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CONCEPTUAL DESIGN DESCRIPTION

3000-kWe SUBSEA NUCLEAR POWER PLANT

ERDA Research and Development Report

*Prepared for the United States
Energy Research and Development Administration
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Rockwell International

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I. INTRODUCTION

This report describes the conceptual design and performance of a subsea nuclear power system for application in offshore oil and gas production. The system can be designed and built with minimum additional development, based on space nuclear power technology, components, and systems completed during the past 20 years. The concept is particularly well suited to meet the requirements of the offshore oil application for adequate safety, high reliability, and acceptable costs.

The system is designed to provide 3000 kWe power to oil pumps, at 4160 V, and 60 Hz, for a period of 4 years, in an automatic, unattended mode. At the end of this period, the system is returned to a refurbishment center, where the reactor core is replaced and other parts of the systems are inspected, refurbished, or replaced, as required. With this periodic refueling and maintenance, the total system design life is 20 years.

The nuclear power system is largely contained within two separate pressure vessels, connected by an enclosed pipe chase. One vessel contains the reactor and liquid metal primary coolant system, while the other contains the organic Rankine power conversion systems. These modules are mounted on a barge which provides both a means to transport the system and a mounting structure for the sea floor installation. A waste heat exchanger is mounted on the deck of the barge.

The nuclear power system is designed for unattended operations. It can be operated automatically in a load-following mode, or controlled remotely with the use of supervisory and instrumentation circuits.

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II. OVERALL PLANT DESCRIPTION

A. DESIGN REQUIREMENTS

1. Power Level

The nominal system power level shall be 3000 kWe net electrical power at 60 Hz, 4160 V.

2. Design Life

The overall plant design life will be 20 years. Reactor refueling and plant refurbishment will be performed at 4-year intervals.

3. Operation Modes

The plant will be capable of remote operation, in an automatic or semi-automatic mode, while installed on the ocean floor. Load-following capability will be provided. Normal operation is performed while unattended, but access to the generator module during operation will be possible. Access to the reactor module during operation is not required.

4. Structural Requirements

The reactor module and generator module pressure vessels and connecting pipe chase will be designed to withstand the pressure environment at an ocean depth of 1500 ft.

5. Development Requirements

The system will use existing technology and standard components wherever possible. Component development will be minimized and will consist primarily of component testing.

6. System Configuration

The system will be self-contained and capable of being transported from a base site to an operating site. It will contain the necessary ballast tanks and winches for installation and retrieval from the ocean floor.

7. Maintenance Requirements

The system will be of modular construction for ease of maintenance, refueling, and refurbishment.

8. Safety Requirements

The plant will be designed in accordance with the Nuclear Regulatory Commission's General Design Criteria for Nuclear Power Plant Construction Permits, as given in the Code of Federal Regulations, Title 10, Part 50 (10 CFR 50). The radiation shield will be designed to meet the following requirements.

- 1) Limit the radioactivity induced in the surrounding sea water to levels permitted by current regulations (10 CFR 20)
- 2) Limit the radiation intensities in the generator module, during operation, to levels that permit occupancy for reasonable periods for monitoring or maintenance activities
- 3) Minimize neutron activation of the pressure vessel, boiler, pump, control rod drive units, volume accumulators, and piping manifolds so that replacement and refurbishment of the system will not require undue precautions with respect to radiation levels.

9. Surveillance and In-Service Inspection Requirements

Inspection and surveillance during operation are not expected; however, capability for inspection of pressure boundaries during system refurbishment will be provided.

10. Codes and Standards

The reactor and generator module vessels and connecting pipe chase will be designed in accordance with Section III, Division 1 of the ASME Boiler and Pressure Vessel Code. The generator module vessel will also be designed in accordance with the American Bureau of Shipping codes for manned subsea habitats.

ANSI, ASME, IEEE, and other applicable nationally recognized codes and standards will be used in the design, manufacture, construction, and operation of the systems and components.

B. PERFORMANCE CHARACTERISTICS

The power system is designed to deliver 3000 kWe-net electrical power to oil pumps located on the ocean floor for a period of 4 years between reactor refuelings. Thermal power is supplied by a zirconium hydride (ZrH) nuclear reactor. An organic Rankine cycle converts the thermal power to electrical power.

Figure 1 is a schematic of the overall power system cycle, including powers, temperatures, pressures, efficiencies, and flow rates for all cycle components. Table 1 lists the performance characteristics for the complete power system.

The reactor generates 10.4 MWt of thermal power, and is cooled by liquid metal NaK which enters the reactor at 600°F and leaves at 800°F. The hot NaK flows to a heat exchanger where it heats the toluene organic working fluid. An ac helical induction EM pump is used to transport the NaK through the loop. Expansion tanks are employed to accommodate volume changes in the NaK at various temperatures. The design provides for 200 kWt, or 2% of the thermal power in the NaK piping, to be conducted from the piping to sea water. This assures a heat path for reactor decay heat following reactor shutdown.

The toluene fluid receives its thermal power from the heat exchanger in the reactor module and is piped to the generator module. The 689°F vapor is expanded through the turbine which drives the generator. The turbine exhaust vapor is superheated and transfers heat in the regenerator to preheat liquid toluene on the way to the heat exchanger. The vapor then is liquified in the condenser and enters the hotwell. From there, the toluene liquid is pumped up to 650 psia and is passed through the generator, turbine bearings and NaK pump, cooling these heat-generating components. The toluene liquid next enters the regenerator where it is preheated to 366°F. The toluene then enters the heat exchanger where it is heated by the NaK, completing the cycle.

Heat from the condenser is removed by a liquid coolant that carries waste thermal power out of the generator module. Here, the heat is rejected to the sea water by means of a waste heat exchanger. The waste heat exchanger is cooled by the natural convection of surrounding sea water.

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Figure 1. 3000 kWe Subsea Nuclear Power Plant Cycle

TABLE 1
SYSTEM PERFORMANCE CHARACTERISTICS

<u>Powers</u>		<u>Temperatures (° F) (continued)</u>	
Net electrical (MWe)	3.0	Sea water	50
Reactor thermal (MWt)	10.4	Heat rejection system log mean ΔT	27
NaK piping loss (MWt)	0.2	<u>Pressures (psia)</u>	
NaK-toluene heat exchanger (MWt)	10.2	NaK core ΔP	4.0
Turbine work (MW)	3.4	NaK heat exchanger ΔP	3.0
Generator shaft input (MW)	3.3	NaK piping ΔP	3.0
Generator gross (MWe)	3.1	NaK loop ΔP	10.0
Regenerator thermal (MWt)	4.4	Main toluene pump outlet	650
Condenser thermal (MWt)	7.1	Regenerator liquid inlet	640
Heat rejection system (MWt)	7.1	Toluene heat exchanger inlet	605
NaK pump hydraulic (kW)	9.2	Toluene heat exchanger outlet	600
NaK pump input (kWe)	47.3	Turbine inlet	500
Boost pump hydraulic (kW)	2.6	Regenerator vapor inlet	1.50
Boost pump input (kWe)	4.8	Condenser toluene inlet	1.30
Main toluene pump hydraulic (kW)	83.2	Condenser toluene outlet	1.25
Main toluene pump input (kW)	138.7	Boost pump outlet	21
Heat rejection pump hydraulic (kW)	33.0	Heat rejection loop ΔP	40
Heat rejection pump input (kWe)	59.0	<u>Efficiencies (%)</u>	
Generator heat removal (kWt)	163.8	Overall power system	28.8
<u>Temperatures (° F)</u>		Turbine	76.6
NaK reactor inlet	600	Shaft bearing	99.0
NaK reactor outlet	800	Generator	95.0
NaK heat exchanger inlet	798	Regenerator effectiveness	91.0
NaK heat exchanger outlet	602	NaK pump	19.5
Toluene heat exchanger inlet	366	Boost pump	55.0
Toluene heat exchanger outlet	700	Main toluene pump	60.0
Heat exchanger log mean ΔT	157	Heat rejection pump	56.0
Turbine inlet	689	<u>Flow Rates (lb/s)</u>	
Regenerator vapor inlet	458	NaK	235
Regenerator vapor outlet	156	Toluene	36.1
Condenser toluene outlet	108	Heat rejection	281
Main toluene pump outlet	111	Toluene cooling NaK pump	5.8
Regenerator liquid inlet	127	Toluene cooling generator and turbine	30.3
Regenerator liquid outlet	366		
Regenerator log mean ΔT	55		
Condenser coolant inlet	65		
Condenser coolant outlet	95		

C. CONFIGURATION

The power system consists of a reactor module (shown in Figure 2), a generator module (shown in Figure 3), and a waste heat exchanger (shown in Figure 4). The reactor module and generator module are enclosed in steel pressure vessels of a thickness suitable for a 1500-ft ocean depth. The two modules and the heat exchanger are mounted on a barge, as shown in Figure 5.

Shown with the barge is the base, which is permanently installed on the ocean floor at the oil field site. The barge and base are towed together to the site where first the base and then the barge are lowered to the ocean floor by cable and controlled buoyancy. Two winches and four ballast tanks are mounted on the barge for installation and recovery operations. In addition, compartments of both the barge and base may be flooded to provide negative buoyancy.

The reactor module contains the following major components:

- 1) Reactor
- 2) Shield
- 3) Control rod drive system
- 4) NaK piping
- 5) NaK pump
- 6) NaK - toluene heat exchanger
- 7) NaK expansion tank

The generator module contains the following:

- 1) Turbine
- 2) Generator
- 3) Regenerator
- 4) Condenser
- 5) Hotwell
- 6) Toluene pumps and piping
- 7) Controls
- 8) Heat rejection pump and piping

Figure 2. Reactor Module

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Figure 3. Generator Module

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Figure 4. Waste Heat Exchanger

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Figure 5. Barge and Base Layout

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As shown in Figure 2, the reactor module is 10 ft (OD) at the upper end, 8 ft - 6 in. (OD) at the lower end, and is 22-ft long. The vessel cylinder wall thicknesses are 3.5 in. for the 10-ft diameter, and 3.0 in. for the 8-ft 6-in. diameter. The hemispherical heads are 2.375-in. thick for the upper end, and 2-in. thick for the lower end. The reactor module component dimensions are summarized in Table 2.

As shown in Figure 3, the generator module is 15 ft 11-1/4 in. OD and 41 ft 1-1/2 in. in length. The vessel cylinder wall thickness is 5-5/8 in., and the hemispherical heads are 3-3/4 in. thick. The generator module component dimensions are summarized in Table 3.

A 14-in. diameter pipe chase is provided between the reactor and generator modules to contain organic piping and electrical and instrumentation cables. The organic piping consists of the main organic lines between the NaK - toluene heat exchanger in the reactor module and the turbine and regenerator in the generator module, and the NaK pump cooling lines between the NaK pump in the reactor module and the main organic pump and regenerator in the generator module. Electrical lines are provided to supply power to the NaK pump and control rod drive motors. Instrumentation cables are provided between the control panels in the generator module and the reactor and primary loop instrumentation located in the reactor module. The pipe chase is connected to flanges on the reactor and generator module vessels. A loop is provided in the pipe to accommodate thermal expansion.

The waste heat exchanger is located between the reactor and generator modules. It has overall dimensions of 5-ft height by 13.3-ft width by 25.3-ft length. The waste heat exchanger inlet and outlet coolant pipes are connected to flanges on the generator module.

The barge dimensions are 52 ft - 6 in. in width, 79 ft - 2 in. in length, and 16 ft - 6 in. in height from the bottom to deck level. It has a draft of 7 ft - 2 in.

The base dimensions are 60 ft - 6 in. in width, 83 ft - 2 in. in length, and 16 ft in height. The base and barge together have a draft of 9 ft-3 in.

A summary of system and component weights is given in Table 4.

TABLE 2
REACTOR MODULE DIMENSIONS
(1500 ft depth capability)

Component	Dimensions (in.)	Component	Dimensions (in.)
<u>Pressure Vessel</u>		<u>Piping</u>	
Diameter (OD)		8-in. full flow	
Lower end	102	OD	8.625
Upper end	120	ID	7.981
Length	264	Wall thickness	0.322
Side Wall thickness		6-in. half flow	
Lower end	3.0	OD	6.625
Upper end	3.5	ID	6.065
End wall thickness		Wall thickness	0.28
Lower end	2.0	<u>NaK-Toluene Heat</u>	
Upper end	2.375	<u>Exchanger</u>	
<u>Reactor</u>		Overall length	203
Fuel element length	36.2	Active tube length	156
Vessel diameter	48.0	Shell OD	14
Reflector thickness, equivalent	3.75	Shell wall thickness	0.438
Fuel assembly across flats	6.541	Tube OD	0.313
Fuel element OD	0.637	Tube wall thickness	0.020
Fuel element pitch	0.659	Tube pitch	0.477
Cladding thickness	0.025	<u>Expansion Tank (2)</u>	
Control rod OD	2.64	Tank length	28
<u>Shield</u>		Tank OD	32
Borated stainless steel (side only)	5.19	Tank wall thickness	0.375
Serpentine concrete		<u>NaK Pump</u>	
Side and bottom	24	Diameter	22.0
Top	40	Length	57.0
		Iron stack length	36.0
		Stator base	12.0
		Magnetic gap	1.525
		NaK duct gap	1.30

TABLE 3
GENERATOR MODULE DIMENSIONS
(1500 ft depth capability)

Component	Dimensions (in.)	Component	Dimensions (in.)
<u>Turbine</u>		<u>Condenser</u>	
Casing OD	92	Height	98
Pitch line diameter	75	Width	98
Length	21	Thickness	25
<u>Generator</u>		Tube OD	0.375
Height	88.0	Tube wall thickness	0.025
Width	70.6	Fin thickness	0.018
Length	156.2	Fins/in.	8.7
<u>Regenerator</u>		Tube pitch	
Height	98	Vertical	0.80
Width	98	Lateral	0.975
Thickness	27	<u>Pressure Vessel</u>	
Tube OD	0.375	Diameter (OD)	191.25
Tube wall thickness	0.025	Length	493.5
Fin thickness	0.018	Side wall thickness	5.625
Fins/in.	8.7	End wall thickness	3.75
Tube pitch			
Vertical	0.80		
Lateral	0.975		

TABLE 4
SYSTEM WEIGHT SUMMARY

System	Weight (lb)
Reactor Module	
Pressure vessel	108,300
Shield	103,100
Core	7,700
Drive mechanisms	1,000
NaK piping system	1,800
NaK pump	4,900
Core vessel	8,300
Heat exchanger	4,100
Structure, miscellaneous	<u>2,800</u>
Total	242,000
Generator Module	
Pressure vessel	451,000
Turbine generator	26,500
Regenerator and condenser	11,500
Piping systems	6,000
Batteries, wiring, etc.	44,000
Structure, miscellaneous	<u>7,000</u>
Total	546,000
Sea Water Heat Exchanger	
Piping, coolant	87,600
Structure, miscellaneous	<u>2,000</u>
Total	89,600
Barge	
Hull	800,000
Ballast tanks	88,000
Downhaul winch system	<u>60,000</u>
Total	948,000
Base	<u>1,078,400</u>
System Total	2,904,000

III. REACTOR MODULE COMPONENTS

A. UNITIZED CORE ASSEMBLY

The reactor core, core vessel, control rod drive shafts, bellows seals, and top shield plug are designed to be handled as a unit. The unitized core assembly, shown in Figure 6, is 3 ft 5-1/2 in. in diameter by 11 ft in height, and weighs 14,500 lb. After removing the control rod drive units and bolting a control rod retainer plate in place, the entire assembly can be removed by a shielded handling cask for subsequent dismantlement in a hot cell.

The unitized core assembly contains the 19 fuel assemblies, 19 control rods, and 18 beryllium radial reflector pieces, held in place by upper and lower grid plates bolted to the core barrel. The reactor core is suspended from the top shield plug by six hanger rods. The space between the reactor core and top shield plug is provided for the control rod drive shafts and bellows seals.

B. REACTOR CORE

1. Fuel Element

The fuel element (or fuel pin) is shown schematically in Figure 7. Each fuel element consists of a 1.5-in. long x 0.570-in. diameter bottom reflector slug, 28 in. of segmented fuel slugs (seven 4-in. long x 0.570-in. diameter), and a 1.5-in. long x 0.570-in. diameter top reflector slug, within a 25-mil thick x 0.637-in. OD stainless-steel cladding tube sealed by welded top and bottom end plugs. The 8.5-mil thick annular clearance between fuel and cladding tube, which is provided to accommodate fuel swelling, is filled with NaK to provide a good thermal bond. A 3-in. gas space, initially back-filled with helium to approximately 3 psia, is provided above the top reflector slug to accommodate the NaK thermal expansion and the NaK displaced by fuel swelling. Each element has a 20-mil diameter spiral wire wrap on a 6-in. pitch to provide element-to-element spacing and to promote channel-to-channel mixing within the fuel assemblies.

The top and bottom reflector slugs are made of beryllium metal. The fuel slugs are made from 10.5 wt % uranium-zirconium metal and are hydrided to

Figure 6. Unitized Core Assembly

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Figure 7. Fuel Element

an H/Zr ratio of 1.65. The uranium is enriched to 63% U^{235} . The cladding, end plugs, and wire wrap are made of Type 304 stainless steel.

2. Fuel Assembly

The fuel assembly layout is shown in Figure 8. A cross-sectional view is shown in Figure 9. Each fuel assembly consists of 72 fuel elements arranged on a 0.6585-in. triangular pitch between two 35-mil wall hexagonal shaped ducts. The outer duct is 6.541 in. OD across flats and the inner duct is 2.83 in. OD. The fuel elements are positioned within the assemblies by the upper and lower grid plates and the locating pins at each end of the fuel elements. Lock wires through the lower locating pins hold the fuel elements in place and prevent rotation. Flow holes are provided in the grid plates to allow for proper coolant distribution to the fuel elements. Inlet and outlet nozzles are provided at the ends of the assemblies, which allow the assemblies to be positioned between the reactor grid plates. The inlet nozzle also contains a fuel handling head.

The ducts, grid plates, and nozzles are made of Type 304 stainless steel.

The space inside the inner hexagonal duct is provided for location of the reactor control rods. All 19 assemblies in the reactor core contain a control rod.

3. Control Rods

The core reactivity is controlled by 19 boron carbide control rods which are located in the center ducts of the 19 fuel assemblies. The outer 18 control rods are grouped into six gangs of three rods each. The center rod is operated individually.

The poison material is naturally enriched (19.8% B^{10}) boron carbide in the form of hot-pressed pellets. The pellets are 2.47 in. in diameter and 2.8-in. long and have a density of 95% of theoretical. The chemical form of the material is stoichiometric B_4C . The 28-in. long stacks of pellets are contained in 2.64-in. OD by 80-mil wall Type 304 stainless-steel tubes. The control rods are sealed in order to contain the helium produced by the $B^{10}(n,\alpha)Li^7$ reaction. A 10-mil diametral gap between the pellets and cladding is provided for fabrication tolerances and to accommodate the irradiation induced swelling of the

Figure 8. Fuel Assembly

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Figure 9. Fuel Assembly Cross Section

boron carbide. The thermal bond is helium gas initially loaded to ~ 3 psia. The helium gas pressure will increase during reactor operation due to the release from the B_4C pellets of some of the helium produced from neutron capture. A 10-in. long gas plenum is provided above the pellet stack to accumulate the released gas.

The NaK coolant flow to the control rods is provided through an orifice at the lower end of the center duct of the fuel assembly. Required flow rate, as well as control rod heat generation rate, has not yet been determined; however, it has been estimated that the required flow is $\sim 1\%$ of the fuel assembly flow.

4. Reactor Design Summary

A summary of the reactor core component design parameters is given in Table 5.

5. Nuclear Performance

A summary of the reactor nuclear performance is given in Table 6. The reactor has a beginning-of-life (BOL) cold, clean excess reactivity of $\$27.23$. The reactivity loss from room temperature to full power, after equilibrium xenon 135 and hydrogen redistribution have been achieved, is $\$5.44$. The reactivity loss due to uranium burnup, fission products, and hydrogen loss is $\$21.29$ for four years full power operation. This leaves an end-of-life (EOL) reactivity margin of $\$0.50$. A detailed breakdown of the reactivity requirements is given in Table 7. The reactivity gain from U^{238} burnout and Pu^{239} buildup is indicated as a negative reactivity loss.

The 19 B_4C control rods provide a total control worth of $\$33.53$ which gives a cold BOL shutdown margin of $\$6.30$. Assuming failure of one control rod drive with three rods in the full out position, the cold BOL shutdown margin is $\$1.01$.

6. Thermal-Hydraulic Performance

A summary of the main core thermal-hydraulic performance parameters is given in Table 8. These parameters must be considered as preliminary because detailed thermal-hydraulic analyses have not been performed. The radial and axial power peaking factors will be a strong function of control rod manipulation. The values listed should be achievable with proper control rod management.

TABLE 5
REACTOR DESIGN SUMMARY

Core	
Number of fuel assemblies	19
Fuel assembly pitch (in.)	6.581
Spacing (mils)	40
Distance across flats (in.)	6.541
Duct wall thickness (inner and outer) (mils)	35
Equivalent core diameter (in.)	30.12
Core barrel ID (in.)	37.375
Active fuel length (in.)	28
Active core volume (liters)	327
Fissile mass (kg U ²³⁵)	63.6
Fuel Assembly	
Number of fuel elements	72
Fuel element pitch (in.)	0.6585
Wire wrap diameter (mils)	20
Fuel element OD (in.)	0.637
Cladding thickness (mils)	25
NaK bond thickness (mils)	8.5
Fuel diameter (in.)	0.570
Uranium (wt %)	10.5
Uranium enrichment (%)	63
Initial H/Zr ratio	1.65
Cladding material	Type 304 SS
Control Rod	
Number of control rods	19
Number of rod drives	7
Poison material	B ₄ C
Pellet density (gm/cm ³)	2.4
Poison diameter (in.)	2.47
Cladding thickness (mils)	80
Control rod OD (in.)	2.64
Cladding material	Type 304 SS
Reflector	
Number of radial reflector elements	18
Reflector material	Be
Equivalent radial reflector thickness (in.)	3.5
Axial reflector thickness (in.)	1.5

TABLE 6
REACTOR NUCLEAR PERFORMANCE
(\$)

Cold, clean reactivity	27.23
Recoverable losses	5.44
Hot reactivity	21.79
Nonrecoverable losses	21.29
EOL reactivity margin	0.50
Control worth	33.53
BOL shutdown margin	6.30
Worth of 3 rods	5.29
BOL shutdown margin with 3 rods out	1.01

TABLE 7
REACTIVITY REQUIREMENTS
(\$)

Temperature defect	1.26
Power defect	0.53
Xenon 135	2.32
Hydrogen redistribution	<u>1.33</u>
Total Recoverable Losses	5.44
U ²³⁵ burnout	15.48
U ²³⁶ buildup	2.17
U ²³⁸ burnout	-1.20
Pu ²³⁹ buildup	-4.83
Fission products	7.12
Equilibrium Sm-149	1.05
Hydrogen loss	<u>1.50</u>
Total Nonrecoverable Losses	<u>21.29</u>
Total Requirements	26.73

TABLE 8
CORE THERMAL-HYDRAULIC PERFORMANCE

Reactor power (MWt)	10.4
Core outlet temperature (°F)	800
Core inlet temperature (°F)	600
Coolant flow rate (lb/s)	235
Coolant velocity (ft/s)	5.7
Core pressure drop (psi)	4.0
Average fuel temperature (°F)	775
Peak fuel temperature (°F)	965
Average power density (kW/liter)	32.1
Average specific power (kW/kg U ²³⁵)	165.1
Peak linear rod power (kW/ft)	6.4
Average burnup (metal atom %)	0.74
Peak burnup (metal atom %)	1.4
Radial peak-to-average power	1.3
Axial peak-to-average power	1.5

C. CONTROL ROD DRIVE UNITS

The reactor has seven control rod drive units mounted atop the shield plug as seen in Figure 2. The center unit is used to drive only the center control rod. The other six units each drive a gang of three absorber rods.

The drive unit, shown in Figure 10, uses a rack and pinion mechanism driven by a 1/15 hp motor. A worm gear on the drive motor shaft drives a spur gear mounted on the hub of the armature of a magnetic clutch coupling. Attached to the rotor portion of the magnetic clutch is a shaft on which the pinion is mounted. During normal operation, the magnetic clutch coupling is energized. When a scram is signaled, the magnetic clutch coupling is deenergized allowing the armature to detach from the rotor core. A 10-turn potentiometer, which is used to indicate the position of the absorber rod, is driven by the rack through a separate pinion gear. A limit switch driven by the rack prevents rod overtravel.

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Figure 10. Control Rod Drive Unit

A hydroformed nesting metal bellows is used on the control rod drive shaft to provide a seal between the NaK coolant and the nitrogen atmosphere inside the reactor module. The bellows used is 4.44 in. OD x 3.56 in. ID and has 255 convolutions. It has two plys, with each ply formed from 8-mil thick Inconel 718.

One control rod gang of three absorber rods, drive extensions, and bellows has a weight of 168 lb. The calculated scram time for the full 28-in. travel is 0.84 s after the magnetic clutch circuit opens. The control rods reach a peak velocity during scram of 47 ft/s. Design and location of a snubber have not been determined

A summary of the control rod drive system design is given in Table 9.

TABLE 9
CONTROL ROD DRIVE SYSTEM – DESIGN SUMMARY

Number of drive units	7
Drive unit type	Rack and Pinion
Drive unit size (in.)	7-1/2 x 9-3/16 x 36
Withdrawal and insertion rates (in. /min)	4
Scram mechanism	Magnetic Clutch
Scram time (s)	0.84
Maximum absorber velocity (ft/s)	47
Weight of 3 rod gang and drive train (lb)	168
System seal	Bellows
Drive unit environment	N ₂ @ 150°F
Position indicator	Potentiometer

D. RADIATION SHIELD

The radiation shield in the reactor module is made of serpentine concrete, which is a type of concrete made from Portland cement and an aggregate of crushed serpentine rock. Serpentine rock is a mineral of asbestos having a fairly extensive distribution throughout the world. It is essentially a hydrous magnesium silicate with the formula $3\text{MgO} \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$. The water of hydration

in serpentine rock amounts to about 13.5 wt %. A characteristic of this molecule is that it has the ability to retain its water of crystallization to much higher temperatures than is normally the case with hydrated molecules.

Table 10 presents some of the physical properties of serpentine concrete; Table 11 presents its composition. Figure 11 presents the water retention capability of serpentine concrete as a function of both temperature and time.

TABLE 10
PHYSICAL PROPERTIES OF SERPENTINE CONCRETE

Density [gm/cm^3 (lb/ft^3)]	2.06 to 2.2 (130 to 140)
Thermal Conductivity (Btu/hr-ft-°F)	~ 0.5
Coefficient of expansion, per °F	$\sim 18 \times 10^{-6}$
Compressive strength (psi)	1900 to 2300

TABLE 11
COMPOSITION OF SERPENTINE CONCRETE

Element	Composition (wt %)
O	51.2
Si	20.9
Mg	13.5
Ca	6.8
Fe	3.1
Al	1.9
H	1.6
Others	1.0

The side and bottom concrete shielding is 24-in. thick. It is contained between the pressure vessel and an inner liner which are both made of ASME - A516 carbon steel. This shield thickness limits the dose rate at the reactor module pressure vessel surface during full-power operation to 800 rem/h. The dose rate vs distance from the vessel surface is shown in Figure 12.

Figure 11. Water Retention in Serpentine Concrete vs Heating Time and Temperature

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Figure 12. Dose Rate at Full Power vs Sea Water Distance
from Reactor Module Pressure Vessel Surface

In order to limit the maximum temperature of the concrete to less than 800°F during operation, a borated stainless steel thermal shield is located between the radial beryllium reflector and the concrete shield. The thermal shield is 5-3/16 in. thick and has a boron content of 1.0 wt %. The temperature distribution in the serpentine concrete during full power operation is shown in Figure 13.

The top shield plug is 40-in. thick, and is also made of serpentine concrete. It is contained in Type 304 stainless steel. This shield thickness is required to limit neutron activation of equipment located in the top head of the reactor module to levels that will permit unlimited access for maintenance during system refurbishment.

During reactor operation, the NaK reactor coolant becomes radioactive. The radioisotopes are produced by neutron interactions with the coolant material in the reactor. The most important activation reactions in NaK involve the capture of neutrons by Na^{23} (100% isotopic abundance) to produce Na^{24} , and by K^{41} (6.91% isotopic abundance) to produce K^{42} . Na^{24} decays by beta emission with a half-life of 15.0 h and emits one 2.75 MeV and one 1.37 MeV gamma ray per disintegration. K^{42} also decays by beta emission with a half-life of 12.4 h and emits a 1.52 MeV gamma ray in 18% of the disintegrations.

The Na^{24} activity was calculated to be 0.78 Ci/kWt and the K^{42} activity was calculated to be 0.32 Ci/kWt. The dose rate during operation and after shutdown at a distance of 5 ft from the reactor module is shown in Figure 14. Curves are given for the dose rate when the reactor module is submerged and when it is in air.

E. LIQUID METAL COMPONENTS

1. NaK Piping

The NaK piping (Figure 15) is all-welded construction of Schedule 40, Type 304 stainless steel, seamless pipe. The 800°F NaK leaves the reactor vessel in two 6-in. pipes that are 68-in. long. These pipes then join to form the 8-in. reactor outlet manifold pipe that is 91-in. long. The manifold spans a 103° arc in a horizontal plane beneath the two expansion compensator tanks. The two NaK flow streams enter each end of the manifold, meet at the center,

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Figure 13. Temperature in Serpentine Concrete Shield

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Figure 14. Radiation Level at 5 ft from Pressure Vessel vs Time After Shutdown

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Figure 15. NaK Piping

and leave as a combined flow in an 8-in. diameter, 90-in. long pipe, arriving at the NaK-toluene heat exchanger.

From the heat exchanger, the 600°F NaK continues in an 8-in. pipe for a distance of 33 in. to reach the electromagnetic pump. The NaK leaves the pump in an 8-in. diameter, 41-in. long pipe and arrives at the reactor inlet manifold.

The reactor inlet manifold is a mirror image of the outlet manifold. It spans a 103° arc, is an 8-in. diameter, 91-in. long pipe, and is in the same horizontal plane as the outlet manifold. The flow enters the center of the manifold, splits and flows to either end, and enters the reactor inlet piping. The inlet piping consists of two 6-in. pipes that are 150 in. in length. These pipes bring the flow back to the reactor inlet plenum, completing the loop.

Bellows are employed in the reactor inlet and outlet pipes to accommodate the thermal expansion from ambient to operating temperatures. Bellows are not required in any of the other piping.

All piping is designed to meet the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Nuclear Components. This is a Class 1 component and is evaluated in accordance with Paragraph NB 3600 of the Code.

2. Expansion Compensators

Two expansion compensator tanks are provided in the primary coolant system to accommodate the thermal expansion of the NaK from ambient to operating temperature. Figure 16 shows a schematic of an expansion compensator. The two tanks are located above, and are piped into the reactor outlet manifold. The tanks are 32-in. OD and 28-in. tall, and are constructed of 3/8-in. thick Type 304 stainless steel. Two tanks are provided because they can be more easily located in the reactor module than a single tank.

The change in total NaK volume in the primary system from a temperature of 100°F to the average operating temperature of 700°F is 9.6 ft³. The interior volume of each expansion compensator is 8.6 ft³ for a total capacity of 17.2 ft³. The difference between NaK volume and tank capacity is occupied by an argon cover gas, initially loaded to 2.3 psia, to provide one atmosphere pressurization of the primary loop during operation. The NaK pump requires a minimum inlet pressure of 11 psia to prevent cavitation.

Figure 16. Expansion Compensator

3. NaK Pump

The design of the ac helical induction pump is illustrated in Figure 17. The pump uses a 6-pole design with a 12-in. stator bore and 36-in. active iron stack. The magnetic gap is 1.525 in. and the radial fluid thickness is 1.30 in. A 0.030-in. thick stainless steel cylindrical duct contains the fluid flow through the pump. A 0.020-in. thick cylindrical barrier is in the magnetic gap to provide both double wall protection and separation between the fluid and the windings. Thermal insulation, ~ 0.10 in. thick, is used between the outer duct and the Inconel barrier to reduce the heat flow into the windings.

The overall axial length of the pump is ~ 57 in. The outside diameter is 22 in., including the metallic sleeve covering over the cooling jacket. The estimated total weight of the pump is 4930 lb. The inside diameter of the stator housing is 20.5 in. and its length is 50 in. The only protrusions along the stator housing are the inlet and outlet connections for the cooling fluid.

The operating pump capacity for the NaK at 600° F is 2120 gpm. The pump creates a net head of 10 psi. All fluid flow calculations are based upon the use of two splitters that make two complete revolutions within the 36-in. stack length.

Each coil installed in the 36 slots in the stator is 10-turn and is connected 2 wye. The winding is insulated with Class H insulation.

The pump is cooled by a cooling jacket with ducts machined around the stator housing. The cooling jacket is designed to be capable of transferring the 40,000 W necessary for sufficient cooling of the pump. The cooling fluid is toluene with an inlet temperature of 111° F. The toluene enters the jacket through a single inlet connection and exits through a single connection.

The calculated operating performance characteristics of the pump are given in Table 12.

F. NaK - TOLUENE HEAT EXCHANGER

The reactor thermal power is transferred from the NaK to the toluene working fluid in a U-shaped heat exchanger located at the upper end of the reactor module. The heat exchanger, shown in Figure 18, is of shell and

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Figure 17. ac Helical Induction NaK Pump

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Figure 18. NaK - Toluene Heat Exchanger

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TABLE 12
NaK PUMP PERFORMANCE CHARACTERISTICS

Flow [gpm (lb/s)]	2120 (235)
Head (psi)	10
NaK temperature (° F)	600
Input power (kWe)	47.3
Power factor (%)	29
Voltage (V)	480
Frequency (Hz)	60
Current (amp)	196
Output power (kW)	9.2
Efficiency (%)	19.5

tube design with the high pressure toluene in tubes flowing counter to the NaK on the shell side. The heat exchanger operates above the critical pressure of the toluene so that no phase change occurs as heat is added.

The NaK enters the heat exchanger at 798° F and leaves at 602° F, transferring 10,225 kWt to the toluene. The NaK has a pressure drop of 3.0 psi in the heat exchanger. The toluene enters the heat exchanger at 366° F and is heated to 700° F. It enters at a pressure of 615 psia and loses 5.0 psi in the heat exchanger. The average NaK heat transfer coefficient is 2330 Btu/h-ft²-° F, that of the toluene is 600, and the wall conductance is 8400. Therefore, the mean overall heat transfer coefficient in the heat exchanger is 451 Btu/h-ft²-° F.

The heat exchanger consists of a bundle of 499 Type 304 stainless steel tubes, each having an OD of 5/16 in. and a wall thickness of 0.020 in. The active tube length is 156 in. which leads to a heat transfer area (based on the mean tube diameter) of 496 ft². The tube bundle is contained in a 14-in. diameter, Schedule 40 shell. The overall length of the heat exchanger with headers is 203 in.

The heat exchanger characteristics are given in Table 13.

TABLE 13
NaK - TOLUENE HEAT EXCHANGER CHARACTERISTICS

Heat load (kWt)	10,225
NaK flow (lb/s)	235
Temperature (°F)	
In	798
Out	602
Toluene flow (lb/s)	36.1
Temperature (°F)	
In	366
Out	700
Boiler type	Single-pass countercurrent shell-and-tube
Shell OD (in.)	14
Shell wall thickness (in.)	0.4375
Tube OD (in.)	0.3125
Tube wall thickness (in.)	0.020
Number of tubes	499
Tube pitch (in.)	0.477 - triangular pattern
Tube length (in.)	156
Surface area (ft ²)	496
Tube Side (psi)	
Friction loss	2.9
Tube inlet loss	0.1
Tube outlet loss	0.9
Nozzle losses	<u>1.0</u>
Total pressure drop	4.9
Shell side (psi)	
Friction loss	2.0
Nozzle loss	<u>1.0</u>
Total pressure drop	3.0

G. REACTOR MODULE PRESSURE VESSEL

The reactor module pressure vessel, as shown in Figure 2, is made of ASTM A516, and has a thickness determined for a design depth of 1500 ft. It is flanged at one end for ease of refueling and refurbishment. A small flanged nozzle at the same end is provided for toluene piping and the necessary control and instrumentation leads. A welded lip seal is provided at each flange to insure a watertight structure.

The reactor module vessel is 10 ft (OD) at the upper end, 8 ft - 6 in. (OD) at the lower end, and is 22-ft long. The vessel cylinder wall thicknesses are 3.5 in. for the 10-ft diameter, and 3.0 in. for the 8 ft - 6 in. diameter. The hemispherical heads are 2.375-in. thick for the upper end, and 2-in. thick for the lower end.

The reactor module vessel is designed to be mounted vertically on the power system barge. A mounting flange is provided for this purpose at the transition region between the large and small diameters. Internal supports transmit the load of the reactor module components to the vessel and barge at the mounting flange location.

The internal atmosphere of the vessel is nitrogen at 14.7 psia. The exterior is provided with corrosion protection by zinc rich epoxy paint plus passive anodic systems.

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IV. GENERATOR MODULE COMPONENTS

A. TURBINE

The turbine is a single stage, supersonic, impulse type which was chosen for its simplicity and reduced costs. The toluene leaves the heat exchanger at 700°F and 600 psia, passes through a throttle valve, and enters the turbine tangentially at 689°F and 500 psia. The vapor is expanded in the turbine to a pressure of 1.50 psia and a temperature of 458°F, and then exhausts axially to the regenerator. Toluene has a high molecular weight which leads to low sonic velocities. The turbine has a design point efficiency of 76.6%, a pitch diameter of 75 in., and a blade height of 5.25 in. It rotates at 3600 rpm, and is directly coupled to a 60-cycle, 3600-rpm generator. The turbine casing has a 92-in. overall diameter, and has a thick wall for protection from turbine blade failure. The turbine characteristics are given in Table 14.

TABLE 14
TURBINE CHARACTERISTICS

Type	Supersonic Impulse
Stages	1
Temperature inlet (°F)	689
Temperature outlet (°F)	458
Pressure inlet (psia)	500
Pressure outlet (psia)	1.50
Efficiency (%)	76.6
Speed (rpm)	3600
Toluene flow rate (lb/s)	36.1
Pitch diameter (in.)	75
Blade height (in.)	5.25
Casing OD (in.)	92

B. GENERATOR

The generator chosen for this application is a General Electric 3600 rpm, 3 phase, 60 Hz, 4160 V, 2-pole synchronous machine. The frame size required is No. 8512, which has the dimensions shown in Figure 19. It receives 3.3 MW

Figure 19. 3000 kWe Synchronous Generator

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of shaft power from the turbine, and delivers 3 MWe to the load with a 95% electrical efficiency. The generator is completely enclosed and is cooled by the toluene condensate, which flows at 30.3 lb/s and removes 163.8 kWt. Table 15 lists the generator characteristics.

TABLE 15
GENERATOR CHARACTERISTICS

Power Input to Shaft (kW)	3276
Gross Electrical Power Output (kWe)	3112
Cooling Requirement (kWt)	163.8
Voltage (V)	4160
Frequency (Hz)	60
Speed (rpm)	3600
Efficiency (%)	95
Number of Poles	2
Length (in.)	156.2
Width (in.)	70.6
Height (in.)	88.0

C. REGENERATOR

The function of the regenerator is to preheat the liquid toluene before it enters the NaK-toluene heat exchanger by means of the hot turbine exhaust vapor. The effect of the regenerator is to increase cycle efficiency by a factor of about 1.5.

The regenerator uses a tube-and-fin heat exchanger matrix; the low pressure hot turbine exhaust vapor flows normal to the tubes and over the fins, while the liquid flows through the tubes. This arrangement is used because the vapor has a low heat transfer coefficient and thereby benefits from the large fin surface area, and at the same time, the tubes safely contain the high pressure liquid. It is important to have a low pressure loss on the vapor side. Studies have shown that a pressure loss of 0.25 psi in the regenerator costs about one point in system efficiency or about 3% in power output. Therefore, the regenerator design evaluation balanced flow area for the vapor flow against the size, weight, and cost of the regenerator and generator module vessel.

The turbine exhaust vapor enters the regenerator at a temperature of 458°F and a pressure of 1.5 psia; it leaves at 156°F and 1.3 psia. The liquid enters at 127°F and 640 psia, and leaves at 366°F and 605 psia. The heat transferred to the liquid is 4.37 MWt.

The regenerator core dimensions are 7.75 ft x 7.75 ft x 1.8 ft. It uses 0.375 in. OD tubes, with a wall thickness of 0.025-in. The fins are 0.018-in. thick, have a height of 0.27 in., and are spaced 0.115 in. center-to-center. The tubes are arranged on a triangular array with a vertical pitch of 0.800 in. and a lateral pitch of 0.975 in. Tubes, fins, and manifolds are constructed of aluminum alloy.

Table 16 lists the characteristics of the regenerator.

TABLE 16
REGENERATOR CHARACTERISTICS

Thermal power (kWt)	4370
Inlet vapor temperature (°F)	458
Outlet vapor temperature (°F)	156
Inlet liquid temperature (°F)	127
Outlet liquid temperature (°F)	366
Regenerator effectiveness	0.91
Inlet vapor pressure (psia)	1.50
Outlet vapor pressure (psia)	1.30
Inlet liquid pressure (psia)	640
Outlet liquid pressure (psia)	605
Vapor and liquid flow rates (lb/s)	36.1
Core dimensions (in.)	22 x 93 x 93
Tube OD (in.)	0.375
Tube wall thickness (in.)	0.025
Vertical pitch (in.)	0.800
Lateral pitch (in.)	0.975
Fin thickness (in.)	0.018
Fin spacing (in.)	0.115
Fin type	Integral Helical

D. CONDENSER

The condenser receives toluene vapor from the regenerator, cools the vapor down to the saturation temperature, condenses the toluene to a liquid, and discharges the liquid to the hot well. The coolant for the condenser is a 50-50 mixture of ethylene glycol and water that circulates between the condenser and the sea water heat exchanger.

The condenser uses the same type tube-and-fin heat exchanger matrix as the regenerator. The toluene flows over the tubes and fins while the coolant flows inside the tubes. This is desirable because the toluene heat transfer benefits from the fins, and a high pressure capability is required in the tubes. If a leak develops in the sea water heat exchanger, the full pressure due to the ocean depth will be contained within the condenser tubes.

The condenser core dimensions are 7.75 ft x 7.75 ft x 1.67 ft. It uses the same size tubes as the regenerator. The condenser has six heat exchanger sections with parallel coolant flow. This arrangement reduces the coolant pressure drop to reasonable levels. The first of these sections desuperheats the vapor, while the remaining five perform condensation. The condensate is collected in a hot well which is situated below the tube banks at the bottom of the condenser. Table 17 lists the characteristics of the condenser.

E. ORGANIC PUMPS

1. Toluene Pumps

The toluene fluid is pumped by a low-pressure (20 psi) boost pump and a high-pressure (630 psi) main pump. The boost pump, which assists during system startup, is driven by a 6.5 hp electric motor. The main pump is driven mechanically by the turbine shaft.

The main pump receives the hot well condensate from the boost pump, and delivers the pressurized fluid in a split stream to the regenerator. The main stream (30.3 lb/s) first cools the turbine bearings and generator before entering the regenerator. The side stream (5.8 lb/s) cools the NaK pump and joins the main stream at the regenerator entrance. The performance characteristics of the toluene pumps are given in Table 18.

TABLE 17
CONDENSER CHARACTERISTICS

Thermal power (kWt)	7100
Core dimensions (in.)	20 x 93 x 93
Vapor inlet temperature (°F)	156
Toluene condensing temperature (°F)	107.5
Coolant inlet temperature (°F)	65
Coolant outlet temperature (°F)	95
Vapor inlet pressure (psia)	1.30
Toluene condensing pressure (psia)	1.25
Coolant pressure drop (psi)	20
Toluene flow rate (lb/s)	36.1
Coolant flow rate (lb/s)	281
Tube OD (in.)	0.375
Tube wall thickness (in.)	0.025
Vertical pitch (in.)	0.800
Lateral pitch (in.)	0.975
Fin thickness (in.)	0.018
Fin spacing (in.)	0.115
Fin type	Integral Helical

TABLE 18
TOLUENE PUMP PERFORMANCE CHARACTERISTICS

Pump	Boost	Main
ΔP (psia)	20	630
Hydraulic efficiency (%)	60	60
Electrical efficiency (%)	92	—
Hydraulic power (kW)	2.64	83.2
Pump motor power (kWe)	4.8	—
Pump shaft power (kW)	4.4	138.7

2. Coolant Pump

The coolant pump circulates a 50% ethylene glycol and 50% water mixture in the waste heat rejection loop between the condenser and the external sea water heat exchanger. The coolant cycles between 65° and 95°F, and transfers 7.1 MWt at a flow rate of 281 lb/s and a ΔP of 40 psia.

The pump is powered by an 80 hp electric motor. The pump performance is given in Table 19.

TABLE 19
COOLANT PUMP PERFORMANCE CHARACTERISTICS

Fluid: % Ethylene Glycol—% Water	50-50
Specific gravity	1.06
Flow rate (lb/s)	281
ΔP (psia)	40
Hydraulic power (kW)	33.0
Electrical power (kWe)	59.0
Hydraulic efficiency (%)	56

F. GENERATOR MODULE PRESSURE VESSEL

The pressure vessel which houses the power conversion system is a horizontal cylinder with hemispherical domed heads at each end (see Figure 3). It is made of ASTM A516; its thickness was determined for a design depth of 1500 ft. The vessel is flanged at one end to facilitate removal of large items of equipment for refurbishment, repair, or replacement. A smaller flanged opening is provided for the pipe chase, which contains piping and instrumentation and control leads from the reactor module. The waste heat exchanger piping also penetrates the module side, and the electrical power leads leave the module through an electrical feedthrough connection.

The generator module vessel is 15 ft 11-1/4 in. OD and has a 5-5/8 in. wall thickness. The hemispherical heads are 3-3/4 in. thick. The total vessel length is 41 ft 1-1/2 in.

As the design and placement of the generator module provides for limited manned entry during reactor operations, a service capsule mating hatch (tea cup) is provided on the top of the pressure vessel. The vessel is designed in accordance with Section III of the ASME Boiler and Pressure Vessel Code for nuclear containment and also in accordance with the American Bureau of Shipping codes for manned subsea habitats.

During operation the vessel is normally pressurized to 14.7 psia with nitrogen, which is replaced with an oxygen atmosphere during servicing periods. The exterior is provided with corrosion protection by zinc rich epoxy paint plus passive anodic systems.

V. WASTE HEAT REJECTION SYSTEM

The waste heat rejection system is a totally closed system, using a low-freezing-point coolant mixture of 50% ethylene glycol and 50% water, which removes 7.1 MW of thermal energy from the condenser and dissipates the energy to the sea water via a tube bundle located on the deck of the barge between the reactor module and the generator module. A sketch of the waste heat exchanger is shown in Figure 4. The tubes have headers to minimize the system pressure drop by providing numerous parallel flow paths. The temperature rise in the waste heat loop is minimized to achieve maximum overall cycle efficiency. Heat rejection is by natural convection of the sea water around the tubes. The tubes are designed to withstand a pressure differential, either internally or externally, equivalent to the hydrostatic head of the sea water at design depth. The system will normally be operated with a slight ΔP across the tube, with the external sea water pressure being slightly higher than the internal coolant pressure.

The coolant mixture enters the condenser at 65°F, and exits at 95°F. It is cooled in the waste heat exchanger by sea water at an assumed temperature of 50°F. The low ΔT requires a flow rate of 281 lb/s to reject the 7.1 MW of thermal energy. The coolant pump supplies the 40 psi pressure necessary to maintain the flow rate through the waste heat exchanger, condenser, and piping.

Based on the performance of undersea heat exchangers and their fouling characteristics, a configuration using 5-ft high vertical tubes having six fins spaced 60° apart was adopted. The tubes are 1.5 in. OD with a 0.05-in. wall thickness. Each fin is 0.227-in. thick and has a height of 0.887 in. The tubes and fins are 90% Copper - 10% Nickel alloy to inhibit salt-water corrosion and marine growth. Tests have indicated that little or no surface fouling will occur on undersea heat exchangers operating at the depths under consideration (500 ft or deeper). Therefore, no fouling allowance was included in the design. Table 20 summarizes the seawater heat exchanger characteristics.

TABLE 20
SEA WATER HEAT EXCHANGER CHARACTERISTICS

Thermal power (kWt)	7100
Coolant inlet temperature (°F)	65
Coolant outlet temperature (°F)	95
Seawater temperature (°F)	50
Coolant flow rate (lb/s)	281
Heat exchanger dimensions (ft)	5 x 13.3 x 25.3
Number of parallel loops	76
Number of tubes per loop	40
Tube OD (in.)	1.5
Tube wall thickness (in.)	0.050
Number of fins per tube	6
Fin height (in.)	0.887
Fin width (in.)	0.227
Tube center-to-center spacing (in.)	4.0
Heat transfer area (ft ²)	17,610
Coolant pressure drop (psi)	20
Coolant: % Ethylene Glycol — % water	50-50
Coolant Velocity (ft/s)	5.3
Fin effectiveness	0.51

VI. CONTROL AND OPERATIONS

The nuclear power system is designed for remote startup, shutdown, and restart. It is also designed to be load-following, although a constant load is expected to be maintained through the use of recirculation in the oil pumps and gas compressors.

Once firmly installed on the sea bottom, and after all power and instrumentation connections have been made and verified, startup of the nuclear system can begin. Startup can be accomplished remotely from the supervisory station, the service vessel, or manually from the operating panel in the generator module.

A diagram of the control system is shown in Figure 20. The major flow, flux, and temperature control loops are routed through the control computer and are reinforced by trim loops for pressure, temperature, flow, and turbine speed control.

A. STARTUP

The startup of the power plant involves bringing the reactor up to low power, preheating the components of the system to their operational temperatures, and then bringing the entire plant to rated operating power. The time for startup is limited by the time required to bring the secondary heat transfer loop to operating temperature, using heat produced by the reactor. This should be ~ 6 to 7 h at 10% power. The reactor power is brought up to some nominal level (10 to 20% full power), and held constant while the secondary loop is heating up. The flow of the NaK is sufficient to assure adequate heat removal capabilities from the core without exceeding the normal temperature rise through the core.

The reactor is brought to power by inserting reactivity through programmed control rod withdrawal. Flux monitors are used to measure the reactor period, which is used in the safety instrumentation to limit the reactivity rate to a preset value. The simplest startup mode is achieved by using a constant rate of reactivity insertion. Should it become desirable to use multiple input reactivity rates to achieve faster startup, the flux monitors can be used to determine the appropriate reactivity rate switching points.

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As the reactor starts producing sensible heat, the turbine bypass valve and the main toluene pump bypass valve are opened, and the boost pump is started, using auxiliary battery power. Heat from the reactor is transferred to the NaK and, as the NaK temperature rises, there will be some heat transfer to the toluene. The rate of increase of temperature of the toluene will be slow at first, since much of the heat transferred to the toluene will be used to heat up the equipment in the secondary loop. This equipment, except for the turbine, will be brought up to temperature along with the toluene. When the temperature and pressure of the toluene have been increased so that vaporization will occur in the boiler, the turbine throttle valve will be opened to admit a small flow of vapor through the turbine bringing the turbine up to temperature. As the turbine temperature increases, the flow of toluene through the turbine is increased, and the flow through the bypass valve is decreased. The main toluene pump is mounted on the turbine shaft, and will come on line as soon as the turbine turns. The pressure at the turbine inlet is controlled by the turbine bypass valve, which is used to accommodate the increased head when the main pump comes on line.

After the turbine is brought up to speed and is synchronized, power is supplied to the plant auxiliaries by the generator. The reactor is then brought up to full power, and external loads are switched to the generator.

B. POWER OPERATIONS

Power is supplied by the nuclear system for pumping oil and/or compressing natural gas, plus operating other electrical equipment in the oil - gas production installation. Power is also supplied to auxiliary and instrumentation and control systems (both the nuclear plant and the production plant). These will operate from a battery-supplied, ac-regulated circuit. The batteries will be connected to the generator to maintain their charge. Therefore, it is not necessary to maintain tight constraints on the generator output. This allows considerable flexibility in the design of the power plant control and instrumentation systems.

The voltage at the output of the generator is maintained constant by controlling the exciter voltage. The frequency of the output is determined by the speed of the turbine shaft, and a mismatch between the load and the power

supplied is reflected in changes of the shaft speed. The accuracy required of the control system is governed by the accuracy required for the shaft speed and the generator frequency. The toluene pump is shaft mounted, and the effects of shaft speed on the pressure and flow rate of the toluene must be considered.

The parameters of principal interest for the proper operation of the power plant are: (1) the reactor outlet temperature, (2) the temperature rise through the reactor core, and (3) the temperature and pressure at the inlet of the turbine.

The turbine is supplied with a throttle valve to regulate the inlet conditions to meet the immediate output requirements. This, together with the heat capacity of the working fluid, supplies the immediate load-following requirements. Pressure at the inlet to the throttle is maintained by opening or closing the turbine bypass valve. Floating proportional control is used to match the reactor power with the load requirements, according to the appropriate partial-load characteristics. A deadband is supplied in the power feedback loop to minimize the necessity of actuating the control rod drive to follow small changes in the load. Small changes are accommodated by changes in the cycle performance due to the throttle and turbine bypass valves actions, and by the negative temperature coefficient of the reactor.

Changes in the load requirements are due to variations in the power requirements for the oil pumps and the possible loss of one or more pumps on line. When the load changes are large, it is necessary to feed back the power requirements to vary the reactor power level. In addition to power matching, variation in the toluene temperature at the boiler outlet is used as a trim control to assure proper operating conditions in the working fluid.

Changing the power in the primary loop requires changing the flux level in the reactor by moving the control rods, and also changing the NaK flow rate to maintain the proper temperature rise through the reactor core. The power feedback from the partial load schedule and boiler outlet temperature trim signals are used to vary the NaK flow rate by controlling the NaK pump. The flux controller also includes a trim signal from the reactor outlet temperature, so that an increase in the reactor outlet temperature above preset limits causes a decrease in the flux level.

C. SHUTDOWN

The nuclear system is designed to be shut down via remote control from the supervisory station or from the service vessel. Manual shutdown capability is also provided for at the control panel in the generator module. An automatic shutdown (scram) system is also provided. This uses 2-out-of-3 coincidence to minimize the possibility of inadvertent scrams. Table 21 lists the parameters which can cause automatic shutdown.

TABLE 21
AUTOMATIC SHUTDOWN SIGNALS

High reactor flux
High reactor outlet temperature
Low reactor coolant flow
Loss of electrical power
Water in the modules
Reactor period (during startup only)
Low toluene flow
Low heat rejection system coolant flow
Acceleration (earthquake)

If the nuclear system is shut down, either manually or automatically, and the reason for the shutdown has been cleared, the system may be restarted by the same procedures used for the initial startup.

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VII. INSTALLATION, RECOVERY, AND REFURBISHMENT

A. INSTALLATION

1. Base and Barge Mating

Assuming that the base and barge sections are launched separately, the two sections are assembled in shallow water of depths to 40 ft. The mating is carried out in the following steps with the use of divers. Cables are paid out from the barge to the base, whose tanks are then flooded causing it to sink to the bottom. The barge is then positioned over the base, and the latter is winched up by the cables until it is joined to the barge. Compressed air is then blown into the tanks of both barge and base, to achieve the desired trim and freeboard needed for towing to the field site.

2. Emplacement

The emplacement method consists of lowering the base section to the ocean floor, securing it, and then winching the barge down onto the base (see Figure 21). The services of divers, surface support vessel, and a diving capsule are required in the following steps:

- 1) The electro-hydraulic control cable is connected from the support vessel to the base. The tanks are flooded until, under the control of the barge winches, the base section sinks to the ocean floor. It is secured by flooding the remaining tanks.
- 2) The hydraulic lines are removed from the base and are connected to the barge's mating tea cup. The soft tanks are flooded, and the barge is lowered to a depth of 100 ft. The hydraulic lines are now transferred to the diving capsule on board the support vessel. The capsule is lowered and mated to the tea cup. After tea cup dewatering, the operators, riding in the capsule, winch the barge down onto the base at the ocean bottom. The barge's remaining tanks are flooded to consolidate its position on the base, and the diving capsule returns to the surface.
- 3) The electric transmission cable pull-in is accomplished by preparing the terminal connection assembly on board the surface support vessel.

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Figure 21. Installation of Subsea Nuclear Power Plant

The assembly is lowered to the barge by crane, and is guided by wires to the corresponding connection port on the generator module. Operators using the diving capsule descend to the barge and enter the generator module's 1-atmosphere environment, where they complete the cable pull-in and connecting operations.

B. RECOVERY

Recovery of the barge with its power station takes place in the reverse order. The surface support vessel and a new or refurbished power station barge are brought to the site. Operators descend with the diving capsule and disconnect the electric transmission cable. Water is blown from the tanks by compressed air supplied by the surface support vessel, and the barge is winched off of the base and raised to a 100-ft depth. The capsule is disengaged, the hydraulic lines are connected to the tea cup, and the barge tanks further blown until the barge surfaces. All lines are transferred to the surface support vessel and the barges are interchanged. The new barge is emplaced and the retrieved barge is returned for refurbishment.

C. REFURBISHMENT

Base site facilities are provided for refueling and refurbishment of the nuclear power systems. (A conceptual base site facility is shown in Figure 22.) A barge docking and wharf-side work area and a dry dock are provided. Adjoining facilities include a machine shop, hot cell, fuel storage vaults, core assembly room, repair area, and administration building. The covered area comprises 36,100 ft² and contains the facility areas, systems, and major equipment listed in Table 22.

Every four years the subsea nuclear station will be refurbished and refueled. After the nuclear power system has been shut down and the barge retrieved from the ocean floor and towed to the base site, the barge is put in dry dock. The unitized core assembly is removed from the pressure shell by use of a shielded cask designed to fit over the top of the core after the reactor module head and control rod drives are removed. The cask is then moved by crane into the hot cell for disassembly of the core assembly. Similarly, all elements of the power conversion system are inspected and refurbished. The

TABLE 22
BASE SITE AREA, SYSTEMS, AND EQUIPMENT

Facility Areas	Ft ²	Systems	Equipment
Administration Area	3,500	Radioactive Exhaust System	Cranes
Repair Area	5,620	Radioactive Drain-Hold Tank System	2 50-tons
Machine Shop	5,000	Liquid Nitrogen System	2 30-tons
Hot Machine Shop	1,610	Argon System	2 5-tons
Dry Dock	12,000	Shop Air Control System	Manipulators and Windows
New Fuel Control	720	Air Conditioning System	2 master-slave manipulators
Operating Personnel Control	660	Communications: (Tel-PA System)	1 crane manipulator
Radioactive Waste and Spent Fuel Vault	1,520	Fire Suppression System	2 windows
New Fuel Storage Vault	1,400	Radioactive NaK Handling System	Machine tools
New Fuel and Core Assembly	1,370	Toluene Handling System	Inspection equipment
Operating Gallery	720	Cooling Water System	Office equipment
Hot Cell	1,370	Compressed Air System	Handling cask
Corridor	700	Dry Dock Dewatering System	
TOTAL	36,200	Personnel Life Support System	
Machine Shop Dock	1,900	X-Ray Dark Room, Film DVL System	
Radioactive Shipping Dock	1,500	Domestic Water System	
Wharf Side Repair Area	3,750	Domestic Sewer System	
Wharf Side Repair Area	6,750	Process Heating System	
TOTAL	13,900	Radioactive Monitoring and Control System	

- LEGEND**
- 1. SUB STATION
 - 2. SECURITY
 - 3. NEW FUEL CONTROL
 - 4. OPERATING PERSONNEL CONTROL
 - 5. NEW FUEL STORAGE VAULT
 - 6. RADIOACTIVE WASTE & SPENT FUEL VAULT
 - 7. WHARF SIDE WORK AREA
 - 8. NEW FUEL & CORE ASSEMBLY
 - 9. DRY DOCK
 - 10. CONTROLLED ACCESS MACHINE SHOP
 - 11. MACHINE SHOP
 - 12. ADMINISTRATIVE AREA
 - 13. GENERAL REPAIR AREA
 - 14. DOCK
 - 15. HOT CELL
 - 16. OPERATING GALLERY
 - 17. PARKING

Figure 22. Base Site Facility.

spent fuel assemblies and other radioactive wastes are stored and periodically placed in casks for shipment to a processing facility.

All equipment remaining on the barge, including the pressure shells, is refurbished. Should the pressure shells require replacement, heavy duty portable cranes will be brought to the facility.

In summary, the base site will provide the facilities necessary for the following major activities:

- 1) Final assembly of the reactor module, the generator module, and the waste heat exchanger; installation of these systems on the barge.
- 2) Receipt, inspection, and storage of new fuel assemblies.
- 3) Loading fuel assemblies into the reactor core vessel.
- 4) Final closure of the reactor vessel.
- 5) Loading NaK into the reactor primary system.
- 6) Performing dry and wet low-power criticality tests and final checkout of reactor systems.
- 7) Installing main pipe chase containing instrumentation and control cables and organic piping; completing connections and closures in reactor and generator modules.
- 8) Filling power conversion system and waste heat rejection system with organic fluids.
- 9) Performing final system checkouts.
- 10) Receiving spent barge-mounted nuclear generating stations (after four years operation at offshore production site).
- 11) Visual inspection of dry dock barge.
- 12) Draining power conversion system and waste heat rejection system of organic fluids, and back-flush, clean, and seal; storing or disposing of fluids.
- 13) Disconnecting instrumentation and control cables, organic piping, and pipe chase.

- 14) Draining NaK from primary coolant system, and back-filling with nitrogen.
- 15) Removing reactor module head and control rod drive mechanism.
- 16) Removing unitized core assembly into shielding cask.
- 17) Moving shielding cask to shielded, atmosphere-controlled hot cell.
- 18) Removing spent fuel assemblies, moving to spent fuel storage, and preparing for shipment.
- 19) Inspecting and testing reactor vessel, pressure vessel, and head.
- 20) Refurbishing reactor system components.
- 21) Installing new fuel assemblies and control rods.
- 22) Refurbishing power conversion system and waste heat exchanger.