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AEC RESEARCH AND DEVELOPMENT REPORT

HEAVY WATER REACTORS
FOR SEA WATER DISTILLATION PLANTS

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HEAVY WATER REACTORS FOR SEA WATER DISTILLATION PLANTS

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January 1964

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ABSTRACT

Conceptual designs of reactors moderated with D_2O have been prepared for a study of the use of large reactors for sea water distillation. Two designs are presented: a near-term reference design producing 3500 MW thermal with pressurized liquid D_2O coolant, and a more advanced design producing 8300 MW thermal with organic coolant. Steam costs are estimated for dual-purpose plants in which the by-product steam from back-pressure turbines is sent to the saline water plant. These estimates show that the net steam cost varies from 11 to 16¢/million Btu for the 3500-MWt plant, and from 4 to 9¢/million Btu for the 8300-MWt plant, as the power credit changes from 3 to 1 mill/kwh.

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HEAVY WATER REACTORS FOR SEA WATER DISTILLATION PLANTS

INTRODUCTION

In April 1963, the Division of Reactor Development, USAEC, asked the Du Pont Company, Atomic Energy Division, to participate in a study of dual-purpose reactors designed to produce steam suitable for the generation of electricity with the primary objective of providing process heat for a sea water distillation plant by using the exhaust steam from the turbines. This study was requested by the Office of Science and Technology Task Group and was being conducted by a Subcommittee with representatives from the Office of Saline Water and Bureau of Reclamation of the Department of the Interior, the Federal Power Commission, and the Division of Reactor Development of the Atomic Energy Commission (DRD).

Two reactor designs were submitted by Du Pont for inclusion in the study:

- A 3500-MWt reactor, moderated and cooled with D_2O , that could be built with a minimum of development effort.
- An 8300-MWt reactor, moderated with D_2O and cooled with organic, that would require a large amount of development work, could be constructed in the mid-70's, and represented better long-range economic potential.

Specifications were obtained for these reactor plants with the help of a reactor design and cost code prepared as part of the study program of heavy-water-moderated power reactors^(1,2). The results were given to the Du Pont Engineering Department and to Sargent and Lundy, Engineers, for refinement of the mechanical design and cost estimates. This information was then transmitted to the Bechtel Corporation, the architect-engineer for all reactor concepts considered in the study. The fuel design for the 8300-MWt reactor was transmitted to ORNL for evaluation of the fuel cycle costs.

Subsequently the DRD requested that a 3500-MWt organic-cooled design be submitted as a companion to the 8300-MWt design. This organic-cooled design replaces the 3500-MWt D_2O -cooled design in Bechtel's final report.

Further studies are being made by the Du Pont Engineering Department and Sargent and Lundy on the design features and the economic feasibility of D_2O - and organic-cooled reactor plants in 3500- and 8300-MWt sizes.

This report presents the reactor designs and assumptions as they were submitted to the Division of Reactor Development and to Bechtel Corporation.

SUMMARY

Designs were prepared and submitted for evaluation of two reactors: a 3500-MWt reactor cooled with liquid D₂O upon which engineering design could start immediately, and an 8300-MWt organic-cooled reactor for completion in the mid-70's. Both reactors have a cylindrical shape with vertical fuel assemblies consisting of three concentric fuel tubes contained inside zirconium alloy pressure tubes. The liquid-D₂O-cooled reactor has fuel of slightly enriched (1.2% U²³⁵) UO₂ clad in Zircaloy, and the organic-cooled reactor has natural uranium carbide tubes clad in Sintered Aluminum Product (SAP). A summary of the design parameters is given in Table I.

TABLE I

Reactor Design Summary

Reactor power, MWt	3500	8300
Fuel	UO ₂	UC
U ²³⁵ enrichment	1.2%	Natural
Coolant pressure, psi	1700	300
Core length, ft	15	20
Number of fuel positions	420	1400
Coolant outlet temperature, °C	304	380
Coolant inlet temperature, °C	264	280
Power of average flat zone assembly, MWt	9.8	6.3
Maximum fuel temperature, °C	1800	604
Maximum fuel rating ($fkd\theta$), watts/cm	38	-
Maximum sheath temperature, °C	330	470
Maximum heat flux, pcu/(hr)(ft ²)	467,000	332,000
Average fuel exposure, MWD/tonne U	15,000	8,500
Steam pressure at turbine throttle, psia	650(sat.)	787(a)
Gross electrical output, MW	620	1330
Net electrical output, MW	550	1190
Steam pressure at turbine outlet, psia	45	95
Steam temperature at turbine outlet, °F	274	324
Process steam generated, 10 ⁹ Btu/day	240	580

(a) 160°F superheat

The construction costs were estimated in terms of 1963 dollars with labor costs and site conditions typical of a southern California coastal site. Our preliminary estimates of these costs are presented in Table II. Interest on money borrowed during construction is not included.

TABLE II

Reactor Cost Summary
(Costs in Thousands of Dollars)

Reactor power, MWt	3500	8300
Direct labor and material costs		
Reactor and primary coolant system	27,300	72,800
Turbine plant	28,000	67,500
Auxiliary facilities	<u>19,600</u>	<u>28,800</u>
Total direct costs	74,900	169,100
Indirect costs (55%)	<u>41,200</u>	<u>93,000</u>
Total capital costs	116,100	262,100
D ₂ O inventory	29,000	33,000

Preliminary fuel costs for the near-term 3500-MWt reactor and the mid-70's 8300-MWt reactor are given in Table III. Fuel fabrication costs were estimated on the basis of the construction and operation of a privately owned fuel fabrication plant designed to produce fuel for the single reactor. Fuel reprocessing charges were estimated from Nuclear Fuel Services charges for the 3500-MWt plant and on the basis of a hypothetical two-ton-per-day fuel reprocessing plant for the 8300-MWt design. Uranium costs correspond to toll enrichment with separative work charges of \$30/kg U and a U₃O₈ price of \$5/lb. In the 8300-MWt case the reprocessing cost is low enough so that the plutonium credit (\$6.70/g Pu) provides a significant subsidy, whereas for the 3500-MWt case, the reprocessing charges and plutonium credit are approximately equal.

TABLE III

Fuel Cost Summary
(Fuel Costs in \$/kg of U)

Reactor power, MWt	3500	8300
U ²³⁵ enrichment	1.2%	Natural
Fuel exposure, MWD/tonne	15,000	8,500
Fuel fabrication cost	38.80	16.80
Cost of uranium	48.91	13.00
Shipping and reprocessing	35.30	17.50
Inventory	5.07	1.62
Plutonium credit	<u>(35.20)</u>	<u>(28.40)</u>
Net fuel costs	92.88	20.52

The reactor designs were optimized for fixed charge rates typical of municipal, state, or federal ownership, as specified by the Task Group, of 7.3% for depreciating and 5.0% for non-depreciating capital items. The reactor is to have a 90% availability and the combined plant, a load factor of 80%. With these assumptions the cost of steam to the desalination plant as a function of a price at which power can be sold is summarized in Table IV.

TABLE IV

Steam Cost Summary

(Steam Costs, ¢/million Btu)

Reactor power, MWt	3500	8300
Capital charges	12.1	11.2
D ₂ O inventory charges	2.1	1.0
Operating charges	3.0	1.5
D ₂ O losses or organic makeup	0.8	1.6
Fuel cycle costs	<u>9.3</u>	<u>3.4</u>
Total costs	27.3	18.7
Power credit at 1 m/kwh	5.5	4.9
Net steam costs	16.3	8.9
Power credit at 3 m/kwh	16.5	14.7
Net steam costs	10.8	4.0

Additional reactor designs were prepared for study purposes with the design and cost computer code: (1) a 3500-MWt organic-cooled design, and (2) a 3500-MWt boiling-H₂O-cooled design for comparison with the design proposed by the Oak Ridge National Laboratory⁽⁴⁾. Preliminary cost estimates for these designs are compared with the reference designs in Table V. The 3500-MWt organic-cooled design was used rather than liquid-D₂O-cooled design in Bechtel's final report.

Also included for comparison is a low pressure liquid-D₂O-cooled reactor⁽¹⁾ designed to produce 3500 MWt of low pressure steam and no electricity. Its net steam cost of about 20¢/10⁶ Btu represents an upper limit for reactors of this size, and shows that the incentive to build dual-purpose reactors depends on a satisfactory credit for the electricity produced. The relatively small capital charges of this steam-only system

result primarily from eliminating the turbine plant and reducing the wall thickness of the pressure tubes, piping, steam generators, and containment building. The large operating charges include buying the electrical power to run the plant.

TABLE V

Steam Cost Comparison of Reactor Types

Reactor power, Mwt	3500	3500	3500	3500	8300
Coolant	Liquid D ₂ O	Liquid D ₂ O	Boiling H ₂ O	Organic	Organic
System pressure, psia	300 ^(a)	1700	1500	300	300
Steam costs, ¢/million Btu					
Capital charges	4.7	12.1	14.9	14.2	11.2
D ₂ O inventory charges	1.7	2.1	1.4	1.3	1.0
Operating charges	5.5	3.0	3.3	3.1	1.5
D ₂ O losses and organic makeup	0.7	0.8	0.2	1.8	1.6
Fuel cycle costs	<u>7.1</u>	<u>9.3</u>	<u>12.8</u>	<u>9.3</u>	<u>3.4</u>
Total costs	19.7	27.3	32.6	29.7	18.7
Power credit at 3.0 m/kwh	-	16.5	24.6	19.2	14.7
Net steam costs	19.7	10.8	8.0	10.5	4.0

(a) Process heat only

The 3500-Mwt liquid-D₂O-cooled design has a relatively high enrichment (1.2% U²³⁵) optimized for near-term estimates of zirconium, fuel fabrication, and fuel reprocessing costs. It would probably be economical to store the spent fuel until the fuel reprocessing industry grows to the point at which more economical recovery of the plutonium in the spent fuel is possible. As these costs are reduced, savings will be made by reducing the fuel enrichment, fuel burnup costs, and average fuel exposure.

The 8300-Mwt organic-cooled design uses cast UC fuel tubes. Fuel cycle studies were made with cast UC rods and with mechanically compacted UO₂ tubes as alternative fuels and with slightly enriched uranium rather than natural uranium. Table VI lists the effect of changes in fabrication and reprocessing costs and in plutonium buy-back credit on the fuel cycle costs for each of these cases.

TABLE VI

Effect of Fuel Cycle Parameter on Steam Costs
 (8300-MWt Organic-Cooled
 Heavy Water Reactor, Municipal Financing)

Fuel type	<u>UC Tubes</u>		<u>UC Rods</u>		<u>UO₂ Tubes</u>
Enrichment, % U ²³⁵	0.7	1.2	0.7	1.2	1.2
Fuel cycle costs, \$/kg U	19.6	73.6	25.5	79.5	72.1
Exposure, MWD/kg	8.5	17.0	8.5	17.0	15.0
Fuel cycle component of the steam cost, ¢/10 ⁶ Btu					
Reference design	3.4	6.5	4.5	7.9	8.1
Effect of:					
Increased fabrication cost, \$5/kg	0.9	0.4	0.9	0.8	0.6
Increased reprocessing cost, \$5/kg	0.9	0.4	0.9	0.8	0.6
Increased Pu credit, \$1/g	-0.6	-0.3	-0.6	-0.4	-0.4

DISCUSSION

1. BASES FOR THE STUDY

1.1 GENERAL

The reactor station ground rules as presented by the Office of Science and Technology Task Group⁽³⁾ for this study are shown in Appendix A. Since the original set of ground rules on which these D₂O reactor designs are based were altered, these designs are not completely consistent with the ground rules on such items as the turbine back pressure and temperature rise across the brine heaters (Ground Rule No. 2). These differences have been accounted for in the comparison study by Bechtel Corporation⁽³⁾.

The entire study was carried out in a period of about eight weeks which required that maximum use be made of information that was already developed as part of the Du Pont heavy water power reactor program. This limited the degree of optimization and design that could be accomplished to suit these reactors to this particular purpose. The reactor design and cost code at the Savannah River Laboratory was used to obtain the core designs and the preliminary reactor cost estimates for 3500-MWt reactors (about the upper limit of the cost equations used in the code). The reactor core design and operating conditions for the 8300-MWt design were selected largely on the basis of studies made in the smaller sizes.

1.2 REACTOR COOLANTS

With heavy water reactors a wide choice of possible coolants is available including boiling and liquid D₂O and H₂O, organic fluids, and gas.

For the 3500-MWt reactor, liquid D₂O coolant was selected since this represents the concept upon which construction could be started immediately with a minimum of development effort. This concept minimizes the total cost of building a single reactor to be on-line by 1968.

For the 8300-MWt reactor to be on-line by 1975, both organic and boiling H₂O (as proposed by ORNL⁽⁴⁾) appear to have equivalent potential for lowest costs for these plants. The reactor design selected for this study is organic-cooled primarily because more consideration has been given to this concept in the Du Pont program, so that reactor designs in this size were more readily available for this study. If such a reactor were to be constructed, either coolant concept could be employed and both would presumably be preceded by a smaller prototype designed to go on-line in 1969 or 1970.

1.3 STEAM CONDITIONS

The reactor is designed primarily to produce steam for the desalination plant and as such the steam temperature to the desalination plant was specified in the ground rules to provide maximum sea water temperatures of 250°F for the 3500-MWt plant, and temperatures of 250, 300, and 350°F for the 8300-MWt plant. Within these restrictions it is expected that the sale of electricity will represent a significant subsidy to the cost of generating process steam so the reactors are designed to produce steam to the turbine throttle at about the maximum conditions consistent with the technology expected at the specified completion dates.

If power is sold at more than 2 m/kwh the cost of steam to the desalination plant could be reduced by reducing the turbine back pressure and increasing the amount of electricity generated. A complete optimization for a particular plant would require a knowledge of the cost of producing water as a function of the temperature of the steam supplied to the desalination plant as well as the sales price expected for the electricity.

1.4 REACTOR COSTS AND FINANCING

The reactors are optimized as specified in the ground rules for annual fixed charge rates of 7.3% for depreciating and 5.0% for nondepreciating capital items. Steam costs are also calculated, as a matter of interest, for charge rates of 14.1% for depreciating and 12.5% for nondepreciating items. Heavy water is assumed to cost \$20/lb and to be a nondepreciating item. All costs are expressed in 1963 dollars, and labor, productivity, and wages are representative of a southern California site.

If the reactor were designed for the higher charge rates the optimum system would have a higher power rating from the core at the expense of somewhat increased fuel cycle costs. Examples of 300-MWe power reactor plants optimized for these two types of charge rates have been developed as part of the heavy water power reactor program^(5,6).

1.5 FUEL COSTS AND FINANCING

For the 3500-MWt reactor the fuel fabrication costs are based upon the current estimated costs of supplying such fuel, assuming that all the fuel for the reactor is supplied by one fuel fabricator. The reprocessing costs are based on those quoted for the Nuclear Fuel Services plant. These relatively high fabrication and reprocessing costs lead to

a relatively high enrichment (1.2% U^{235}) and fuel exposure. The spent fuel has a U^{235} concentration below 0.25% (assumed diffusion plant tails). Reprocessing depends upon plutonium values being high enough to pay the reprocessing costs.

For the 8300-MWt plant the fuel fabrication costs are based on those calculated for a one-ton-per-day fabrication plant capitalizing its investment at a 15% fixed charge rate. Spent fuel processing costs are based upon those for a two-ton-per-day reprocessing plant and the value of plutonium is \$6.70/g in nitrate solution. For these conditions it is about a toss-up whether to use relatively short-lived natural uranium fuel or slightly enriched fuel with increased exposure. The natural fuel cycle was chosen for the reference case because later in the reactor life, it is presumed that fuel fabrication and reprocessing charges would go down while the plutonium credit may increase. Each of these factors would make the natural uranium fuel cycle relatively more economical.

The type of financing used in handling the fuel inventory does not affect the optimum fuel cycle because the fuel inventory charges are such a small item for heavy water reactors.

2. 3500-MWt REFERENCE DESIGN

2.1 CORE DESIGN

General

The major design parameters for the liquid-D₂O-cooled 3500-MWt reactor are listed in Table 2.1. This is a vertical reactor in which the primary coolant flows upward past 420 fuel assemblies contained in pressure tubes (Figure 2.1). The D₂O moderator outside the pressure tubes is at low pressure and temperature. Complete design and preliminary cost data are given in Appendix B.

The design includes all the auxiliary facilities, structures, and land required for the reactor and turbine-generator plant.

TABLE 2.1

Design Parameters for 3500-MWt
Liquid-D₂O-Cooled Reactor

Fuel	UO ₂ Tubes	
U ²³⁵ enrichment, wt %	1.19	
Coolant pressure, psi	1700	
Core length, ft	15	
Number of fuel positions	420	
Reactor power, MW to steam generators	3524	
Coolant outlet temperature, °C	304	
Coolant inlet temperature, °C	264	
Power of average flat zone assembly, MWt	9.8	
Maximum fuel rating (fkdθ), watts/cm	38	
Maximum sheath temperature, °C	330	
Maximum heat flux, pcu/(hr)(ft ²)	467,000	
Average fuel exposure, MWD/tonne U	15,000	
Steam pressure at turbine throttle, psia	650	
	<u>Electricity Only</u>	<u>Electricity and Steam</u>
Gross electrical output, MW	1090	620
Net electrical output, MW	1000	550
Steam generated, 10 ⁹ Btu/day	-	240
Steam pressure at turbine outlet	1.5" Hg	45 psia
Steam temperature at turbine outlet, °F	92	274

FIG. 2.1 REACTOR TANK DESIGN FOR INSULATED PRESSURE TUBES

Fuel Assembly

The liquid-D₂O-cooled fuel assembly (Figure 2.2) consists of three concentric tubes of UO₂ enriched to 1.19% U²³⁵. Each assembly contains 300 pounds of UO₂. The tubes are 7-1/2 feet long and are fabricated by vibratory compaction followed by swaging. The tubes are clad with 0.020 inch of Zircaloy and have the following dimensions:

<u>Fuel Tube No.</u>	<u>Clad OD, in.</u>	<u>Clad ID, in.</u>
1	3.70	3.24
2	2.57	2.01
3	1.27	0.68
2-2

Full Scale

Zr-2.5% Nb Pressure Tube
 Zircaloy Insulating Liner
 Vibratory Compacted UO_2 Fuel Tubes Clad with 0.020" of Zircaloy

FIG. 2.2 FUEL ASSEMBLY FOR LIQUID- D_2O -COOLED REACTOR

Spacing ribs are attached to the inner sheaths of the outer two fuel tubes by electron beam welding before the UO_2 is loaded into the sheaths.

The assembly is designed for the same coolant temperature rise in each channel and for equal burnout safety factors on each fuel tube.

Pressure Tube

The pressure tubes are cold-worked zirconium - 2.5% niobium tubes to which stainless steel end fittings are attached by tandem-extruded joints. Tube thickness is based on a design stress that is one-fourth of the ultimate tensile strength. Heat losses from the coolant to the moderator are

FIG. 2.3 CORE LAYOUT FOR 3500-MWt LIQUID-D₂O-COOLED REACTOR

minimized by an insulating annulus of stagnant D₂O inside the pressure tube. The annulus and the outer coolant channel are defined by a Zircaloy insulating liner that has spacing ribs attached to its ID by electron beam welding. The insulating liner also supports the fuel column, and the whole assembly can be removed from the pressure tube if necessary by withdrawing the liner.

Lattice Design

Figure 2.3 shows one quadrant of the reactor core. The core contains 420 fuel assemblies on a 10-inch square pitch, is 15 feet long and 20 feet in diameter, and has a 20-inch D₂O reflector surrounding the core and 24-inch reflectors at each end.

Reactor control is provided by top-mounted, mechanically actuated control rods. The 37 control clusters are in lattice positions, and each contains the equivalent of 2-1/2 rods. The rods provide axial and radial flattening of the reactor as well as power control.

There are 40 safety rods in interstitial positions (not shown in Figure 2.3). These rods are fully withdrawn above the core when the reactor is operating, and fall by gravity to shut the reactor down.

Fuel Cycle

Interim replacement of the fuel is required if reactivity is to be maintained for long fuel exposures. A workable charging scheme for this reactor is to replace one-third of the fuel assemblies from both the flat and buckled zones at each planned shutdown. The average exposure for an initial enrichment of 1.19% is 15,000 MWD/tonne U (17,000 in flat zone and 13,000 in buckled zone). Energy generation costs do not increase greatly if the design exposure is decreased, because the required fuel enrichment also decreases.

The optimum refueling scheme might include charging fresh fuel to the buckled zone for a cycle and then to the flat zone for a cycle, or providing a higher enrichment in the buckled zone.

2.2 REACTOR TANK AND SHIELD DESIGN

The D₂O moderator is contained in a stainless steel tank to which the pressure tubes are welded. The tank also contains the top and bottom thermal shields, which are simply plates of stainless steel separated by D₂O. The radial thermal shield consists of an annular carbon steel tank that contains carbon steel plates cooled by H₂O (Figure 2.1). Heat produced in the moderator and shields can be used to preheat sea water for the distillation plant.

2.3 HYDRAULICS AND HEAT TRANSFER

A process flow diagram of the plant is shown in Figure 2.4. The primary coolant system consists of eight loops, each containing one pump and one vertical U-tube steam generator. Coolant is distributed to the pressure tubes by headers and pigtails as shown in Figure 2.1. Essentially all the primary piping and equipment are constructed of carbon steel. To attain the highest possible steam temperature, about 15% of the total heat transfer area is in an economizer in which the secondary feedwater is heated to the boiling point.

FIG. 2.4 FLOW DIAGRAM FOR 3500-MW_t LIQUID-D₂O-COOLED PLANT⁽⁷⁾

The primary system pressure is 1700 psi and the saturation temperature is 320°C. This pressure is specified so that the surface temperature is limited to about 330°C by surface boiling. The average coolant effluent temperature is 304°C, but with the proposed charging scheme in which one-third of the fuel is replaced at each shutdown, the effluent from the hottest assembly is about 310°C. Allowing for hot spot factors, it is expected that some boiling will occur at the outlet of the hottest subchannels. The coolant temperature rise is 40°C at 350,000 gpm.

The maximum heat rating of an average exposure element in the flat zone is 38 watts/cm (1800°C), and the maximum heat flux is 467,000 pcu/(hr)(ft²). Initial heat ratings of freshly charged elements may be as high as 44 watts/cm (2000°C) and heat fluxes may reach 540,000 pcu/(hr)(ft²) under the proposed charging scheme.

Steam pressure at the turbine throttle valve is 650 psia. As a dual-purpose plant, the turbine exhaust pressure is 45 psia and the plant produces 550 MW of electricity and 240×10^9 Btu/day of steam at 274°F. As a single-purpose plant, with a condenser at 1.5 inches of mercury absolute pressure, about 1000 MW of electricity is produced.

2.4 TURBINE PLANT

The turbine plant contains two 1800-rpm, noncondensing, tandem compound, double flow turbines. These units are designed to operate with 650 psia saturated throttle steam and to exhaust steam at 45 psia. Each turbine has two stages of extraction to provide steam for feedwater heating. The turbine exhaust steam is then piped directly to the desalination plant. Condensate is returned to the turbine plant at 274°F and is heated to a final temperature of 388°F by the two stages of feedwater heaters. A more detailed description of the turbine plant and a detailed breakdown of the turbine plant costs are provided in Reference 7. The turbine building arrangement drawings, prepared by Sargent and Lundy, are reproduced in Figures 2.5, 2.6, and 2.7.

FIG. 2.5 GENERAL ARRANGEMENT PLAN "A-A" - TURBINE BUILDING - 3500-MW_t LIQUID-D₂O-COOLED PLANT

PLAN "B-B"

FIG. 2.6 GENERAL ARRANGEMENT PLAN "B-B" - TURBINE BUILDING - 3500-MW_t LIQUID-D₂O-COOLED PLANT

FIG. 2.7 GENERAL ARRANGEMENT SECTIONS - TURBINE BUILDING -
3500-MW† LIQUID-D₂O-COOLED PLANT

2.5 CONTAINMENT

A conventional low-leakage steel shell is provided to contain the steam and fission products released in the maximum credible accident, which is a rupture of the primary piping. For this reactor the required containment volume is determined by the equilibrium pressure after the accident rather than by the equipment size.

The general arrangement drawings of the containment building were prepared by Sargent and Lundy and are shown in Figures 2.8, 2.9, and 2.10.

2.6 COOLANT TREATMENT

The coolant and moderator are maintained at high pH and low oxygen content to minimize corrosion of the carbon steel components. They are purified by running continuous sidestreams through deionizers and distillation columns. An annual leakage of 2% of all the D₂O in the system is assumed.

2.7 REACTOR PLANT AUXILIARY SYSTEMS

The reactor plant auxiliary systems consist of:

- Waste Disposal System
- D₂O Distillation System
- Fuel Handling System
- Coolant Storage and Makeup Systems
- Moderator Storage and Makeup Systems
- Off-Gas System
- Liquid Poison System
- Moderator Cooling System
- Coolant and Moderator Purification Systems

The design and cost estimates for these systems were made by Sargent and Lundy and are described in Reference 7.

FIG. 2.8 GENERAL ARRANGEMENT PLAN - REACTOR BUILDING -
3500-MWt LIQUID-D₂O-COOLED PLANT

FIG. 2.9 GENERAL CROSS SECTION "A-A" - REACTOR BUILDING -
3500-MWt LIQUID-D₂O-COOLED PLANT

FIG. 2.10 GENERAL CROSS SECTION "B-B" - REACTOR BUILDING -
3500-MWt LIQUID-D₂O-COOLED PLANT

3. 8300-MWt REFERENCE DESIGN

3.1 CORE DESIGN

General

Major design parameters for the organic-cooled 8300-MWt reactor are listed in Table 3.1. This is a vertical pressure tube reactor that contains 1400 fuel assemblies. The D₂O moderator is contained in a calandria. Complete design and preliminary cost data are given in Appendix B.

TABLE 3.1

Design Parameters for 8300-MWt Organic-Cooled Reactor

Fuel	UC tubes	
U ²³⁵ enrichment	Natural	
Coolant pressure, psi	300	
Core length, ft	20	
Number of fuel positions	1400	
Reactor power, MW to steam generators	8392	
Coolant outlet temperature, °C	380	
Coolant inlet temperature, °C	280	
Power of average flat zone assembly, MWt	6.3	
Maximum fuel temperature, °C	604	
Maximum sheath temperature, °C	470	
Maximum heat flux, pcu/(hr)(ft ²)	332,000	
Average fuel exposure, MWD/tonne U	8500	
Steam pressure at turbine throttle, psia	787	
Steam temperature at turbine throttle, °F	676	
	<u>Electricity Only</u>	<u>Electricity and Steam</u>
Gross electrical output, MW	2850	1330
Net electrical output, MW	2660	1190
Steam generated, 10 ⁹ Btu/day	-	580
Steam pressure at turbine outlet	1.5" Hg	95 psia
Steam temperature at turbine outlet, °F	92	324

Full Scale

- Zircaloy Calandria Tube
- ▨▨▨▨ Zr-2.5% Nb Pressure Tube
- ▧▧▧▧ Cast UC Fuel Tubes Clad
with 0.020" of SAP

FIG. 3.1 FUEL ASSEMBLY FOR ORGANIC-COOLED REACTOR

Fuel Assembly and Pressure Tube

The organic-cooled fuel assembly (Figure 3.1) consists of three concentric tubes of natural uranium carbide. Each assembly contains 500 pounds of UC. The individual tubes, each 10 feet long, are made by enclosing cast UC cores in extruded sheaths of Sintered Aluminum Product (SAP) that have a 0.020-inch wall. The inner sheaths of the two outer fuel tubes are ribbed extrusions. Cross-section dimensions of the fuel tubes are listed below.

<u>Fuel Tube No.</u>	<u>Clad OD, in.</u>	<u>Clad ID, in.</u>
1	3.20	2.66
2	2.24	1.56
3	1.13	0.42

The eventual optimum fuel assembly may have a central rod instead of the smaller diameter tube.

The pressure tubes are cold-worked Zr - 2.5% Nb tubes to which stainless steel end fittings are attached by tandem-extruded joints. The pressure tube is lined with a diffusion barrier to prevent hydriding of the zirconium alloy. A 0.120-inch annulus of inert gas is provided between the pressure tube and calandria tube to minimize heat losses to the moderator and contamination of the coolant or moderator.

Lattice Design

Figure 3.2 shows one quadrant of the 8300-MWt reactor core. The core contains 1400 fuel assemblies on a 9-inch square pitch, is 20 feet long and 32 feet in diameter. A 20-inch radial reflector and 24-inch axial reflectors of D_2O are provided. Reactor control is provided by 89 control positions, each containing 2-1/2 conventional control rods; 80 safety rods occupy interstitial positions.

FIG. 3.2 CORE LAYOUT FOR 8300-MWt ORGANIC-COOLED REACTOR

Fuel Cycle

Fuel is replaced a full position at a time by an on-line charging machine. The \$8,000,000 allowed for this item in the cost table (Appendix B) includes two complete machines (one spare) and all the equipment required to handle, store, and cool the fuel until it can be placed in the storage basin. The average exposure of the fuel with natural uranium is 8500 MWD/tonne U (9800 in flat zone and 7300 in buckled zone).

3.2 REACTOR TANK AND SHIELD DESIGN

The D₂O moderator is contained in a calandria consisting of aluminum tubes, tube sheets, and shell. The axial and radial thermal shields consist of annular carbon steel tanks that contain carbon steel plates cooled by H₂O. An annual leakage of 0.5% of all the D₂O in the system is assumed.

3.3 HYDRAULICS AND HEAT TRANSFER

A process flow diagram of the plant is shown in Figure 3.3. The primary coolant system consists of eight loops, each containing a pump, two steam generators, an economizer heat exchanger, and a superheater. Coolant is distributed to the pressure tubes through upper and lower plenums. The loop piping and equipment are constructed of carbon steel.

The primary system pressure is 300 psi, and the organic inlet and outlet temperatures are 280 and 380°C, respectively. The fuel surface temperature is limited to 470°C. The maximum fuel temperature is 604°C and the maximum heat flux is 332,000 pcu/(hr)(ft²).

3.4 TURBINE PLANT

The secondary steam is first used in the noncondensing turbine to produce electric power and is then conducted to the first-stage evaporator in a multiple-effect evaporator plant used to distill sea water. The turbine plant contains three tandem compound, four-flow, 1800-rpm turbines, operating at an exhaust pressure of 95 psia. The throttle steam conditions were 787 psi and 670°F. Each turbine unit has two stages of extraction for feedwater heating. The steam flow to each turbine is 10.5×10^6 lb/hr, and the corresponding total gross electrical generation for the plant is 1330 MW.

FIG. 3.3 FLOW DIAGRAM FOR 8300-MWt ORGANIC-COOLED PLANT⁽⁷⁾

The general arrangement drawings of the turbine building, prepared by Sargent and Lundy, are shown in Figure 3.4. A more detailed description and a detailed breakdown of the costs of the turbine plant have been provided by Sargent and Lundy in Reference 7. Also included in this report are turbine plant designs in which different exhaust pressures were incorporated. Turbine plants with 45 and 182 psia exhaust pressure as well as the 95 psi pressure were included in their study.

3.5 CONTAINMENT

A conventional steel containment vessel is provided to minimize leakage of fission products after the maximum credible accident. A concrete shadow shield is formed inside the steel shell. For this low pressure reactor the required building size is determined by the equipment layout, so the wall thickness is the minimum of 5/8 inch and the top head thickness is the minimum of 1/2 inch.

The general arrangement of the containment building is shown in Figures 3.5 and 3.6.

3.6 REACTOR PLANT AUXILIARY SYSTEMS

The reactor plant auxiliary systems consist of:

- Organic and Non-Organic Water Disposal Systems
- D₂O Distillation System
- Fuel Handling System
- Organic Coolant Storage and Makeup System
- Moderator Storage and Makeup System
- Organic and Non-Organic Off-Gas Systems
- Liquid Poison System
- Coolant and Moderator Purification Systems
- Emergency and Shutdown Cooling System
- Coolant Particulate Removal System
- Steam Tracing System

The design and cost of these systems were made by Sargent and Lundy and are given in Reference 7. Also included in this reference are the design bases and a composite flow diagram for the various systems.

3.7 DEVELOPMENT WORK REQUIRED

Before the construction of the 8300-MWt reactor the following development work is required.

- (1) Mechanical design and testing of the pressure tube and related liners, fittings, and seals.
- (2) Testing and inspection of fuel assemblies to establish satisfactory mechanical designs and exposure life for carbide fuel.
- (3) Determination of heat transfer limits for surfaces cooled by organic liquids.
- (4) Prevention of fouling of heat transfer surfaces and decomposition of the coolant.
- (5) Development of on-line refueling equipment.

In developing the design and preliminary cost estimates for this reactor it has been assumed that the above work will produce satisfactory fuel, cladding, and pressure tube designs and will verify the operating conditions on which the design is based.

FIG. 3.4 GENERAL ARRANGEMENT PLAN - TURBINE BUILDING -
8300-MW† ORGANIC-COOLED PLANT

FIG. 3.5 GENERAL ARRANGEMENT PLAN "A-A" - REACTOR BUILDING - 8300-MWt ORGANIC-COOLED PLANT

FIG. 3.6 GENERAL ARRANGEMENT SECTIONS "B-B" AND "C-C" - REACTOR BUILDING - 8300-MW_t ORGANIC-COOLED PLANT

4. OTHER 3500-MWt DESIGNS

4.1 ORGANIC-COOLED REACTOR

Major design parameters of a 3500-MWt reactor that could serve as a prototype of the 8300-MWt organic-cooled reactor are listed in Table 4.1. This is a vertical pressure tube reactor with 640 positions on a 9-inch square pitch. The core is 20 feet long and 22 feet in diameter. The D₂O moderator is contained in a calandria. Complete design data and preliminary costs are given in Appendix B.

TABLE 4.1

Design Parameters for 3500-MWt Organic-Cooled Reactor

Fuel	UC tubes	
U ²³⁵ enrichment	Natural	
Coolant pressure, psi	300	
Core length, ft	20	
Number of fuel positions	640	
Reactor power, MW to steam generators	3541	
Coolant outlet temperature, °C	380	
Coolant inlet temperature, °C	280	
Power of average flat zone assembly, MWt	6.3	
Maximum fuel temperature, °C	604	
Maximum sheath temperature, °C	470	
Maximum heat flux, pcu/(hr)(ft ²)	332,000	
Average fuel exposure, MWD/tonne U	7400	
Steam pressure at turbine throttle, psia	787	
Steam temperature at turbine throttle, °F	676	
	<u>Electricity Only</u>	<u>Electricity and Steam</u>
Gross electrical output, MW	1202	695
Net electrical output, MW	1110	620
Steam generated, 10 ⁹ Btu/day	-	233
Steam pressure at turbine outlet	1.5" Hg	45 psia
Steam temperature at turbine outlet, °C	92	274

4.2 BOILING-H₂O-COOLED REACTOR

Design parameters of a direct cycle boiling-H₂O-cooled reactor that can be compared with the liquid-D₂O-cooled, organic-cooled, and ORNL boiling-cooled reactors, are listed

in Table 4.2. This is also a vertical pressure tube reactor in which the moderator is contained in a calandria tank. It contains 1020 fuel positions on a 9-inch square pitch, and the core is 15 feet long and 27 feet in diameter. Complete design and preliminary cost data are given in Appendix B.

TABLE 4.2

Design Parameters for 3500-MWt Boiling-H₂O-Cooled Reactor

Fuel	UO ₂ tubes	
U ²³⁵ enrichment, wt %	1.19	
Coolant pressure, psi	1500	
Core length, ft	15	
Number of fuel positions	1020	
Reactor power, MW to turbine	3516	
Coolant outlet temperature, °C	315	
Coolant inlet temperature, °C	300	
Power of average flat zone assembly, MWt	4.0	
Maximum fuel rating, fkdθ, watts/cm	25	
Maximum sheath temperature, °C	325	
Maximum heat flux, pcu/(hr)(ft ²)	180,000	
Average fuel exposure, MWD/tonne U	13,000	
Steam pressure at turbine throttle, psia	1500	
	<u>Electricity Only</u>	<u>Electricity and Steam</u>
Gross electrical output, MW	1258	820
Net electrical output, MW	1175	750
Steam generated, 10 ⁹ Btu/day	-	220
Steam pressure at turbine outlet	1.5" Hg	45 psia
Steam temperature at turbine outlet, °F	92	274

The boiling-cooled fuel assembly is shown in Figure 4.1. Like the liquid-cooled design it contains three concentric tubes of mechanically compacted UO₂ enriched to 1.19% U²³⁵.

The dimensions of the fuel tubes are given below.

<u>Fuel Tube No.</u>	<u>Clad OD, in.</u>	<u>Clad ID, in.</u>
1	4.09	3.28
2	2.88	1.84
3	1.44	0.42

FIG. 4.1 FUEL ASSEMBLY FOR BOILING-H₂O-COOLED REACTOR

If one-third of the assemblies are replaced at each planned shutdown, the average exposure of the core is 13,000 MWD/T U (15,000 in flat zone and 12,000 in buckled zone).

The primary coolant system consists of four loops, each containing a pump and one steam separator. The H₂O coolant enters the core subcooled and leaves at about 30% quality. After the steam is separated from the two-phase mixture, it goes directly to the turbine. The separated liquid is mixed with the effluent from the regenerative feedwater heaters and recycles through the core. A process flow diagram of a boiling-cooled plant to produce electricity

only is shown in Figure 4.2. If such a plant is to produce steam for sea water distillation, a distillation plant replaces the low pressure stages of the turbine, the condenser, and some of the feedwater heaters.

FIG. 4.2 FLOW DIAGRAM OF BOILING-H₂O-COOLED PLANT

The primary system pressure is 1500 psi and the saturation temperature is 315°C (599°F). The maximum heat flux from the fuel is 180,000 pcu/(hr)(ft²).

4.3 LIQUID-D₂O-COOLED REACTOR FOR PROCESS HEAT ONLY

Major design parameters and capital costs of a low pressure, liquid-D₂O-cooled reactor are listed in Table 4.3. This reactor is the same size as the 3500-MWt reference design, but produces steam at 45 psia in its steam generators. Savings in construction costs result from eliminating the turbine plant and reducing wall thicknesses of the pressure tubes, primary system piping, steam generators, and containment building.

TABLE 4.3

Design Parameters for 3500-MWt Process Heat Reactor

Coolant	Liquid D ₂ O
Fuel	UO ₂ tubes
U ²³⁵ enrichment, wt %	1.19
Coolant pressure, psi	300
Core length, ft	15
Number of fuel positions	420
Reactor power, MW to steam generators	3520
Coolant outlet temperature, °C	190
Coolant inlet temperature, °C	150
Power of average flat zone assembly, MWt	9.8
Maximum fuel rating, fkdθ, watts/cm	38
Maximum sheath temperature, °C	320
Maximum heat flux, pcu/(hr)(ft ²)	470,000
Average fuel exposure, MWD/tonne U	16,000
Steam pressure, psia	45
Steam temperature, °F	274
Steam generated, 10 ⁹ Btu/day	290
Capital costs, thousands of dollars	
Reactor plant	\$19,000
Auxiliary facilities	<u>15,400</u>
Total direct	34,400
Indirect costs (60%)	<u>20,600</u>
Total	\$55,000
D ₂ O inventory	\$29,000

APPENDIX A

GROUND RULES FOR STUDY

The ground rules for the entire study of the use of large reactors for sea water distillation were provided by the Office of Science and Technology Task Group under the chairmanship of Dr. Roger Revelle. The ground rules as given in Bechtel's report⁽³⁾ are reproduced below:

1. The Office of Science and Technology (OST) Task Group has specified that the primary purpose of reactor station is to produce steam for a sea water distillation plant.
2. The OST Task Group specified that the electrical production is to be obtained by passing the steam from the reactor plant through a turbine using brine heaters as a condenser. The brine heaters are to heat sea water to the maximum temperature consistent with sea water evaporator technology for the time evaporator plant must be on the line. The Office of Saline Water specified these temperatures as 250°F for current technology stations, 300°F for 1975 stations, and 350°F for 1980 stations. For the purpose of this study, the optimum temperature difference across the brine heater can be assumed to be approximately 15°F for 250 and 300°F maximum brine temperatures and 10°F for 350°F maximum brine temperature. The final choice of brine temperature is to be governed by the temperature which produces the lowest cost water, but a maximum brine temperature of lower than 250°F is not to be used.
3. The reactor plant is to produce steam at conditions consistent with power reactor technology at time reactor must be committed for construction.
4. The OST Task Group specified that a typical Southern California coastal site location is to be assumed. Typical site conditions and parameters are to be selected by the Department of Interior and reviewed by the Atomic Energy Commission.
5. The following annual fixed charge rates, which the Federal Power Commission has given as representative of the two types of financing, are to be used:

	<u>Depreciating</u>	<u>Nondepreciating</u>
Municipal, state, or federal	7%	5%
Investor-owned public utility	14%	12½%

These rates include (where such items are applicable) interest, administrative cost of obtaining money, return on capital, 30-year depreciation, interim replacements, property insurance, nuclear liability insurance, federal income taxes, state and local taxes, and grants in lieu of taxes.

6. The reactor station design is to be optimized at the municipal, state, or federal fixed charge rate.

7. The price of heavy water is to be assumed as \$20 per pound.

8. All costs are to be expressed in terms of 1963 dollars.

9. The OST Task Group specified that a combined plant factor of 80% is to be assumed. This is based upon a 95% load demand, a reactor availability of 90%, a turbine availability of 97%, and a brine heater availability of 97%.

10. Uranium enrichment obtained by toll processing at \$30 separative work charge and 0.25 wt % U^{235} diffusion plant tails concentration with the Atomic Energy Commission retaining title to the tails.

11. The size stations to be considered along with the approximate time each should be on the line, the class of reactor, the price of natural uranium, fuel fabrication cost basis, spent fuel processing cost basis, value of plutonium, and the temperature to which the sea water is to be heated is shown on Table I. Cases 1 through 5 represent five examples of current technology. Case 6 represents an example of 1975 reactor technology and will illustrate the effect of varying the maximum sea water temperature. It is recognized that a 350°F maximum sea water temperature is representative of 1980 evaporator technology. Cases 7, 8, and 9 represent technology in the 1980's and will illustrate the effect of the three major fuel cycles and the effect of varying the fuel fabrication and spent fuel processing rates for each of the representative fuel cycles.

12. Fuel cycle costs for Cases 1, 2, and 3 are to be based upon commercial guarantees. Spent fuel processing costs for Cases 1, 2, and 3 are to be based upon those quoted for the Nuclear Fuel Services (NFS) plant.

13. Fuel fabrication costs for Cases 4 and 5 are to be based upon commercial quotations assuming one fuel fabricator supplied all fuel for the reactor. Spent fuel processing costs for Cases 4 and 5 are to be based upon those quoted for the NFS plant.

14. Fuel fabrication costs for Case 6 are to be based upon those calculated from a one-ton-per-day fabrication plant capitalizing its investment at a 15% fixed charge rate. Spent fuel processing costs for Case 6 are to be based upon those calculated from a two-ton-per-day spent fuel processing plant capitalizing its investment at a 15% fixed charge rate. The civilian nuclear power industry has been estimated* to be discharging four tons per day of fuel in 1975. The reactor of Case 6 will discharge approximately one ton per day of spent fuel. The use of a two-ton-per-day spent fuel processing plant assumes that there will be two organizations in the spent fuel processing business in 1975.

15. Fuel fabrication costs for Cases 7, 8, and 9 are to be based upon those calculated from 2, 5, and 10 ton-per-day fabrication plants capitalizing their investment at a 15% fixed charge rate. The reactor stations of these cases will consume approximately one ton per day of fuel. Spent fuel processing costs for Cases 7, 8, and 9 are to be based upon those calculated from 4, 10, and 30 ton-per-day spent fuel processing plants capitalizing their investment at a 15% fixed charge rate. The civilian nuclear power industry has been estimated* to be discharging 8 tons per day of spent fuel in 1980. Natural uranium prices of \$6, 7, and 8 per pound of U_3O_8 and plutonium values of \$9.10, \$9.60, and \$10.00 per gram of plutonium Pu^{239} and Pu^{241} in nitrate solution are to be assumed on the basis that if the nuclear industry has grown to the point where the higher throughput rates can be used, the low cost reserves of natural uranium will be depleted. Only three sub-cases are to be calculated for each of Cases 7, 8, and 9. For example, the first sub-case would use \$6 uranium, with a two-ton-per-day fabrication plant, four-ton-per-day spent fuel processing plant and a \$9.10 plutonium credit, etc.

16. Assume cost of converting uranyl nitrate hexahydrate to uranium hexafluoride to be \$5.60/kg of uranium.

17. Assume cost of shipping to be \$12/kg of uranium for Cases 1, 2, and 3; \$4/kg for Cases 4 and 5; \$2.50/kg for Cases 6 and 7; and \$5/kg for Cases 8 and 9. This recognizes that slightly enriched high burnup fuels are more expensive to ship than less highly enriched lower burnup fuels shipped in greater volume, that natural uranium lower burnup fuels will be still less expensive, and that slightly high burnup fuels shipped in larger volume will be less expensive to ship in the future. These shipping costs include cost of shipping spent fuel to reprocessing site and cost of shipping uranium and plutonium to AEC receiving plants or back to reactor stations.

*USAEC "Civilian Nuclear Power-A Report to the President-1962"

18. Fuel enrichment and burnups are to be optimized for municipal, state or federal, and investor-owned public utility fixed charge rates. Fuel inventory is to be treated as a nondepreciating item. Effect of investor-owned utilities using debt financing for fuel inventory is also to be shown. The cost of debt capital is assumed to be 7.7% per year composed of 4.5% interest, 0.8% insurance, and 2.4% taxes. Calculations are to be based upon an equilibrium fuel cycle.

19. The results of the evaluation of the nuclear energy low pressure steam supply systems are to be presented in the form of graphs showing the cost of energy available in the steam delivered to the evaporator plant when the by-product power is credited at unit values from 1 to 6 mills per kilowatt hour.

APPENDIX B

TABLE B.1

Reactor Designs and Preliminary Costs

Coolant	Liquid D ₂ O	Boiling H ₂ O	Organic ^(a)	Organic ^(a)
Power, MWt	3500	3500	3500	8300
<u>Fuel Design</u>				
Fuel geometry	Tubes	Tubes	Tubes	Tubes
Fuel material	UO ₂	UO ₂	UC	UC
No. of fuel tubes	3	3	3	3
Cladding material	Zircaloy-2	Zircaloy-2	SAP	SAP
Pressure tube material	Zr - 2.5% Nb	Zr - 2.5% Nb	Zr - 2.5% Nb ^(b)	Zr - 2.5% Nb ^(b)
Calandria tube material	-	Zircaloy-2	Aluminum	Aluminum
Pressure tube liner material	Zircaloy-2	-	-	-
Lattice pitch, in.	10	9.0	9.0	9.0
System pressure, psia	1700	1530	300	300
Design pressure, psia	2000	1783	368	368
Design temp, °C	320	315	380	380
Cladding thickness, mils	20	20	20	20
Weight of fuel, lb/ft	20	40	25	25
Inlet temp, °C	264	300	280	280
Outlet temp, °C	304	315	380	380
Outlet steam quality, wt %	-	30	-	-
Moderator temp, °C	80	80	80	80
Outer coolant channel thickness, in.	0.20	0.125	0.125	0.125
Fuel length, in.	180	180	240	240
Fuel density, % theoretical	92	92	-	-
U ²³⁵ content, %	1.185	1.185	Natural	Natural
H ₂ O in moderator, %	0.25	0.25	0.25	0.25
Calandria or liner thickness, mils	30	20	30	30
Insulating annulus thickness, mils	60	60	120	120
Power of avg. flat zone assembly, MW	9.83	4.04	6.3	6.3
Power conducted to moderator, MW	0.175	0.01	-	-
Max flow at T _{in} , gpm	918	195	510	510
Max subchannel velocity, ft/sec	47.9	65	51	51
Pressure drop, psi	42.4	68	122	122
Max surface temp, °C	330	325	470	470
Max fuel temp, °C	1800	1300	604	604
fkdθ, watts/cm	38	25	-	-
Max heat flux, pcu/(hr)(ft ²)	467,000	180,000	332,000	332,000
Min BOSF	1.8	1.8	2.0	2.0
<u>Hot Clean Lattice Parameters</u>				
Cell Σ _a , cm ⁻¹	0.00486	0.001	0.00506	0.00506
Disad. factor × Σ _f , cm ⁻¹	0.102	0.10	0.0818	0.0818
η	1.52	1.30	1.30	1.30
ε	1.02	1.03	1.03	1.03
p	0.906	0.90	0.880	0.880
f	0.957	0.90	0.931	0.931
k _∞	1.34	1.23	1.10	1.10
L ² , cm ²	182	60	165	165
τ, cm ²	151	140	139	139
M ² , cm ²	333	200	304	304
D ² , m ⁻²	9.20	11.3	3.11	3.11

(a) "Santowax" R - trademark of Monsanto Chemical Co.

(b) Pressure tube is lined with an aluminum diffusion barrier.

TABLE B.1 (Continued)

Coolant	Liquid D ₂ O	Boiling H ₂ O	Organic (a)	Organic (a)
Power, MWt	3500	3500	3500	8300
<u>Fuel Design</u> (Continued)				
Calandria Tube, in.				
OD	-	4.90	3.82	3.82
ID	-	4.86	3.76	3.76
Pressure Tube, in.				
OD	4.60	4.74	3.52	3.52
ID	4.28	4.34	3.44	3.44
Insulating Liner, in.				
OD	4.16	-	-	-
ID	4.10	-	-	-
Fuel Tubes - Clad Diameters, in.				
No. 1 OD	3.70	4.09	3.20	3.20
ID	3.24	3.20	2.66	2.66
No. 2 OD	2.57	2.88	2.24	2.24
ID	2.01	1.84	1.56	1.56
No. 3 OD	1.27	1.44	1.13	1.13
ID	0.68	0.42	0.42	0.42
<u>Core Design</u>				
Thermal power, MW	3500	3500	3500	8300
Moderator power, MW	212	140	141	336
No. of fuel positions	420	1020	640	1400
No. of control positions	37	37	37	89
Min reactivity in control, %	1.0	1.0	1.0	1.0
No. of safety positions	40	40	40	80
Core radius, in.	123	165	132.1	192.6
Flat zone radius, in.	97	127	71.0	125.5
Core length, ft	15	15	20	20
Radial reflector, in.	20	20	20	20
Axial reflector, in.	24	24	24	24
Total coolant flow, gpm	350,000	145,000	297,000	704,000
No. of coolant loops	8	4	8	8
Uranium inventory, tonnes	50.7	244	145	312
Avg specific power, MW/tonne	73	14	25	27
Max specific power, MW/tonne	104	22	48	46
Fuel exposure in BZ, MWD/tonne	13,000	12,000	6,700	7,300
Fuel exposure in FZ, MWD/tonne	17,000	15,000	9,000	9,800
Avg exposure, MWD/tonne	15,000	13,000	7,400	8,500
<u>Shield Design</u>				
Shield Thickness, in.				
Radial thermal	11.8	7.9	9.4	9.9
Top thermal	31.3	15.0	17.3	17.4
Bottom thermal	31.3	15.0	17.3	17.4
Radial biological	114	114	114	114
Shield Heat Load, Btu/hr				
Radial thermal	237,000	73,000	144,000	229,000
Top thermal	-	190,000	398,000	816,000
Bottom thermal	-	190,000	398,000	816,000

TABLE B.1 (Continued)

Coolant	Liquid D ₂ O	Boiling H ₂ O	Organic ^(a)	Organic ^(a)
Power, MWt	3500	3500	3500	8300
<u>Steam Generator Design</u>				
D ₂ O velocity, ft/sec	13.9	-	-	-
Heat transfer area, ft ²	350,000 ^(c)	-	-	-
Length of tubes, ft	44.4	-	-	-
No. of tubes	60,100	-	-	-
Pressure on steam side, psig	665	-	-	-
Steam temp, °C	260	-	-	-
Input power to steam generator, MW	3524	-	-	-
H ₂ O inventory, lb in 1 generator	29,000	-	-	-
D ₂ O inventory, lb in 8 generators	242,000	-	-	-
Input power, MW	-	-	3541	8392
Organic inventory, lb	-	-	536,000	1,310,000
Pressure drop, ft	-	-	75	70.7
Equiv. steam piping diameter, ft	-	-	5.58	8.36
Pressure drop in piping, psi	-	-	8.0	8.0
Superheater				
No. of U-tubes	-	-	23,004	54,956
Length of U-tubes, ft	-	-	33.3	33.8
Heat transfer area, ft ²	-	-	125,460	303,800
Organic inlet temp, °C	-	-	380	380
Organic outlet temp, °C	-	-	366.5	366.4
Steam outlet temp, °C	-	-	357.6	358.2
Shell diameter, ft	-	-	7.3	11.2
Pressure drop, ft	-	-	11.7	12.6
Cost, \$/ft ²	-	-	15.00	14.34
Boiler				
No. of U-tubes	-	-	49,658	122,970
Length of U-tubes, ft	-	-	45.0	44.0
Heat transfer area, ft ²	-	-	365,760	885,600
Steam pressure, psia	-	-	806.8	806.8
Steam temp, °C	-	-	270.6	270.6
Organic outlet temp, °C	-	-	291.0	291.0
Shell diameter, ft	-	-	6.9	10.8
Pressure drop, ft	-	-	47.7	43.2
Cost, \$/ft ²	-	-	20.37	19.73
Economizer				
No. of U-tubes	-	-	27,292	68,300
Length of U-tubes, ft	-	-	23.0	22.0
Heat transfer area, ft ²	-	-	102,740	245,900
Organic outlet temp, °C	-	-	280	280
H ₂ O inlet temp, °C	-	-	223.3	223.3
Shell diameter, ft	-	-	7.3	11.3
Pressure drop, ft	-	-	15.5	14.9
Cost, \$/ft ²	-	-	16.19	15.81

(c) Includes economizer section

TABLE B.1 (Continued)

Coolant	Liquid D ₂ O	Boiling H ₂ O	Organic (a)	Organic (a)
Power, MWt	3500	3500	3500	8300
<u>Turbine Design</u>				
Back pressure, psia	45	45	45	95
Stages of feedwater heater	2	4	3	2
Feedwater temp, °F	388	509	434	434
Throttle pressure, psia	650	1500	787	786.7
Throttle temp, °F	495	596	676	676.4
Gross turbine efficiency, %	17.6	23.3	19.6	15.9
Gross electric output, MW	620	820	695	1330
Power used by auxiliaries, MW	70	70	75	140
Net electrical power, MW	550	750	620	1190
Reactor fission power, MW	3713	3641	3642	8636
Net system efficiency, %	14.8	20.6	17.0	13.8
Load factor, %	8.0	80	80	80
Steam to evaporators, 10 ⁹ Btu/day	240	220	233	580
<u>Containment Vessel Design</u>				
Pressure, psig	18.5	18.1	-	-
Radius, ft	116	120	126	145
Partial height, ft	131	120	143	143
Wall thickness, in.	1.5	1.50	0.625	0.625
Top head thickness, in.	0.75	0.75	0.50	0.50
<u>D₂O Inventory, lb (thousands)</u>				
Axial shields	84	-	-	-
Pressure tube extensions	53	-	-	-
Pigtails	116	-	-	-
Coolant headers	47	-	-	-
Primary coolant piping	175	-	-	-
Primary coolant pumps	26	-	-	-
Steam generator	242	-	-	-
Pressurizer vessel	24	-	-	-
Moderator HX system	100	40	27.8	57.0
Miscellaneous	110	70	100.0	140.0
Core - moderator, coolant, and reflector	513	830	752.4	1,454.0
Total	1,450	940	880.2	1,651.0
<u>Organic Inventory, lb (thousands)</u>				
Plenum chambers	-	-	115.5	232.8
Pressure tube extensions	-	-	42.1	89.8
Primary coolant piping	-	-	835.6	1,133.4
Primary coolant pumps	-	-	19.8	47.0
Steam generator	-	-	535.7	1,312.4
Total	-	-	1548.7	2,815.4

TABLE B.1 (Continued)

Coolant	Liquid D ₂ O	Boiling H ₂ O	Organic (a)	Organic (a)
Power, MWt	3500	3500	3500	8300
<u>Organic Decomposition Rate, lb/hr</u>	-	-	1067	2,487
<u>Pressure Drops, ft of coolant</u>				
Pigtails	122	94	-	-
Pressure tube extensions	50	10	74	91
Coolant headers	10	-	-	-
Plenum chambers	-	-	143	143
Primary coolant piping	159	44	28	83
Steam generator	60	-	75	71
Fuel assembly, including orificing	113	400	308	308
Total	514	640	628	696
<u>Reactor Costs, thousands of \$ (labor at \$4.75/hr)</u>				
Top thermal shield	660	1,340	620	1,230
Bottom thermal shield	660	1,310	600	1,210
Radial thermal shield	370	680	770	1,110
Radial biological shield	70	80	80	110
Shield cooling	40	70	80	90
Calandria or moderator tank	490	750	480	930
Reactor enclosures	80	90	80	100
Pressure tubes	1,940	5,700	1,330	2,850
Insulating liner	310	-	-	-
Pressure tube hardware	230	590	210	440
Pressure tube extensions	700	1,810	860	1,850
Pigtails	500	380	-	-
Coolant headers	120	800	-	-
Plenum chambers	-	-	840	2,200
Safety rods	680	680	700	1,400
Control rods	1,810	1,800	1,850	4,400
Coolant monitoring instrumentation	1,190	1,600	2,700	5,430
Nuclear instrumentation	110	110	110	110
Fuel charging machines	1,800	1,800	5,500	8,800
Primary coolant piping	2,080	4,430	1,950	2,370
Primary coolant pumps	5,200	2,670	3,580	8,400
Pressurizer vessel	170	-	-	-
Steam separators	-	2,900	-	-
Thermal insulation	30	40	50	100
Primary coolant instrumentation	660	220	1,000	1,000
Steam generator	7,400	-	12,100	28,700
Total	27,300	29,850	35,490	72,830

TABLE B.1 (Continued)

Coolant	Liquid D ₂ O	Boiling H ₂ O	Organic ^(a)	Organic ^(a)
Power, Mwt	3500	3500	3500	8300
<u>Auxiliary Facilities and Building Structures,</u> thousands of \$ (labor at \$4.75/hr)				
Moderator heat exchanger	860	380	520	1,120
Piping for moderator heat exchanger	100	70	80	140
Moderator storage tank	70	90	100	200
Moderator purification system	180	180	180	180
Moderator pumps	110	50	70	170
Coolant makeup system	130	130	60	110
Coolant purification system	290	240	60	80
Moderator makeup system	60	60	60	110
D ₂ O distillation system	340	340	170	340
Shutdown coolers	-	40	90	290
Off-gas recombination system	550	550	550	1,100
Liquid poison system	230	230	230	270
Internal structures	3,600	2,600	2,600	6,200
Heating and air conditioning	210	200	310	440
Waste disposal	800	800	880	1,800
Reactor building crane	60	130	80	120
Coolant storage tank	80	70	250	440
Land and land rights	400	400	400	400
Access roads and ground improvements	600	600	600	600
Misc. structures	520	520	520	720
External fuel handling	2,400	2,400	2,400	3,300
Containment vessel	3,300	3,900	2,500	2,320
Containment vessel substructure	1,200	1,600	2,200	2,430
Misc. systems and piping	2,600	2,600	2,600	3,700
Containment vessel externals	280	420	540	460
Shadow shielding	650	550	740	840
Waste gas handling system	-	-	130	220
Steam tracing system	-	-	120	170
Coolant particulate removal system	-	-	100	130
Organic degassification and pressurizing system	-	-	180	270
Organic waste disposal system	-	-	100	130
Total	19,620	19,510	19,420	28,800
<u>Turbine Plant Costs, thousands of \$</u>				
(Sargent & Lundy)	28,000	-	-	67,500
(Estimated)	-	35,000	30,000	-
<u>Operating Costs, thousands of \$ per yr</u>				
Organic makeup (15¢/lb)	-	-	1,120	2,610
D ₂ O losses	579	94	90	165
Operating and maintenance (includes interim replacements)	2,130	2,130	2,130	2,500
Total	2,709	2,224	3,340	5,275

TABLE B.2

Preliminary Fuel Cycle Costs

Coolant	Liquid D ₂ O		Boiling H ₂ O		Organic		Organic	
Power, MWt	3500		3500		3500		8300	
Financing, \$/kg U	Private	Municipal	Private	Municipal	Private	Municipal	Private	Municipal
Preparation and fabrication	38.80	38.80	38.80	38.80	27.00	27.00	16.80	16.80
Uranium depletion	48.91	48.91	48.90	48.90	13.00	13.00	13.00	13.00
Shipping	4.00	4.00	4.00	4.00	4.00	4.00	2.50	2.50
Inventory	5.07	2.03	8.90	3.60	1.62	0.65	1.62	0.65
Reprocessing	31.30	31.30	-	-	-	-	15.00	15.00
Total	128.08	125.04	100.60	95.30	45.62	44.65	48.92	47.95
Plutonium credit	35.20	35.20	-	-	-	-	28.40	28.40
Net fuel cost	92.88	89.84	-	-	-	-	20.52	19.55
Annual fuel cost, \$/yr	6,700,000	6,500,000	8,600,000	8,200,000	6,600,000	6,400,000	6,100,000	5,800,000
Average exposure, MWD/tonne U	15,000	15,000	13,000	13,000	7,400	7,400	8,500	8,500
Throughput, tonnes/yr	72.1	72.1	85.2	85.2	143	143	298	298

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TABLE B.3

Fuel Cycle Characteristics

Coolant	Liquid D ₂ O		Boiling H ₂ O		Organic		Organic	
Power, MWt	3500		3500		3500		8300	
Region	<u>Outer</u>	<u>Inner</u>	<u>Outer</u>	<u>Inner</u>	<u>Outer</u>	<u>Inner</u>	<u>Outer</u>	<u>Inner</u>
Average exposure, MWD/tonne U	13,000	17,000	12,000	15,000	6,700	9,000	7,300	9,800
Throughput, tonnes/yr	49.6	22.5	65.3	19.9	110	33.3	191	107
Spent fuel assay, g/kg U								
U ²³⁵	0.24	0.12	3.17	2.00	2.64	1.89	2.42	1.69
Pu ²³⁹	3.04	3.01	2.95	3.00	2.65	2.79	2.70	2.81
Pu ²⁴⁰	1.50	2.01	1.21	1.64	0.97	1.37	1.08	1.50
Pu ²⁴¹	0.31	0.41	0.24	0.34	0.15	0.22	0.17	0.24
Pu ²⁴²	0.15	0.31	0.09	0.18	0.05	0.10	0.06	0.12
Total Pu	5.00	5.74	4.49	5.16	3.82	4.48	4.01	4.67

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