the stainless-steel moderator-can thickness between 0.016 and 0.024 inch. The effect on fuel-cycle costs of the enrichment variation with moderator-can thickness is indicated in figure V-9. This variation in moderator-can thickness is expected to make a negligible variation in the capital costs of the plant.

G. Comparison of Zirconium and Stainless-Steel Moderator Canning

The use of structural materials with low neutron cross sections has been investigated for possible use as moderator-element canning material in sodium-graphite reactors. Zirconium

FIG. V-8—Effects of the fuel-cladding thickness on the fuel-cycle cost, for a sodium-graphite reactor.

FIG. V-9—Effects of the moderator-canning thickness on the fuel-cycle cost, for a sodium-graphite reactor.

alloys are being investigated for use at the higher coolant temperatures proposed for the advanced sodium-graphite reactor.

A reduction in fuel enrichment is possible when zirconium is used as the moderator canning material. This lower fuel enrichment reduces fuel-inventory charges and the net fuel-burnup charges. This difference in total fuel-cycle costs is indicated in figure V-10. It is evident that considerably greater incentives exist for increasing exposure than considering the use of alternate clad material.

The net reduction in fuel-cycle costs is approximately 0.3 mill/kw-hr at all levels of fuel exposure. This fuel-cycle cost reduction, if capitalized at 80 percent plant factor and 14 percent annual capital charges, justifies an increase in capital investment of \$4,500,000, or an increase of \$2,900,000 in direct construction cost. Approximately 47,400 pounds of zirco-

nium would be required in the moderator and reflector elements in the reference design. The "break even" point on the zirconium versus stainless-steel cans is approximately \$60 per pound of zirconium canning.

The cost of zirconium moderator cans has not been estimated, but it is expected to be less than the "break even" point of \$60 per pound. At the present time, alloys of zirconium are under development that may have the strength required at the coolant temperatures of the sodium-graphite reactor and the advanced sodium-graphite reactor.

H. Variation in Sodium Flow Area

In the reference design, the maximum sodium velocity is 19.5 ft/sec and the pressure drop across the core is 12.9 psi. This sodium velocity and pressure drop present no engineering problems. The four primary pumps are each rated at 725 horsepower. An increase in sodium flow area per channel decreases the sodium velocity, pressure drop, and pumping power. This decrease in pumping power increases the net plant output and net plant efficiency.

The increase in sodium flow area also introduces additional neutron "poison" into the reactor core. An increase in fuel enrichment is required to maintain core reactivity.

A decrease in the sodium flow area to 6 square inches would require a 1,250 horsepower increase in the primary pumping capacity. Since the primary pumping power requirement is approximately 1 percent of the total power output of the turbogenerator, this variation in pumping power has a negligible effect on net plant efficiency. The net effect on energy costs would be less than 0.1 mill/kw-hr. The capital cost of the additional pump capacity required with the smaller flow areas would also make a minor increase in power-generating costs (less than 0.1 mill/kw-hr).

For the 300-Mwe(e) sodium-graphite reactor, it appears that the sodium flow area can be determined by considerations other than

FIG. V-10—Effects of the fuel-exposure level on the fuel-cycle cost, for a sodium-graphite reactor.

FIG. V-11—Effects of the fuel-exposure level on the total energy cost, for a sodium-graphite reactor.

variation in power-generating costs if the area is kept within the limits of 6 to 12 square inches. The variation in each of the various factors of power-generating costs affected is small. In addition, any increase in power-generating costs caused by increased pumping power is partially or completely compensated for by a decrease in the fuel-cycle cost.

I. Effects of Fuel Exposure

The effects of fuel exposure on total energy cost were investigated by arbitrarily increasing the fuel enrichment to obtain a given exposure level for the reference design characteristics. The evaluation of these effects shows that large incentives exist for increasing the exposure-level potential for the sodium-graphite reactor concept. The relative differential cost as related to the reference exposure level is shown in figure V-11.

J. Comparison of UC and U-10 Percent Molybdenum Alloy

In evaluating sodium-graphite reactors, it appears essential that high-thermal-conductivity fuel be developed that can be carried to high burnup.

Uranium monocarbide (UC), which has a melting point of 4,300°F, a thermal conductivity of approximately 14 Btu/hr/sq ft/°F/ft, and a uranium density of approximately 15 g/cm³, appears to be an excellent fuel for high-temperature sodium-cooled reactors. High burnup limitations, essential to any fuel, can be proven only after extensive irradiation tests.

Uranium monocarbide promises to reduce power-generating costs in several ways. Two of the cost reductions that can be achieved with UC are as follows:

1. *High power density in the fuel.* Fuel-inventory charges for the reactor core load-

ing are a significant part of power-generating costs. This cost would be even more important if the uranium were sold to the utility instead of leased at the relatively low rate of 4 percent per annum.

2. *Higher thermal efficiency.* Although some increase in sodium temperature is possible with present technology, a significant increase in sodium temperature (to 1,200°F) requires a fuel, such as UC, that can operate reliably at higher temperatures. Higher sodium temperatures will permit adoption of modern, efficient steam cycles in nuclear plants.

The enrichment required for UC or UO₂ is lower for all fuel exposures. This lower en-

richment, and the associated lower fuel inventory, makes a significant reduction in fuel-inventory charges.

K. Summary Conclusions

In evaluating the significant parameters that affect the principal reactor characteristics previously defined, it is evident that fuel exposure as related to the reference exposure is the dominant effect. The incentive for higher exposures is in the order of several mills/kw-hr, which would tend to overshadow the economic effects indicated for the other specified reactor characteristics.

VI. GAS-COOLED REACTORS

A. Description of Reactor Plant

The gas-cooled reactor is a heterogeneous, UO_2 -fueled, thermal reactor that uses graphite as the moderator and helium as the coolant. The system utilizes a closed helium loop through which helium is circulated. Heat is transferred through heat exchange equipment to the steam generating plant. The significant reference design characteristics of the gas-cooled reactor plant are given in table VI-1.

B. Fuel Management Program

The fuel management program used for the reference design is based on a uniformly enriched core at beginning of life, with batch loading from the outside to the inside of the

core. It was assumed that the reactor was shut down for refueling. Preliminary studies have been made by other groups of refueling machines that would permit fuel movement with the reactor under power. By use of such mechanisms, a highly refined fuel management program might be justified to achieve a high degree of power flattening without the offsetting effects of reducing the plant availability factor. However, fuel management programs of this type were not evaluated in this study.

C. Core Power Density and Fuel Specific Power

The reactor-core power density and fuel specific power are directly related to plant-capital-cost effects and fuel-cycle cost. Increases in

TABLE VI-1.—SUMMARY OF THE REFERENCE-DESIGN CHARACTERISTICS FOR THE GAS-COOLED REACTOR PLANT

A. Plant Data:		C. Reactor Description—Continued	
1. Plant rating, Mw(e).....	300	3. Fuel Elements—Continued	
2. Plant thermal rating, Mw(t).....	915	c. Fuel-element geometry.....	rods
3. Gross turbine power, Mw(e).....	336	d. Cladding thickness, in.....	0.020
4. Net plant efficiency, %.....	32.8	4. Materials Inventory:	
B. Turbine-Cycle Conditions:		a. Fuel, metric tons U.....	91.5
1. Throttle temperature, °F.....	950	b. Pu production (conversion ratio).....	0.680
2. Throttle pressure, psi.....	950	5. Reactor Control:	
3. Condenser backpressure, in Hg.....	1.5	a. Method of control.....	rods
4. Final feed-water temperature, °F.....	325	b. Number of elements.....	148
C. Reactor Description:		D. Plant-Performance Data:	
1. Reactor Core:		1. Primary-coolant exit temperature, °F.....	1,000
a. Active diameter, ft.....	27.5	2. Primary-coolant inlet temperature, °F.....	460
b. Active height, ft.....	20	3. Reactor Δt , °F.....	540
c. Active core volume, cu ft.....	11,800	4. Primary-system operating pressure, psi.....	500
d. Lattice arrangement.....	square	5. Coolant flow rate, lb/sec.....	1,150
2. Reflector:		6. Core power density, kw/liter.....	2.75
a. Material.....	graphite	7. Fuel exposure, Mwd/metric ton of U (average).....	15,000
b. Radial thickness, ft.....	2.5		
3. Fuel Elements:			
a. Fuel material.....	UO_2		
b. Clad material.....	SS		

core power density for a fixed thermal output will reduce the size and cost of the reactor pressure vessel, the graphite investment, the plant shielding, the control-drive rod mechanisms, and the associated buildings and structures. In view of the relatively large size of gas-cooled reactor cores and the limits in vessel thickness superimposed by the required field-fabrication techniques, system pressure also affects power density. Figure VI-1 shows the relation between pressure and power level as affected by the number of rods per cluster as defined below. Figure VI-2 relates core diameter to thermal rating with similar assumptions. Therefore, an interrelated effect exists between plant-capital cost and fuel-cycle cost for gas-cooled reactors of this type as a result of operating-pressure limits. This interrelation exists because of heat-transfer limitations imposed on the fuel element as a result of gas-pressure levels, which determine the relative heat-transfer coefficients for a given pressure level and pumping-power ratio. The reactor-core power density has an effect on fuel-cycle cost and the fuel loading, which are

determined by fuel-use charge, relative fabrication charges, the moderator-to-fuel ratio, fuel-enrichment levels, and burnup cost. Although an increase in core power density will result in capital-cost reductions of plant components, an adverse effect will generally result in fuel-cycle cost. This occurs because of a finer subdivision in the basic fuel units to obtain increased performance per unit volume, which within thermal limits and fission-gas pressure-buildup effects requires a greater percentage of stainless steel for the fuel unit and an increase in fabrication cost.

The objective in analyzing the core power density for a gas-cooled reactor type is to relate plant-cost and fuel-cycle-cost effects to determine the point where the combined effects of these two variables result in the lowest energy cost. Average core power density may be increased by several methods. The fuel-rod diameter may be reduced and the total number of fuel rods per unit volume increased. Alternatively, the moderator-to-fuel ratio may be varied to obtain the same result. A third means of achieving higher power density is to

FIG. VI-1—Relation between the reactor thermal rating and the primary system pressure, for a gas-cooled reactor.

Fig. VI-2—Relation between the reactor thermal rating and the core diameter, for a gas-cooled reactor.

reduce the peak-to-average power with a reactor core. This may be accomplished by variations in enrichment both radially and axially, or by variations in the moderator-to-fuel ratio radially. Each of these methods requires additional investment to obtain such a variation.

The effects of core power density on plant-equipment cost are shown on figure VI-3. The plant-equipment cost includes all items that vary directly with core size, such as the reactor vessel, the vessel internals, the control rod drive mechanisms, the primary shielding, and the supporting buildings and structures. The relation between power density and specific power is shown on figure VI-4.

Effects of core power density on total energy cost for four different values of fuel exposure are shown on figure VI-5. The method by which power density was varied was by changing fuel-rod diameters and the numbers of rods per unit cell. The number of rods was varied between 7 and 37 rods per cluster. Maximum central-fuel temperatures were held constant.

Thermal power was held constant and the core size was reduced appropriately as the power density was increased. The coolant pressure was increased with an increase in power density to reflect a maximum consistent with vessel size and reasonable wall thicknesses that could be field fabricated. The moderator-to-fuel ratio and hot-channel factors were held constant. However, the materials volume fraction was varied slightly, because of a definite increase in the stainless-steel metal-to-fuel ratio that occurs as the number of rods is increased.

There are two controlling variables that are evident in figure VI-5. As the power density decreases toward the lower limit of its range, the effects of capital cost cause a significant increase in the differential total energy cost. At the higher power densities, the effects of increasing stainless-steel metal-to-fuel ratio causes an increased initial enrichment, which increases the relative burnup cost and use charges. This increase in use charge is partially offset by the reduction in inventory due

FIG. VI-3—Effects of the core power density on the plant-equipment cost, for a gas-cooled reactor.

to the higher power densities that are associated with high specific power. In addition to these effects, the fuel configuration is changed to a greater number of rods per unit cell, which results in higher fabrication charges. The combined effects that limit the power density for a gas-cooled reactor include effects of capital charge, fabrication charges, burnup costs, and use charges.

The effects of exposure on the optimum power density, as indicated by figure VI-5 tend toward a higher power density if average fuel exposures can be increased. This trend reflects principally the effect of fabrication cost, which tends to be less dominant at increased exposures. Conversely, it can be concluded, from figure VI-5, that the tendency toward fabrication-cost reduction for a given exposure indicates that the optimum power

density will be increased as fabrication costs are reduced, or that the optimum exposure can be decreased.

Fuel-rod sizes were varied consistent with the maximum UO_2 -fuel temperature to permit an increase in specific power. The effects of the number of rods on core power density for the reference reactor design are shown on figure VI-6. The relative stainless-steel metal-to-fuel ratio was varied in changing the number of rods per cluster, so that variations of enrichment occur as the number of rods per cluster are increased. The number of rods per cluster is therefore the principal parameter that is varied in developing the relation shown on figure VI-5. An arbitrary zero reference point was selected on this figure to show values of fuel exposure on one curve. Curves for each exposure level are plotted through this zero

FIG. VI-4—Effects of the core power density on the fuel specific power, for a gas-cooled reactor.

reference. In actual fact, the reference point would be the different cost level for each exposure. However, the change in cost shown on figure VI-5 reflects the effects of power density on cost with the trends of the optimum as a function of fuel exposure.

Core specific power reflects the ability of the fuel to generate each unit weight of fuel content and is normally expressed in terms of fractional energy release per unit weight of fuel. Operation at high specific power results in low fuel inventory, which is reflected in reduced fuel-use charges. However, the method of varying parameters in the gas-cooled reactor study associates an increase in core parasitic materials with specific power due to changes in the number of fuel rods per cluster. If the stainless-steel metal-to-fuel ratio were held constant in changing the number of rods per cluster, a more pronounced incentive for high specific power could be demonstrated.

Figure VI-7 depicts a variation in core specific power as a function of power density. Figure VI-8 shows the relation between specific power and reactor thermal rating. This curve indicates that the optimum specific power shifts to lower values with increasing thermal rating.

D. Effects of Moderator-to-Fuel Ratio

The most obvious way of changing the moderator-to-fuel ratio for a gas-cooled reactor is to alter the lattice pitch. Superficially, one would expect the average power density for a given moderator-to-fuel ratio to vary as the inverse square of the lattice pitch. This would normally be true for a system of constant pressure. However, high power density permits a smaller core with the same power level, and hence a higher pressure level within the restrictions associated with large-pressure-vessel fabrication. Therefore, a multiple effect is obtained with improving power density, as a result of improved heat-transfer characteristics at higher pressure levels. This causes the lattice pitch dependence on power density to be higher than that which would be predicted by an inverse-square relationship. In addition to these effects, the effect on the resonance integral of U^{238} and the volume fraction of the moderator, considering coolant void volume, depend very greatly on lattice pitch. In addition to the fuel enrichment necessary to achieve the fuel exposure, the aforementioned effects tend to produce a minimum on the curve on energy cost vs lattice pitch or the moderator-to-fuel ratio.

FIG. VI-5—Effects of the core power density on the total energy cost (based on an arbitrary zero reference point), for a gas-cooled reactor.

Capital cost, including indirect charges, for that portion of the reactor plant that varies as a function of core size is shown on figure VI-9. In considering the effects of variations of lattice pitch, it is necessary to include both variable-capital cost and fuel-cycle cost to accurately reflect dependence. Figure VI-9 shows the effects of exposure level on lattice spacing. This relation shows the relative effects of lattice pitch on total cost due to the

opposing trends. These effects become more pronounced at increased fuel exposures.

E. Effects of the Stainless-Steel Metal-to-Fuel Ratio

The core power density was varied by increasing the number of rods per cluster. Increasing the number of rods per cluster permits higher fuel-element heat fluxes within

FIG. VI-6—Relation between the reactor thermal rating and the core power density, for a gas-cooled reactor.

the fuel-central melting limit and therefore requires that higher clad temperatures prevail for a given heat-transfer coefficient. Although improved heat-transfer characteristics are obtained at increased power density, as a result of higher allowable operating pressures, clad operating temperatures tend to increase. These higher temperatures require an increasing stainless-steel metal-to-fuel ratio in order to preserve clad integrity for free-standing-design ground rules.

The relative stainless-steel content of the core has a pronounced effect on the required enrichment for a given exposure. The relative effects of the stainless-steel content on fuel enrichment are shown on figure VI-10.

Fuel exposure determines the residence time of the fuel in the reactor between refuelings. Exposure is limited by considerations of fis-

sion-gas release, fuel integrity, and clad integrity. The principal cost items affected by fuel exposure are fabrication cost, and to a lesser extent, burnup costs and use charges. An optimum exposure is determined among the effects of reduced fabrication charges and is offset by increasing fuel and use charges. The incentive to use higher exposures diminishes as the exposure has increased to some optimum level. For gas-cooled reactors, which operate at relatively low specific powers, the residence time for a given exposure is materially increased over that of relatively higher-specific-power reactor designs. It is therefore possible that while an incentive may be shown through operating at relatively long exposures, the mechanical stability and integrity of the clad may be limiting factors, because of the pressure and thermal stress cycle. If these

FIG. VI-7—Effects of the fuel specific power on the total energy cost, for a gas-cooled reactor.

effects are ignored, the optimum exposure for parameters investigated in this study is not obtained, indicating an incentive to exposures in excess of 20,000 Mwd/metric ton of U.

Figure VI-11 shows the effects of fuel exposure on energy cost. This curve indicates that the optimum exposure shifts with the number of rods per fuel cluster. For example, the higher fabrication cost and higher stainless-steel volume fractions at the higher number of rods per cluster justify a higher

fuel-exposure level (greater than 20,000 Mwd/metric ton of U), whereas 20,000 Mwd/metric ton of U is about optimum for 7 rods. In addition, consideration is not given to the probability of higher failure frequencies at long exposures due to increased residence time. This would require consideration of possible effects on plant availability, which would quite possibly be compromised as exposures were progressively increased. As has been stated previously, a clear definition of the optimum

FIG. VI-8—Effects of the reactor thermal rating on the fuel specific power, for a gas-cooled reactor.

exposure depends very greatly on the statistics of fuel integrity for prolonged exposures, particularly for reactor designs embodying low-specific-power characteristics.

F. Summary Conclusions

The results of the parametric studies on gas-cooled reactors of the stainless-steel-clad UO_2 configuration indicate that there are five significant parameters effecting energy cost. These variables include core power density, fuel specific power, fuel exposure, the stainless-steel metal-to-fuel ratio, and the moderator-to-fuel ratio. The metal-to-fuel ratio is reflected in

the number of rods per cluster. The moderator-to-fuel ratio is directly related to the lattice spacing. The following conclusions may be made:

1. The optimum power density and fuel specific power are strongly dependent on fuel-exposure levels and are related to fuel-fabrication cost. If fuel exposure is limited by technology or good statistical performance, there is an increasingly strong incentive toward either lower power density than that used in the reference design or toward obtaining lower fabrication cost. Conversely, if significant reductions in fuel-fabrication

cost are obtainable, the incentive to higher fuel exposures are limited.

2. In evaluating the optimum design selection, it is necessary to factor in potential reductions in fabrication cost that would

lead the optimum design selection toward higher optimum power densities and higher fuel specific power. Considering the trends toward fuel-fabrication-cost reductions, as a result of improvements in technology and

FIG. VI-9—Effects of the lattice pitch (and hence the moderator-to-fuel ratio) on the total energy cost, for a gas-cooled reactor.

FIG. VI-10—Effects of the stainless-steel metal-to-fuel ratio on the initial enrichment, for a gas-cooled reactor.

FIG. VI-11—Effects of the fuel-exposure level on the total energy cost, for a gas-cooled reactor.

technique, it would appear desirable to trend the design selection toward shorter exposures in order to improve the capability factor which would be related to fuel residence time.

3. Improvements in fuel specific power will result in shorter reactor-residence time, and should lead to an improvement in fuel reliability. However, this will result in increasing refueling frequency and may adversely affect the plant-availability factor. Between the extremes of Items 2 and 3, an optimum selection exists; however, statistical performance of clad UO_2 fuels would require demonstration before these factors could be accurately evaluated.

4. Effects of the moderator-to-fuel ratio on energy cost tend to be more significant at lower exposures and flattened as fuel expo-

sure is increased. The selection of the optimum lattice pitch is, however, quite independent of exposure level, showing a very normal tendency toward the tighter pitch as the exposure is increased. This effect may be considered negligible, however, and it may be concluded that, by this, pitch is independent of exposure.

5. There is a strong economic incentive to optimize the principal core parameters. This is especially true of the gas-cooled reactor. The ultimate selection of key design parameters, particularly those affecting fuel exposure and reliability, must await experimental evidence of fuel-performance characteristics.

6. Incentives to long exposures tend to be more pronounced for low-specific-power core designs,

Appendix 1

COST BACKGROUND INFORMATION

The cost information used in this report as the basis for estimating the effects of the various core parameters differs in some cases from the cost data provided in Report SL-1674. Such deviation was necessary for the following reasons. The core-parameter study was performed for 300-Mw(e) plants and detailed cost breakdowns on such items as shielding, vessel cost, and buildings and structures were needed to determine the effects of power density on plant cost. In some cases, Report SL-1674 provided the cost breakdowns for plants of different capacity. Also, physics data available for the parameter study was in some cases for units with different design parameters (for example, the boiling-water reactor) the cost data used was consistent with the physics data used in the parameter study.

A summary of the cost data used as the basis for the core-parameter studies is provided in the following pages of this appendix for each of the reactor concepts covered. It is to be noted that a certain degree of inconsistency exists in the capital-cost data provided for the five reactor concepts. The most notable example of this is in the use of indirect-cost data. Most of the cost data shown were provided by the manufacturers who supplied information for the individual studies, and no attempt was made to rationalize these data for consistency in approach for all concepts. In view of the fact that the primary purpose of this study was to show the economic effects of changing

significant core parameters on a particular reactor concept and not to evaluate relative total energy cost levels between concepts, this inconsistency should not affect the interpretation of the results of the study.

(1) *Pressurized-Water Reactor.*

a. *Plant-capital costs.*

<i>Account Description</i>	<i>Cost</i>
Land and Land Rights.....	\$360, 000
Structures and Improvements.....	6, 302, 400
Reactor-Plant Equipment.....	26, 772, 575
Turbo-Generator Equipment.....	16, 831, 100
Accessory Electrical Equipment.....	1, 440, 000
Miscellaneous Power-Plant Equipment..	782, 500
Main Power Transformer.....	991, 000
TOTAL DIRECT CON-	
STRUCTION COST.....	53, 479, 575
INDIRECT CONSTRUCTION COSTS....	7, 800, 000
SUBTOTAL.....	61, 279, 575
Startup Costs.....	465, 000
Contingencies (10%).....	6, 174, 460
Interest (6% annual rate) 8.1%.....	5, 500, 000
TOTAL CAPITAL COST, \$.....	73, 419, 035
TOTAL CAPITAL COST, \$/kw(e)....	244

b. *Fuel-cycle cost (for an average fuel exposure of 14,700 Mwd/metric ton of U).*

	<i>Mills/kw-hr</i>
Fabrication.....	1. 01
Depletion.....	1. 81
Processing and shipping.....	. 55
Plutonium credit.....	— . 87
Use charge.....	. 62
Use of fabrication capital.....	. 20
Total fuel-cycle cost.....	3. 32

(2) *Boiling-Water Reactor.*a. *Capital cost.*

<i>Account Description</i>	<i>Cost</i>
Land and Land Rights	\$360,000
Structures and Improvements	10,249,800
Reactor-Plant Equipment	26,323,860
Turbo-Generator Equipment	17,463,600
Accessory Electrical Equipment	1,413,000
Miscellaneous Power-Plant Equipment	702,500
Main Power Transformer	991,000

TOTAL DIRECT CON- STRUCTION COST	57,503,760
INDIRECT CONSTRUCTION COSTS	8,400,000
SUBTOTAL	65,903,760
Startup Costs	476,000
Contingencies (10%)	6,637,980
Interest (6% annual rate) 8.1%	5,910,000

TOTAL CAPITAL COST, \$	78,927,740
TOTAL CAPITAL COST, \$/kw(e)	263

b. *Fuel-cycle cost* (for an average fuel exposure of 15,000 Mwd/metric ton of U).

	<i>Mills/kw-hr</i>
Fabrication	0.94
Burnup cost	1.61
Use charge	.57
Plutonium credit	-.67
Processing and shipping	.50
Use of fabrication capital	.22

Total fuel-cycle cost	3.17
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(3) *Organic-Cooled Reactor.*a. *Capital Cost.*

<i>Account Description</i>	<i>Cost</i>
Land and Land Rights	\$360,000
Structures and Improvements	6,655,000
Reactor-Plant Equipment	6,550,000
Heat-Transfer Equipment	8,155,000
Turbo-Generator Equipment	12,910,000
Accessory Electrical Equipment	2,795,000
Miscellaneous Power-Plant Equipment	425,000

TOTAL DIRECT CONSTRUCTION COST	37,850,000
INDIRECT CONSTRUCTION COST (Includes startup costs, contingencies, and interest)	23,450,000

TOTAL CAPITAL COST, \$	61,300,000
TOTAL CAPITAL COST, \$/kw(e)	210

b. *Fuel-cycle cost* (for an average fuel exposure of 7,000 Mwd/metric ton of U).

	<i>Mills/kw-hr</i>
Fabrication	0.71
Burnup cost	2.16
Use charge	.84
Plutonium credit	-.92
Processing	.87
Use of fabrication capital	.11

Total fuel-cycle cost	3.77
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(4) *Sodium-Graphite Reactor.*a. *Capital cost.*

<i>Account Description</i>	<i>Cost</i>
Land and Land Rights	\$360,000
Structures and Improvements	7,250,000
Reactor-Plant Equipment	9,400,000
Heat-Transfer Equipment	22,850,000
Turbo-Generator Equipment	11,550,000
Accessory Electrical Equipment	1,500,000
Miscellaneous Power-Plant Equipment	500,000
Main Power Transformer	1,000,000

TOTAL DIRECT CONSTRUCTION COST	54,410,000
INDIRECT CONSTRUCTION COST	16,338,000

SUBTOTAL	70,748,000
Contingencies (10%)	7,075,000
Interest (6% annual rate) 8.1%	6,304,000

TOTAL CAPITAL COST, \$	84,127,000
TOTAL CAPITAL COST, \$/kw(e)	280

b. *Fuel-cycle cost* (for an average fuel exposure of 10,000 Mwd/metric ton of U).

	<i>Mills/kw-hr</i>
Fabrication	1.14
Shipping	.17
Depletion	2.17
Processing	.35
Plutonium Credit	-.52
Use Charge	.69
Use of Fabrication Capital	.12

Total Fuel-Cycle Cost	4.12
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(5) *Gas-Cooled Reactor.*a. *Capital cost.*

<i>Account Description</i>	<i>Cost</i>
Land and Land Rights	\$360, 000
Structures and Improvements	9, 300, 000
Reactor-Plant Equipment	26, 200, 000
Turbo-Generator Equipment	17, 360, 000
Accessory Electrical Equipment	1, 726, 000
Miscellaneous Power-Plant Equipment	762, 500
Main Power Transformer	991, 000
<hr/>	
TOTAL DIRECT CONSTRUCTION COST	56, 699, 500
INDIRECT CONSTRUCTION COSTS	8, 260, 000
<hr/>	
SUBTOTAL	64, 959, 500
Startup Costs	476, 000
Contingencies (10%)	6, 543, 600
Interest (6% annual rate) 8.1%	5, 830, 000
<hr/>	
TOTAL CAPITAL COST, \$	77, 809, 100
TOTAL CAPITAL COST, \$/kw(e)	259

b. *Fuel-cycle cost* (for an average fuel exposure of 10,000 Mwd/metric ton of U).

	<i>Mills/kw-hr</i>
Fabrication	0. 87
Depletion	1. 88
Shipping	. 20
Reprocessing	. 46
Plutonium credit	— . 95
Use charge	. 70
Use of fabrication capital	. 05
<hr/>	
Total fuel-cycle cost	3. 21

Appendix 2

THE ASSUMPTIONS AND GROUND RULES USED IN THE CORE-PARAMETER STUDIES

In any study of this type, it is necessary to make certain assumptions and to apply a reasonably consistent approach to the analysis performed. It is apparent that these assumptions may affect each concept analyzed to a different degree; however, the purpose of this study was to show trends and not quantitative levels of cost. The results of this study indicate the relative economic incentives for changing core parameters, and the parameters that are likely to have the most effect on energy cost. The assumptions and ground rules used were as follows:

1. An attempt was made to hold the reference designs used in this study consistent with the information published in TID-8516 and the TID-8518 series. It was not practical to do this in every case, since much of the key physics data available for the study was based on different designs and a considerable degree of inconsistency exists in the published data for the 10-year program study. However, since the data are based on the cost differential from a reference point, they should be applicable to the design criteria published in conjunction with the AEC's 10-year program.

2. All energy costs are based on 14-percent fixed charges and an 80-percent capability factor.

3. The core-parameter studies are based on 300-Mw(e) units.

4. All fuel-cycle cost data are based on the price of UF_6 prior to July 1, 1961. Fuel-cycle calculations were performed in accordance with standard AEC criteria.

5. The fuel-element fabrication cost vs rod size for the water-moderated reactors was assumed to vary in accordance with the top curve of figure 2-1. Future trends in fabrication cost were based on a range between the lower two curves of Figure 2-1.

6. Wherever practical, the current technical limits in reactor design were indicated in the study; however, these limits were arbitrarily extended to show the potential economic incentive even though it is not clear how these advancements can be achieved.

7. The economic incentives were shown for individual parameter variations. Since many of these variations involve an extension of the technology and some would in fact have an adverse effect on other parameters, the net cumulative gains by core optimization were not shown. These can be derived from the data presented by the knowledgeable designer with some degree of judgment.

8. The reactor type was selected to be consistent with the ten-year program studies for purposes of consistency, even though it has long been apparent that certain aspects of these designs have been changed. For example, there is considerable emphasis now being placed on the direct-cycle boiling-water reactor. The trend in the organic-cooled and sodium-graphite reactors is to use UO_2 fuel, clad with APM for organic-cooled reactors, and UC fuel for sodium-graphite reactors. The results of the parametric study show clearly why these changes should occur.

FIG. 2-1—Effects of the uranium-dioxide pellet diameter on the cost per weight of the contained uranium, for water-moderated reactors.

9. The approach taken in developing the relation of key reactor parameters to associated economic effects is that costs are affected principally by the parameters that determine the following:

- a. Core specific power.
- b. Core power density.
- c. Core parasitic materials.
- d. Fuel-exposure level.

These design characteristics determine both the plant-capital and fuel-cycle costs for any reactor concept. Optimization of these characteristics with respect to the associated core parameters defines relative economic incentives and related trends established by parameter variations. The methods by which parameter variations were made to determine effects on the significant characteristics are summarized for each reactor concept in the remainder of this appendix.

(1) *Pressurized-Water Reactor.*

- a. *Specific power.* Specific-power effects were determined by varying the fuel-rod diameters within the central-melting and burnout limits and by arbitrarily assuming degrees of power flattening for specific rod sizes.
- b. *Power density.* Power-density effects were obtained by varying the pertinent parameters as follows:

1. Varying the moderator-to-fuel ratio for fixed rod sizes.
 2. Varying the rod size with the core volume fractions held constant. (For large cores, physics effects are essentially negligible with constant core volume fractions.)
 3. Arbitrarily assuming various degrees of power flattening on the peak-to-average bulk-coolant temperature rise and the peak-to-average heat flux.
- c. *Core parasitic materials.* Fuel clad to fuel content must be considered relatively constant in varying rod sizes if the "free-standing clad" criteria is to be maintained. If reductions in clad thickness are arbitrarily made for stainless-steel clad, UO_2 fuel, then an associated decrease in fuel enrichment for a given exposure may be made. The effects of clad thickness were investigated by reducing the clad thickness below values that are consistent with the free-standing criteria. Further development work would be required to demonstrate the technical merits of making such reductions, in view of the effects on clad integrity. Effects due to use of zirconium instead of stainless steel were not investigated.

- d. *Fuel-exposure level.* Effects of varying the fuel exposure were investigated by appropriately changing the fuel enrichment as required to obtain a given exposure level. Methods of reactivity control and the effects of exposure on fuel integrity and reliability were not considered.

(2) *Boiling-water Reactor.*

Parameters affecting the principal characteristics for the boiling-water reactor concept were evaluated by procedures identical with those employed for the pressurized-water reactor concept, with steam void fractions held constant at core-exit facilities. Variations in core-exit voids within stability limits were not investigated. The effects of zirconium cladding were not investigated.

(3) *Organic-Cooled Reactor.*

- a. *Specific power.* Specific-power effects were obtained by fuel-plate subdivision as limited by the maximum fuel-surface temperature and the coolant burnout temperature limits.
- b. *Power density.* Power-density effects were not investigated because of a lack of pertinent physics data. (These data could not be generated within the time limitations for performing this study.)
- c. *Core parasitic materials.* The effects of core parasitic materials were investigated only by analyzing the variations in the wall thickness of the channel box.
- d. *Fuel-exposure level.* The effects of fuel exposure were investigated in terms of the principal parameters, without regard to fuel integrity as a function of burnup.

(4) *Sodium-Graphite Reactor.*

- a. *Moderator-to-fuel ratio.* The effects of this variable were determined in the survey in two ways:
 1. Varying the fuel-element spacing (moderator-element size) with the fuel-element geometry held fixed.
 2. Varying the fuel-rod diameter with the fuel-element spacing held fixed.

- b. *Enrichment.* In this study, the enrichment is a dependent variable that changes with the fuel-element spacing, the fuel-rod diameter, and the fuel-exposure level.
- c. *Operating critical mass.* The mass (U^{235}) is a dependent variable that varies with the required enrichment and the core inventory. These items, in turn, depend upon the fuel-rod size, the fuel-element spacing, and the fuel-exposure level.
- d. *Excess reactivity.* This item was varied in the study only for the reference core in which the effect of burnup costs was considered. The excess reactivity required for higher burnup was obtained by increasing enrichment.
- e. *Conversion ratio.* This is a dependent variable that changes as the fuel-rod diameter, the lattice spacing, and the moderator cladding thickness (or material) is varied.
- f. *Peak-to-average flux and power ratios.* These quantities were not varied in the study. An improvement in these peak-to-average ratios is perhaps best affected by varying the fuel-element spacing, which is impractical in the canned-moderator sodium-graphite reactor. The important change to be achieved by "flattening" in the sodium-graphite reactor is a reduction in the fuel-inventory charges, which are not excessive in this reactor. Possible improvements brought about by flattening with a large number of control rods would be minor. Improvement made possible through variation in the slowing-down power of the moderator, by using graphite blocks of graduated density or by inserting a better moderating material (such as BeO) near the surfaces of the core, could be quite effective in reducing inventory charges. This approach was not investigated because of the short time schedule involved.

The important reduction in energy cost achieved through flattening of the flux would be obtained by permitting the reactor power to rise as the power of each element approaches that of the central fuel channel. However, a sound appraisal of the effects of power flattening must be made with the power level fixed.

g. *Power density.* This quantity is a dependent variable in the sodium-graphite reactor. It is determined by the fuel-rod diameter, the lattice spacing, and the permissible power per rod (which is fixed in the reference design by the central-fuel temperature).

h. *Specific power.* The specific power is almost independent of all variables in the sodium-graphite reactor except the limits on the central-fuel temperature and the fuel-rod diameter. With the center temperature fixed, the obtainable power rod is essentially independent of rod diameter. The number of rods per element and the fuel enrichment have a minor effect on this variable because of the flux depression in the element. The specific power in the U^{235} varies inversely with the fuel enrichment.

i. *Hot-channel factors.* A constant hot-channel factor was used in this survey. There is no problem of severe local flux peaking because of the long neutron diffusion length in a sodium-graphite reactor. Variation in the moderator-to-fuel ratio has a negligible effect on the hot-channel factor. The important part of this factor is the disadvantage factor in the fuel ele-

ment. Additional contributing items are manufacturing tolerances, variations in U^{235} content, and flow variations. The major cost item that would be affected by a change in the hot-channel factor is the fuel inventory.

(5) *Gas-Cooled Reactor.*

a. *Specific power.* Specific-power effects were obtained by varying the fuel-rod size within the heat-transfer and fuel-central-melting limitations.

b. *Power density.* Power-density effects were obtained by varying the lattice spacing. The reactor pressure levels were varied accordingly, consistent within field-fabrication limitations.

c. *Core parasitic materials.* The effect of variations in core parasitic materials was not isolated as an independent variable, in view of the assumptions made in changing the number of rods per cluster. The core stainless-steel metal-to-fuel ratios were changed in relation to the number of rods per cluster as required to obtain a consistent clad-design basis. The effects of the stainless-steel metal-to-fuel ratio on initial enrichment were developed in order to indicate the magnitude of the parasitic effect.

d. *Fuel exposure.* Effects of fuel exposure were determined by varying the enrichment required to obtain a given exposure, without regard to reactivity control or element integrity as affected by metal creep, thermal cycling, or fission-gas release.

Appendix 3

AEC CONTRACTORS WHO PROVIDED DATA FOR THE CORE-PARAMETER STUDIES

As previously indicated, the information on which the core-parameter studies were based was furnished by AEC contractors in support of the Commission's 10-year civilian power reactor program. The data provided varied in content and approach. In several cases, therefore, the data as presented in this report were supplemented and presented in a different form, in order to maintain some degree of consistency in showing the effects of a particular parameter on energy cost.

Time did not permit a review of the final document with the manufacturers' personnel prior to publication. Therefore, the trends and conclusions provided in this report are strictly those of the authors and do not necessarily represent the opinions of the respective organizations supplying data for this report.

The AEC contractors who supplied data for the several types of reactors considered are as follows:

1. Pressurized-water reactors.	Westinghouse Electric Corporation.
2. Boiling-water reactors.	General Electric Company.*
3. Organic-cooled reactors.	Atomics International, Division of North American Aviation, Inc.
4. Sodium-graphite reactors.	Atomics International, Division of North American Aviation, Inc.
5. Gas-cooled reactors.	Oak Ridge National Laboratory.*

*No information was provided by these organizations for the specific purpose of preparing core-parameter studies. However, the core-parameter studies were based on information provided by these firms for other purposes, as shown in the list of reference material (see appendix 4).

Appendix 4

SUMMARY OF REFERENCE MATERIAL

The reference material used in preparing the core-parameter studies covered by this report comprise the following:

1. *Pressurized-Water Reactors*

- (a) Core Design Optimization Study for a Large Pressurized Water Reactor, Report WCAP-1284.
- (b) Civilian Power Reactor Program. Part III. Status Report on Pressurized Water Reactors as of 1959, USAEC Report TID-8518 (Bk. 2) (WCAP-1196).

2. *Boiling-Water Reactors*

- (a) Boiling Water Reactor Study, USAEC Report TID-8500 (Parts 1-3), Ebasco Services, Inc., and General Electric Company, April 1959.
- (b) Civilian Power Reactor Program. Part III. Status Report on Boiling Water Reactor Technology as of 1959, USAEC Report TID-8518 (Bk. 5).

3. *Organic-Cooled Reactors*

- (a) R. W. Hardy and B. L. Hoffman, Core Parameter Survey Report for Organic Cooled Reactors, USAEC Report NAA-SR-4510, North American Aviation, Inc., Dec. 15, 1959.

- (b) Civilian Power Reactor Program. Part III. Status Report on Organic-Cooled Power Reactors as of 1959, USAEC Report TID-8518 (Bk. 7).

4. *Sodium-Graphite Reactors*

- (a) Core Parameter Study for a 300 MWE Sodium Graphite Reactor, Atomic International Internal Report (unnumbered).
- (b) Civilian Power Reactor Program. Part III. Status Report on Sodium Graphite Reactors as of 1959, USAEC Report TID-8518 (Bk. 6).

5. *Gas-Cooled Reactors*

- (a) Alfred M. Perry, Economic Effects of Gas-Cooled Reactor Parameters, USAEC Report CF-59-12-40, Oak Ridge National Laboratory, Dec. 9, 1959.
- (b) Information Meeting on Gas-Cooled Power Reactors, Oak Ridge National Laboratory, October 21-22, 1958, USAEC Report TID-7564, Oak Ridge National Laboratory.
- (c) Oak Ridge National Laboratory, Internal Report on Reactor Physics.