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UNDERSEA THERMIONIC REACTORS

by

D. T. Allen, H. C. Carney, C. R. Fisher,
D. J. Heisser, W. G. Homeyer, W. D. Leech,
A. C. Marshall, M. H. Merrill,
and E. J. Steeger

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FOREWORD

Thermionic reactor development has been carried on in the United States for about 13 years. This work has resulted in a large body of knowledge comprising the technology of the thermionic fuel element. The thermionic fuel element has demonstrated a lifetime of 5000 hours and 10,000 hours life is expected by next year with a power production of about one kilowatt per fuel element.

The TRIGA reactor is a water-cooled reactor with a core of hydrided, uranium-zirconium alloy fuel elements. These reactors are normally used in a swimming pool configuration and are the most widely accepted research, training, and test reactor with over 40 units in use all over the world. A TRIGA Mark III reactor is used extensively by Gulf General Atomic in irradiation testing of the thermionic fuel elements. The reactor is licensed to test up to 15 thermionic fuel elements or fuel-clad capsules simultaneously and it has been operated with 10 devices in the core.

Several years ago it was observed that a TRIGA reactor with power producing thermionic fuel elements in the core was, indeed, a power reactor. A water-cooled power plant, based on this concept, was envisioned. The simplicity of the concept, the possibility for silent operation, and the inherent safety of TRIGA reactors could be used in a small power reactor in remote locations, possibly unattended.

Recently the Atomic Energy Commission funded a study to evaluate the concept for undersea service. The evaluation included cost and development areas. The results of this study are given in this document. It is expected that these results will stimulate potential users of such a reactor to specify requirements so that further studies may be more closely directed toward specific applications.

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ABSTRACT

Two reactor power systems designed for undersea application are described. Each reactor incorporates incore thermionic fuel elements (TFEs) for the direct conversion of fission heat to electricity. The fuel elements are similar in design to those being developed and tested for application to space nuclear power plants. The remainder of the reactor core in each design is composed of TRIGA type U-ZrH fuel elements. Both cores are water cooled.

The first of the two conceptual designs is a compact, lightweight plant called NEMO. It is rated at 30 kWe output and is cooled by forced convection. The power plant is intended for manned application with periodic maintenance.

The second reactor power system design is the Thermionic Reactor for Installed Oceanic Service (TRIOS) which is intended for unattended power generation of 5 kWe net for 10,000 hours without maintenance. This reactor is an extension of the TRIGA pool-type design to undersea operation on the ocean floor.

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1. INTRODUCTION

This topical report summarizes the results of a study of thermionic reactor system designs for undersea electric power. It appears entirely feasible that the advantages of thermionic direct conversion such as low specific mass, reliability and compactness can be made to apply as well in hydrospace as in outer space.

Baseline designs are presented for two undersea power plants. The first power plant embodies a compact, 30 kWe thermionic reactor. This plant is called NEMO (Nuclear Electricity for Marine Operations). The reactor employs the TRIGA* type U-ZrH rods as driver fuel.** It has 33 thermionic fuel elements (TFEs) and 73 U-ZrH rods. Core cooling is by forced convection, and heat exchange to sea water is via a tube-in-shell heat exchanger. The result is a compact power plant.

The second is a 5 kWe power plant and similar to a TRIGA reactor. The Thermionic Test Reactor (Ref. 2.1) (TITR) is such a reactor, and it has been operating at Gulf General Atomic for eight years (for one year with FLIP fuel) in the USAEC's thermionic reactor development program. The reactor core is predominantly U-ZrH fuel rods cooled by water in natural convection. This power plant incorporates 9 TFE's and conditions the electrical power output to user requirements. Flow in both reactor primary and secondary coolant loops is by natural convection. Heat transfer to the sea is also by natural convection. This power plant is expected to find application to sea bottom installations and is termed the Thermionic Reactor for Installed Oceanic Service (TRIOS). The design was conceived with particular emphasis placed on reliable maintenance free operation.

* TRIGA reactors are the most widely used research reactors, with more than forty in operation around the world. The TRIGA fuel elements and reactors are discussed in Appendix A.

** The term "driver fuel" in thermionic reactor systems refers to any fuel elements other than the thermionic fuel elements which are used to make the system critical.

Both power plants are designed to conform to the governmental regulations (Ref. 2.2) for commercial power producing reactors for operation in the jurisdiction of the USA. No safety problems are expected for either concept.

The technology required for these reactor power systems is available now. A development testing program is described leading to power system construction. A timetable for this testing program is included along with engineering cost estimates.

2. THE LIGHTWEIGHT, COMPACT POWER PLANT(NEMO)

2.1 DESIGN REQUIREMENTS

The NEMO power system is intended for use undersea in applications where light weight and compactness are important. The system as a portable power supply is depicted on the sketch in Figure 2.1. Radiation dose rates near the power plant are such that it can be integrated with a manned system. With suitable precautions for radiation monitoring, it can be operated up to full power just below the surface at the side of a dock or ship.

Maximum depth of operations is 416 m (1364 ft) in this design. At this depth, the ambient pressure equals the minimum internal pressure of the Primary coolant loop $4.14 (10)^6 \text{ N/m}^2$ (600 psi) . The reactor heat rejection is to water at temperatures from 278 K (40 F) to 300 K(80 F). These limits cover the extremes from operation at depth to operation in tropical surface water.

Maximum accelerations of 5 G's can be tolerated. This represents entering the water from pier or service ship or landing on the sea bottom. This limit is set by the stresses in the structure supporting the lead shielding. There are no limitations to safe operation in any orientation with respect to gravity.

Power output from the NEMO can be conditioned to the requirements of the user. In the baseline design concept, power is delivered as generated by the TFE's. The pair of leads from each TFE is available to the user to connect in series/parallel combination for the required total output current and voltage. Access to the TFE output

FIGURE 2.1
ARTIST'S SKETCH OF NEMO

cables permits the user to bypass any TFEs that may fail in service. A summary of the NEMO system specifications is given in Table 2.1

2.2 DESIGN DESCRIPTION

The thermionic reactor produces electricity directly in the reactor core. The core is made up of the thirty-three thermionic fuel elements (TFEs) and seventy-three U-ZrH driver/moderator rods. The core is cooled with upflowing deionized water which also serves as additional moderator. Components external to the reactor core are required to:

- 1) remove the heat not converted to electricity;
- 2) contain the fission products;
- 3) control the nuclear reaction;
- 4) absorb the radiation emanating from the core; and
- 5) support the reactor structurally.

The NEMO is illustrated in an elevation section in Figure 2.2. The system is enclosed in a tank 2,438 mm (8 ft) in diameter by 2,438 mm (8 ft) long.

2.2.1 System and Auxiliaries

A general layout indicating the major components of the system is shown in Figure 2.3. The reactor is contained within a pressure vessel which is suspended in the center of the tank. The reactor is surrounded by a seven-inch-thick layer of lead for gamma shielding. The volume between the vessel and outer tank is a borated water solution which serves as a neutron shield.

The reactor vessel and heat rejection auxiliaries are filled with deionized water. The water is actively pressurized to maintain $4.14 (10)^6 \text{ N/m}^2$ (600 psi) pressure at all depths and all power conditions. Pressure is supplied from a 1000 psi gas bottle with regulator. Fig. 2.4 indicates the extent of the pressurized loop. The remainder of the system is at equilibrium with the ambient pressure.

TABLE 2.1

NEMO DESIGN TOP SPECIFICATIONS

Thermal Power	750 kWth
Electrical Power (unconditioned)	30 kWe
Voltage	2.9 volts
Current	10,248 amperes
U ²³⁵ Core Loading	35.7 kg (78.7 lb)
Thermionic Fuel Element Replacement Period	10,000 hours
System Mass	
Dry (drained shield tank)	10,985 kg (24,166 lb)
Total mass	31,957 kg (70,306 lb)
Submerged weight	10,747 kg (23,644 lb)
Overall Dimensions	
Diameter	2,438 mm (8 ft)
Length	2,438 mm (8 ft)
Maximum Surface Dose Rate	108,000 mrem/hr
Seawater Throughput	
Flow rate	17.6 kg/sec (139,400 lb/hr)
Temperature increase	20 K (36 F)

FIGURE 2.2
 POWERPLANT ELEVATION

FIGURE 2.3 POWER PLANT GENERAL LAYOUT

FIGURE 2.4 POWER PLANT PRESSURE BOUNDARIES

The primary coolant side of the heat rejection auxiliaries consists of two pumps (for redundancy), a filter, a gas separator and accumulator, the pressurizing system and the heat exchanger to sea water. On the sea water side are strainers, two pumps and a backwash system. These components are all located in the top corner of the tank where they are accessible for periodic service.

The power plant is designed for a 10,000 hour full-power lifetime between major overhauls (replacement of TFEs). Other than filtration, the auxiliaries do not provide treatment of the primary coolant. To maintain its pH and purity, periodic inspection of the primary coolant is prescribed. If the accessibility of the power plant is limited, components can be added to the system to assure coolant purity. A total system lifetime of five years is specified. Serviceability is summarized in Table 2.2 and serviceable items are illustrated in Figure 2.5.

2.2.2 Reactor

The reactor vessel is 11.4mm (0.45 inches) thick. The material exposed to the primary coolant is type 316 stainless steel, with the exception of aluminum containing boron carbide. The sections of lead shielding inside the vessel are canned in stainless steel. Details of the vessel and core are shown in Figure 2.6. The TFEs and driver rods contain sections of beryllium oxide reflector below and above the fueled section. Radially, the reflector is composed of the control drums in water. The drums are held in bearings in the upper and lower grid plates. The driver rods are fastened to the upper grid plate and aligned in the lower plate. The TFEs are fastened at the upper ends of the 533 mm (21 inch) long extension tubes which extend up from the vessel to the cable dome. They are aligned at the bottom by the lower grid plate.

TABLE 2.2

NEMO SERVICEABILITY

SERVICE WITHOUT RADIATION SHIELDS OR SPECIAL FACILITIES

- . Sample, treat, or flush primary coolant
- . Clean sea water strainers
- . Change control motors
- . Service electrical connections
- . Change pumps
- . Replace entire auxiliaries package
- . Clean sea water side of heat exchanger
- . Replace neutron detectors

SERVICE WITH SHIELDED CASK

- . Replace TFEs
- . Replace shutdown rods
- . Replace control element shafts

SERVICE REQUIRING SPECIAL FACILITIES

- . Drain shield water
- . Access to all other components external to vessel (such as neutron source, thermo-couples, pressure sensors).
- . Remove control elements, core and core support by opening vessel at flange.

- DRIVE MOTORS, POWER OUTPUT LEADS ACCESSIBLE FOR MAINTENANCE
- AUXILIARIES ACCESSIBLE AND REMOVABLE WITHOUT EXPOSING CORE
- TFE'S, SHUTDOWN RODS AND CONTROL SHAFTS REPLACABLE WITHOUT REMOVING VESSEL HEAD

FIGURE 2.5 POWER PLANT ACCESSIBILITY FOR SERVICE

FIGURE 2.6 NEMO REACTOR ELEVATION

The vessel is supported at its flange by an 864 mm (34 inch) diameter 13 mm (0.5 inch) thick steel cylinder off the top of the tank. This cylinder also serves to protect the vessel extension tubes above the vessel.

The reactor core is shown in cross section in Figure 2.7. The triangular lattice contains 73 TRIGA driver elements, 33 TFEs and 3 shutdown rods. Stainless steel filler pieces bound the core. The control drums are composed of 50.8 mm (2 inches) of beryllium oxide reflector and 20 mm (0.787 inches) of boron carbide poison on opposite sides of the drum. The space between these two is filled by the reflector water.

The resulting vessel outside diameter is 660 mm (26 inches). A view down on a section of the upper grid plate is shown in Figure 2.8. Flow orificing for uniform core flow distribution is accomplished with holes in the upper grid plate.

The eighteen reactor control drums operate by rotating the boron carbide poison outward and away from the edge of the core bringing the beryllium oxide reflector inward. The drums are driven in groups of three by a drive rod connected to every third drum. Drive to the other drums is through the idler gears as shown in Figure 2.8. The drive rod works against a torque tube assembly. The tube assembly consists of two concentric 0.25 mm (0.010 in) wall stainless steel tubes which act as a torsion spring to restore the drums in the least reactive position. The drum drive & torque tube assembly is illustrated in a schematic diagram of the reactor control in Figure 2.9a and in detail in Figure 2.9b. The tubes also seal the primary coolant from the cable dome.

The six drive rods are each operated by a separate d.c. stepping motor. Each drive motor can hold its three control drums in any of one-hundred positions from poison fully in to fully out to control the reactor power. The motors are located in the dome at the top of the

FIGURE 2.7 NEMO REACTOR SECTION

DRIVEN
CONTROL
ELEMENT

FIGURE 2.8

NEMO REACTOR UPPER GRIDPLATE DETAIL

FIGURE 2.9 CONTROL ELEMENT AND SHUTDOWN
ROD DETAILS

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tank where they are accessible for service or replacement. Since d.c. stepping motors operate through the magnetic induction between stator coils and an iron armature, this type of motor can operate flooded with any fluid.

Three shutdown rods located centrally in the core provide a mechanically separate reactor shutdown system. The rods are boron carbide neutron absorber. They are held out of the core by differential water pressure across a piston in an extension tube above the core. A spring force drives the rods into shutdown position. These rods are withdrawn from the core completely before the control drums are rotated to start the reactor up. The water pressure to maintain them in the withdrawn position is provided by a pressure accumulator at $5.32 (10)^6$ N/m² (800 psi) which is charged by a metering pump from the primary coolant loop. A schematic diagram of the shutdown system is illustrated in Fig. 2.9a. The shutdown rod & channel assembly is also shown in detail in Fig. 2.9b.

2.2.3 Thermionic Fuel Elements (TFEs)

The TFEs in the NEMO are similar to the 6LF TFE which is a modified version of the 6F TFE being developed for space applications. Gulf General Atomic is developing the Thermionic Reactor Power System for the USAEC. The 6LF TFEs have several simplifications in design compared with the 6F TFEs and offer 7 $\frac{1}{2}$ % more fuel and more power producing electrode area per TFE than the F series. The efficiency expected of these converters at the output level of the NEMO is 11%. The first LF series TFE is presently being fabricated.

The NEMO TFE is shown in Figure 2.10. It is assembled as follows: The 6LF is connected at the bottom to a copper sleeve which provides the negative lead return path for the current from the bottom converter. This assembly is slipped into a 38.1 mm (1.5 inch) outside diameter by 1.5 mm (0.058 inch) wall containment tube. The tube wall thickness was selected since it results in the minimum stress due to the combination

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ALTERNATE

FIGURE 2.10 THERMIONIC FUEL ELEMENT
DETAIL

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of external pressure and radial thermal gradient. This stress is $1.07 (10)^8 \text{ N/m}^2$ (15,580 psi). Beryllium oxide reflector pieces are located above and below the 6LF. Above the 6LF cesium reservoir, a positive current lead is attached. The lower 178 mm (7 inches) of the lead is solid copper and serves also as a gamma shield. It is at the same axial location as the lead gamma shielding around the primary vessel. For the next 356 mm (14 inches), the lead is a hollow cylinder of copper surrounding a charcoal fission gas trap. Above the trap the TFE containment tube is sealed with a brazed lead feedthru with ceramic insulators. The volume enclosed is filled to 10^5 N/m^2 (15 psi) with helium to transfer heat from the TFE to the containment tube. Boronated polyethylene is placed above the sealed lead-thru within the extension of the containment tube. This serves as a neutron shield to prevent streaming through the penetrations in the boronated water shield tank.

The TFEs penetrate the primary coolant vessel and are clamped to the vessel extension tubes with a Marman-type flange and o-ring seal.

The charcoal trap contains 218 cc (13 in^3) of charcoal. The charcoal will equilibrate in temperature with the shield water at 302°K (84°F). At this temperature the charcoal can absorb the $6 (10)^{-3}$ moles of gaseous fission products (xenon and krypton) produced in each TFE in 5,000 hours with an end of mission overpressure of 500 N/m^2 (6 torr). The xenon and krypton pressure in the interelectrode space after 5,000 hours depends on how much of the gas produced is released and what the conductance is between the converters and the trap. Limiting calculations indicate a maximum end of mission pressure in the interelectrode space of the TFE of 1033 N/m^2 (7 torr). Calculation of interelectrode conduction through the fission gas is only approximate, but the most conservative assumptions indicate an 18% increase in thermal power will be necessary to maintain converter performance. Alternatively, the system would suffer a degradation of power output with time.

A listing of TFE specifications^{*} is given in Table 2.3. The minimum TFE lifetime of 10,000 hours is based on current TFE operating experience. The demonstration of longer full-power lifetimes on six-cell fuel elements is expected within a few years.

2.2.4 Driver Fuel Elements

The TRIGA[†] driver rods are made of U-ZrH fuel press fit into 0.51 mm (0.020 in.) thick by 38 mm (1.5 inch) diameter stainless steel cladding. These fuel rods also contain beryllium oxide reflector blocks above and below the active core zone. Specifications for the driver rods are summarized in Table 2.4. The fuel and reflector are sealed into the cladding with 6.4 mm (0.25 inch) axial space for expansion and storage of fission product gasses which have diffused or recoiled out of the fuel. Gaseous fission products are retained within the U-ZrH type fuels. Calculated stress in the U-ZrH for $4.14 (10)^6$ N/m² (600 psi) external pressure is $7.25 (10)^7$ N/m² (10,000 psi) which compares to a compressive yield of $2.42 (10)^8$ (35,000 psi). The 6.4 mm (0.25 inch) unsupported stainless driver rod clad will be stressed to $4.57 (10)^7$ N/m² (6618 psi) which compares to a yield stress of $7.6 (10)^7$ N/m² (11,000 psi). At the normal operating power level the maximum driver fuel temperature is 91 K (164 F) above the clad average.

Erbium is dispersed in the fuel as a burnable poison. The TRIGA-FLIP reactors at this power level, and employing the erbium poison, have core loading lifetimes of ten megawatt-years. At the power level of NEMO driver rods, this is a fuel lifetime of nearly eleven years. Since the TRIGA rods are sealed and since they will outlast the remainder of the power system, the rods are not accessible without dismantling the reactor vessel and core.

* See Appendix B, TFE Performance Parameters

† Appendix A discusses the TRIGA fuel elements and reactor.

TABLE 2.3

TFE SPECIFICATIONS

Outside Diameter	38 mm (1.5 in)
Length	
Active core	423 mm (16.65 in)
Reflector top or bottom	51 mm (2 in)
Overall	1,385 mm (54.6 in)
Fuel	UO ₂
Volume Fraction of Fuel Over Active Core Length	28%
Fuel Enrichment	Axially variable up to 93%
Primary Fission Product Containment Envelope	
Materials	Nb and Nb-1Zr
Fuel Element Containment Tube	
Material	316 SS
Thickness	1.5 mm (0.058 in)
Support	
Upper	Clamped to vessel at upper end of nozzle tubes.
Lower	Sliding pin in lower grid plate.
Mass, Each	7.6 kg (16.7 lb)
Electrode Area Per TFE	316 cm ² (49 in ²)
Output Current, Nominal	316 amps
Output Power, Nominal	1013 We
Efficiency	11%

TABLE 2.4

TRIGA DRIVER ROD SPECIFICATIONS

Outside Diameter	38 mm (1.5 in.)
Length	
Active core	423 mm (16.65 in.)
Reflector top or bottom	76 mm (3 in.)
Overall	588 mm (23.15 in.)
Fuel	U-Er-ZrH _{1.6}
Fuel Enrichment	37%
Burnable Poison	Natural Erbium
Cladding	
Material	316 ss
Thickness	0.51 mm (0.020 in.)
Support	
Top	Fastened to upper grid plate with stud and nut.
Bottom	Sliding pin in lower grid plate.
Mass, Each	3.35 kg (7.36 lb.)

2.2.5 Core Support

The upper and lower gridplates are structurally connected together and to the bottom head of the pressure vessel. The lower gridplate is directly mounted on bosses welded into the vessel. The upper gridplate is supported from the lower by a structure just outside the control drums.

2.2.6 Power Distribution

At the upper ends of the extension tubes from the vessel, where the TFEs are clamped, current is conducted from the TFEs through AWG4/0 copper cables. The cables are suspended in an oil-filled dome. An oil-filled duct leads from the dome to the electrical connection and power conditioning equipment. The oil-filled dome also contains the control drive motors. An alternate connection method is discussed in Section 2.9.

2.2.7 Performance

A breakdown of the power balance for the system is given in Table 2.5. The schematic diagram in Figure 2.11 shows the distribution of power and shows the locations and functions of the control instrumentation. This schematic was drawn assuming a manned application where the connection of the individual TFE output cable pairs can be modified in case of any individual TFE malfunction. Batteries are assumed for startup energy to meet the 2.6 kWe power requirement for pumps and control. The controller in the diagram may be an operator or a digital data acquisition and control computer. Note that complete loss of power in the supply line to the control components will have the same effect as a trip signal. That is it will release the shutdown rods and control drums, close off the sea water side of the heat exchanger, stop the pumps and turn off the cesium heater supply.

TABLE 2.5

NEMO POWER SUMMARY

THERMAL

TFEs.....344 kWth
 Driver.....406 kWth
 Total.....750 kWth

ELECTRICAL

Current per TFE at 6 amps/cm².....314 amps

	<u>Per TFE</u>	<u>System Nominal</u>
Gross output of converters.....	1120 We	37.0 kWe
Power loss within TFE can.....	<u>100 We</u>	<u>3.3 kWe</u>
Net TFE output.....	1020 We	33.7 kWe
Power loss in cables.....	26 We	0.9 kWe
Required for primary pump.....		596 We
Required for sea water pump.....		867 We
Required for cesium reservoirs.....		825 We
Required for control.....		
Six d.c. stepping motors.....		252 We
Metering pump (intermittent).....		~0 We
Trip rod solenoids.....		60 We
Sea water shutoff valves (solenoid)..<		<u>200 We</u>
Total requirement power plant system....		2.8 kWe
Net system output.....		30 kWe

FIGURE 2.11 CONTROL AND ELECTRICAL DISTRIBUTION DIAGRAM

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2.3 NUCLEAR ANALYSIS

Preliminary nuclear analysis of the NEMO reactor was aimed at estimating the power distribution in the core between TFEs and driver rods and the worth of the control drums and shutdown rods.

2.3.1 Core Power Distribution

The efficiency of the thermionic power system is proportional to the fraction of the thermal power in the TFEs. The principal advantage of high efficiency is in reducing the shielding requirement. Analysis indicates 45.8% of the thermal power will be in the TFEs. For 30 kWe electric power output and a TFE efficiency of 11%, this is a total thermal power of 750 kWth.

An illustration of the core lattice is sketched on Figure 2.12. Nuclear calculations were based on the dimensions and volume fractions for elements as shown in Tables 2.6, 2.7 and 2.8. Early estimates of volume fractions which are not significantly different were used to obtain atom densities and to prepare 14 group cross sections.

A precise determination of the thermal power distribution would require a three-dimensional transport theory calculation which is beyond the scope of present work. Even if such a calculation could be done rigorously for a unit cell, it would still be an approximation to the true situation, since the core is not a large array of complete unit cells. Depending on the core layout, some TFEs near the outer edge of the core may not have a full complement of surrounding driver elements, while at other locations there are extra driver elements or portions of elements. In addition to the edge effects, several TFEs are removed from the inner lattice to make room for in-core shutdown rods. Removing driver elements for this purpose would give a higher efficiency, but it does not presently appear feasible to locate a shutdown rod penetration in the vessel head between the TFE penetrations.

FIGURE 2.12
LATTICE SECTION IN CORE

TABLE 2.6

TFE DIMENSIONSFueled Region Radial Geometry

<u>Region</u>	<u>Outer Radius mm (inches)</u>	<u>Volume Fraction</u>
UO ₂	12.4 (0.490)	0.427
W	14.0 (0.550)	0.111
Gap	14.4 (0.569)	0.038
Nb	15.8 (0.622)	0.112
Al ₂ O ₃	16.2 (0.636)	0.031
Gap	16.8 (0.661)	0.058
Cu	17.3 (0.680)	0.045
Al ₂ O ₃	17.4 (0.685)	0.012
Gap	17.6 (0.692)	0.017
SS	19.0 (0.750)	0.149
		<hr/>
		1.00000

TABLE 2.6
(Continued)

Intercell Region (Unfueled Length)

<u>Material</u>	<u>Volume Fraction</u>
W	0.198
Nb	0.152
Ta	0.068
Cu	0.045
SS	0.149
Al ₂ O ₃	0.062
Void	0.326
	<hr/> 1.00000
Fueled emitter (inches)	54.6 mm (2.15 in)
Number of fueled emitters	6
Intercell length (inches)	19.0 mm (0.75 in)
Number of intercell lengths in core	5
Core length (TFE & TRIGA elements) (inches)	422.9 (16.65 in)
Axial reflector	beryllium oxide 51 mm (2 in) top and bottom

TABLE 2.7

DRIVER ELEMENT VOLUME FRACTIONS

<u>Region</u>	<u>Outer Radius mm (inches)</u>	<u>Volume Fraction</u>
U-ZrH	0.730	0.947
SS	0.750	0.053
		<hr/>
		1.00000
Axial Reflector	Beryllium Oxide	76mm (3 in) top and bottom

TABLE 2.8

CORE LATTICE COMPOSITION

Pitch/diameter ratio	1.02
Volume fractions in regular lattice:	
TFE	0.291
TRIGA Element	0.581
Water	0.129
	<hr/>
	1.00000

Figure 2.13 illustrates the one-dimensional calculation models actually used to estimate the power distribution of the unit cell. The flux shielding factors obtained from the one-dimensional radial calculation (Figure 2.13a) are used to homogenize the fueled emitter region of the TFE and the portion of the TRIGA fuel adjacent to it. This mixture is usually called the "fueled" region. A similar mixture is prepared for the intercell region and its adjacent driver fuel except that no radial cell calculation to determine shielding factors is done for this region. This is because the geometry of the inner-cell region is complex and because the short axial length of the region implies that the spatial flux variations are probably as much influenced by the axial geometry as by the radial. Therefore, a two-dimensional cell is required.

The two homogenized mixtures are alternated in an axial core calculation (Figure 2.13b) from which the ratio of the power in the fueled region to the total power can be determined. The overall fraction of the thermal power in the TFEs is then calculated as the product of the fractions obtained from the two one-dimensional calculations.

In addition to the TFE power fraction values, the calculations provide values of k_{∞} for fueled emitter cell calculations and k_{eff} for axial reactor calculations. With this one may assess the influence on excess reactivity of design changes which might improve the TFE power fraction.

For the present design, the basic calculations have been done for fully enriched U-235 in the TFE, 70% enrichment in the driver fuel and a pitch/diameter ratio of 1.02. This composition has a high excess reactivity ($k_{eff} \sim 1.19$). It is assumed that this will be reduced to the desired level of $k_{eff} = 1.07$ by reducing the enrichment of the driver fuel to increase the power in the TFEs and reducing the enrichment of the TFE as required to accomplish radial and axial zoning.

ONE-DIMENSIONAL RADIAL
MODEL

ACTUAL CELL GEOMETRY

a.) RADIAL CORE MODEL

b.) AXIAL CORE MODEL

FIGURE 2.13
CALCULATIONAL MODELS
(Not To Scale)

Calculations with various enrichments result in data with which one can graph k_{eff} and power fraction in the TFEs as a function of driver fuel enrichment to estimate the power level for any desired k_{eff} . The effect of fuel temperature and the effect of one-dimensionalizing the cell calculation are included in the power fraction calculation. The latter effect, (which is essentially the difference in the calculational models shown in Figure 2.13a) is taken to be 1% based on past experience.

The TFE enrichments required for satisfactory radial and axial zoning cannot be specified without expensive two-dimensional calculations. Some rough estimates suggest that about $0.04\Delta k$ reactivity loss should be allocated for this zoning. The TRIGA fuel enrichment is, therefore, reduced to the point where $k_{\text{eff}} = 1.07 + 0.04 = 1.11$.

The curves for estimating the power level are shown in Figure 2.14. For a k_{eff} value of 1.11, the driver fuel enrichment is 37%, the efficiency is 47.5% and the reactor power level is 724 kWt. This is rounded up to 750 kWt to leave some margin for the unevaluated two-dimensional effects. The rounding up results in a fractional power in the TFEs of 45.8% as quoted above.

2.3.2 Reactivity Control

The reactivity requirements assumed are illustrated in Figure 2.15. Except for the temperature coefficient, all the quantities making up the excess reactivity are estimates. It is assumed that the reactivity loss with burnup ($0.01\Delta k$) will be covered by the erbium burnable poison. This leaves $0.10\Delta k$ to be covered by mechanical control devices. Note that $0.04\Delta k$ of this is uncertainty.

FIGURE 2.14 k_{eff} AND TFE POWER FRACTION VS. DRIVER FUEL ENRICHMENT

FIGURE 2.15
REACTIVITY REQUIREMENTS

There seems to be no possibility of obtaining the entire $0.10\Delta k$ control margin in the external drums, so that some number of incore shutdown rods are required. It is desirable to limit this number since it appears that the rods must replace TFEs rather than TRIGA elements in the lattice as noted previously. To avoid axial power distribution problems in the TFEs, the total worth of the rods should not exceed the shutdown margin and some portion of the temperature defect so that they would be fully withdrawn at power. However, if the total worth exceeds the shutdown margin, it will be possible to go critical on the removal of one of these rods and the worth per rod must be limited to prevent damage in the event of a rod withdrawal or expulsion accident. Under these criteria, the worth of the in-core rods cannot be allowed to be greater than about $0.05\Delta k$, and it is preferable to keep them at $0.04\Delta k$ to avoid the accident question. This worth can be accomplished based on TRIGA reactor experience with three boron carbide absorber rods. A limit of $0.04\Delta k$ for the rods requires a worth of $0.06\Delta k$ in the external drums.

The present drum configuration satisfying this requirement is 95.25 mm (3.75 inch) diameter with a 50.8 mm (2 inch) sector of beryllium oxide on one side and one of 20 mm (0.79 inch) thick boron carbide on the other. The drum extends the 423 mm core height. Primary coolant water floods the remaining radial volume and is also a reflector. These dimensions could be further optimized.

2.4 SHIELDING ANALYSIS

Shielding calculations have been made for the NEMO power plant. As can be seen from Figure 2.16, the shielding consists of several layers of neutron and gamma shielding material. Neutron shielding is provided by the reflector water and the boron carbide control drum poison. Sheets of boron carbide in aluminum (boral) are located above the upper and below the lower grid plates. A seven-inch thick layer of lead for gamma shielding surrounds the reflector and grid plates. Additional boral plate surrounds the lead to reduce its

FIGURE 2.16 POWER PLANT SHIELDING CONFIGURATION

capture gamma source. The final neutron shield is the borated water solution filling the tank.

A concentration of 0.67% boron in the shield water provides for adequate shielding. At this concentration, boric acid can be maintained in solution to 40 F (Ref 2.7). Ammonium pentaborate or ammonium tetraborate are also candidates since they are known to redissolve more readily than boric acid in the event they precipitate in a thermal cycle. Data is available for the corrosion of various structural materials in boric acid and in ammonium tetraborate (Ref 2.8). From this data, a calculation was made for a time/temperature program representative of operation of the NEMO system. Data used is for concentrations on the order of 0.67% boron. Results are shown in Table 2.9. It appears that corrosion will not be a problem in either borated solution.

Calculated dose rates are presented in Figure 2.17 for full power and shutdown conditions at sea and at pierside or along side a mother ship. Activation of sea water at full power is 1.35 times the maximum permissible concentration for drinking water. Ten hours after shutdown, the dose rate at the boundary of the shield tank is in this environment receiving the allowable quarterly dose of 1 1/4 rem (Ref 2.9).

TABLE 2.9

DISSOLUTION OF COMPONENTS

IN

SHIELD WATER BASED ON THE FOLLOWING PROGRAM:

5,000 HRS AT 373 K (212 F) & 40,000 HRS AT 293 K (68 F) (REF. 2.8)

	Boric Acid H_3BO_3 0.74% Boron (4.16% boric acid)	Ammonium Tetraborate $(NH_4)_2B_4O_7 \cdot 4H_2O$ 0.49% Boron (2.96% Ammonium Tetraborate)
Type 316 Stainless Steel	1.37 m (5.4×10^{-5} in)	1.14 m (4.5×10^{-5} in)
Unalloyed Lead	55.9 m (0.0022 in)	43.2 m (0.0017 in)
Carbon Steel	78.7 m (0.0031 in)	0.96 m (3.8×10^{-5} in)

EQUILIBRIUM ACTIVATION AT FULL POWER

FULL POWER AT SEA

DIVER APPROACH - 1 MINUTE AFTER SHUTDOWN

AT PIERSIDE - FULL POWER

AT PIERSIDE - 1 HOUR AFTER SHUTDOWN

ONSHORE - 10 HOURS AFTER SHUTDOWN

FIGURE 2.17 RADIATION DOSES FROM NEMO

2.5 REACTOR CORE THERMAL ANALYSIS

Heat transfer from the TFEs and driver rods to the primary coolant is at a moderate heat flux $\left[13.3 \text{ W/cm}^2 \left(42,136 \frac{\text{BTU}}{\text{hr ft}^2} \right) \text{average} \right]$ for water cooled reactors. The primary coolant is pressurized to $4.14 (10)^6 \text{ N/m}^2$ (600 psi) to eliminate compressive force on the reactor components at depth. As a result of the low heat flux and high pressure, the fuel elements can be placed closely together. The pitch to diameter ratio of the elements is 1.02.

Parametric calculations for axial flow in rod bundles for a range of Prandtl numbers including water are published (Ref. 2.5). The circumferential variations in fuel element heat flux and temperature are based on that data. The calculation made assumes an isothermal cylinder within an annulus which has both radial and circumferential conductivity. It was conservatively assumed that only the 1.5 mm (0.058 inch) stainless TFE containment tube wall contributed circumferential thermal conductivity.

The core flow rates, heat fluxes, temperatures and pressure differentials are tabulated in Table 2.10. The flow rate was selected so that boiling might occur at the point of maximum TFE containment tube temperature at a reactor power level of about 1 MWth. For the operating point of 750 kWth, this is a reasonable safety allowance.

At the edge of the core, the axial flow passages have the same equivalent diameter as the tricuspid areas between elements in the close packed array. This selection results in the same heat transfer coefficient for elements at the core edge and very nearly the same surface temperatures since the film drop in this reactor is greater than the core temperature rise.

TABLE 2.10

CORE THERMAL HYDRAULICS

Coolant Pressure	$4.14(10)^6 \text{ N/m}^2$ (600 psi)
Saturation Temperature	526K (480F)
Fuel Element Pitch Spacing	39mm (0.030 in.)
Core Area	0.023m^2 (0.242 ft ²)
Core Equivalent Diameter	5.5mm (0.018 ft)
Core Flow	
Mass Rate	8.8kg/sec (70,000 lb/hr)
Volume Rate	537 liters/min (138 gpm)
By Pass	0.4 kg/sec (3222 lb/hr)
Velocity	0.39 m/sec (1.28 ft/sec)
Reynolds Number	6706
Heat Fluxes	
TFE Average	17.9 W/cm^2 (56,762 BTU/hr ft ²)
TFE Maximum	43.9 W/cm^2 (139,067 BTU/hr ft ²)
Driver Average	11.2 W/cm^2 (35,524 BTU/hr ft ²)
Driver Maximum	27.4 W/cm^2 (87,034 BTU/hr ft ²)
Temperature	
Coolant Core Inlet	321 K (117 F)
Coolant Core Outlet	347 K (164 F)
TFE Containment Average	414 K (286 F)
TFE Containment Maximum	456 K (360 F)
Driver Clad Average	384 K (231 F)
Driver Clad Maximum	447 K (344 F)
Coolant Vessel Outlet	339 K (151 F)
Pressure Differentials	
Inlet	3831 N/m^2 (80 psf)
Upper Grid Plate	96 N/m^2 (2 psf)
Core	192 N/m^2 (4 psf)
Exit	958 N/m^2 (20 psf)
<hr/>	
Total Reactor Pressure Differential	5075 N/m^2 (106 psf)

Flow distribution is controlled by the perforations in the upper gridplate (See Figure 2.8). The volume in the radial reflector region is filled with water. Approximately 5% of the primary coolant flow bypasses the core through this region and around the upper gridplate.

The vessel wall and the lead shielding mounted on it are maintained at approximately the inlet coolant temperature by the bypass flow. A simplified calculation of natural convection from the lead to the shield water, from the water to the tank wall and from the tank to the sea was performed. It indicates a loss of heat directly of 4422 W (15,093 BTU/m) of 0.06% of the waste heat. As a result the temperatures of shield water and tank wall are 304 K (87 F) and 302 K (84 F) respectively. In Section 2.9, an alternative reactor cooling method is discussed wherein all of the reactor waste heat is transferred to the sea by convection from the shield tank.

Nuclear afterheat from the core following shutdown is estimated to be 5%. This heat can be rejected directly to the sea by the convection described above with a resulting core temperature of 339K (150 F).

2.6 REACTOR AUXILIARIES

The reactor auxiliaries consist of the primary reactor coolant circuit, the sea water coolant loop, the heat exchanger between them, a pressurizer system and a pump and accumulator to provide hydraulic pressure to the shutdown rod pistons. The system flow schematic is shown in Figure 2.18 along with the locations of temperature and pressure transducers and flowmeters required to monitor the heat rejection.

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FIGURE 2.18 FLOW DIAGRAM NEMO SYSTEM

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The primary coolant follows a simple loop from reactor through a gas separator, through the heat exchanger, through the pumps and back. Two pumps are provided for redundancy. The gas separator will accumulate the small amounts of hydrogen produced by radiolysis in the core. A bypass filter is incorporated for 5% of the primary flow of 537 liters/min (138 gpm). The filter and pump specifications are detailed in Table 2.11. The total of pressure drops external to the reactor core is 11,473 N/m² (1.7 psi), and the total circuit differential is 16,548 N/m² (2.4 psi). No provisions for coolant purity other than the bypass filter are necessary if the system is regularly serviced and checked for changes in pH, conductivity and radioactivity.

The sea water is circulated by two redundant pumps through separate filters and thence through the heat exchanger. An additional system of valves and a pump are included to backwash the strainers. Since the pumps are redundant, the backwashing of one strainer can be performed during reactor operation with flow maintained through the other. Trash catching and fish filtering screens cover the sea water inlets and outlet. Solenoid valves are located in the sea water loop to isolate the heat exchanger in the event of a reactor trip.

The heat exchanger is of baffled cross-counterflow tube and shell design. Double walled tubes will provide double containment of the coolant across the heat exchanger. The high pressure (primary) fluid is on the shell side and the sea water on the tube side, so that the insides of the tubes can easily be cleansed of any sea water deposits. Details of the heat exchanger are given in Table 2.11. Design is based on Reference 2.6. Sizing of components allows for sea water corrosion. Pressure drop in the heat exchanger is 5033 N/m² (0.73 psi) for the sea water and 5447 N/m² (0.79 psi) for the primary coolant water.

TABLE 2.11

REACTOR AUXILIARIES

Primary Coolant Loop

Flowrate	8.8 kg/sec (70,000 lb/hr)
Pipe Diameter	76 mm (3 inches)
Filter	
flow rate	29 liters/min (7.5 gpm) (5% bypass)
porosity	10 μ m
size	102 mm (4 inches) dia x 381 mm (15 inches) long

Pumps

type	seal-less centrifugal
head	17,030 N/m ² (5.7 ft)
flowrate (each)	540 liters/min (142 gpm)
speed	1750 rpm

Sea Water Loop

Flowrate	17.6 kg/sec (139,400 lb/hr)
Pipe Diameter	102 mm (4 inches)
Strainers (basket type)	
pressure drop	2069 N/m ² (0.3 psi)
size	305 mm (12 inches) dia x 457 mm (18 inches) long

Pumps

type	seal-less, centrifugal
head	14,939 N/m ² (5.0 ft)
flowrate (each)	1035 liters/min (272 gpm)
speed	1750 rpm

TABLE 2.11

REACTOR AUXILIARIES - Continued

Heat Exchanger

type	single pass, cross-counter flow (baffled), double walled tubes
material	stainless steel
heat transfer surface	23 m ² (247 ft ²)
number of tubes	688
overall heat transfer coefficient	0.12 w/cm ² K (212 BTU/hr ft ² F)
size	305 mm (1 ft) dia. X 1,676 mm (5.5 ft) long
tube wall thickness	0.76 mm (0.03 in)
shell wall thickness	7.4 mm (0.29 in)

The primary system is pressurized through redundant regulators by a rechargeable gas bottle of 7.3 kg (16 lb) capacity initially charged at $6.9 (10)^7 \text{ N/m}^2$ (1,000 psi). The pressure relief valves (in series for redundancy) release gas during descent or heating directly to the sea. Two bellows pressurizers in series transmit the pressure to the primary coolant water.

Pressure to extract or hold out the shutdown rods comes from a bladder accumulator charged by a small metering pump. The pump operates intermittently on signal from a pressure transducer in the accumulator. Three three-way solenoid valves activate the rods, each independently. When the valves are de-energized, the spring driving the shutdown rod into the core forces the piston to expel water back through the valve into the primary coolant loop. An orifice between the pump and pistons assures a controlled rate of rod removal. Malfunction of the shutdown rod pressurization system by over-pressure will break a rupture disc and the rods would be driven into shutdown position.

2.7 SAFETY

Because of its design and because it uses the TRIGA driver fuel, the NEMO reactor is a safe and reliable power generating system.

The U-ZrH TRIGA-type fuel provides the reactor with the inherent safety of a large prompt negative temperature coefficient. This is an assurance of the nuclear safety of the core.

Double containment of the primary coolant is provided. The containment diagram in Figure 2.19 shows the extent of the primary coolant vessel and auxiliaries which are the primary containment within the borated water comprising the secondary containment. The primary containment is designed to meet the requirements for Class 1 nuclear vessels according to the ASME Boiler and Pressure Vessel Code, Section III (Ref. 2.10). Structural details of the secondary containment have not been designed in the absence of a specific mission or application. The heat exchanger between the primary coolant and the sea water has double walled tubes to maintain double containment. As can be seen from Figure 2.18, the design also incorporates, on the sea water inlet and outlet pipes, solenoid operated valves. The valves close on a reactor trip isolating the heat exchanger. The reactor afterheat (5% of full power) then passes from the primary coolant to the shield water and then through the tank to the sea, all by natural convection.

The fuel and fission products are doubly contained within the TFE. The first continuous containment around the fuel is the refractory metal (mostly niobium) envelope of the welded cell assembly and the walls of the fission gas trap. The second containment is the welded TFE containment. The electrical power leads of each TFE penetrate the TFE containment through a ceramic-to-metal brazed feedthru seal.

FIGURE 2.19 POWER PLANT CONTAINMENT
DIAGRAM

(Details of the TFE are shown in Figure 2.10) Additionally, the fission product trap is enclosed by the positive electrical power lead around its refractory metal walls and within the TFE containment.

The U-ZrH fuel with stainless steel cladding has a history of safe operation in TRIGA reactors. Hydrogen overpressure within the driver rod is insignificant up to fuel temperatures of 1200 K (1700 F). In steady state operation the NEMO driver fuel operates at a maximum temperature of 538 K (508F) which is well below safe limits. The fuel retains most of its fission products, and so there is little internal pressure buildup. There is no reaction of the hydride with water. Since the hydriding reaction is exothermic, water will react more readily with zirconium than with zirconium hydride systems. Zirconium is frequently used in contact with water in reactors, and the zirconium-water reaction is not a safety hazard.

Tests involving the quenching of both powders and solid specimens of U-ZrH after heating to as high as 850°C, and of solid U-Zr alloy after heating to as high as 1200°C have shown that zirconium hydride systems have a relatively low chemical reactivity with respect to water. Tests have also been made to determine the extent to which fission products are removed from the surfaces of the fuel elements at room temperature. Results show that, because of the high resistance to leaching, large fraction of the fission products is retained in even completely unclad U-ZrH fuel. Fuel elements have been irradiated to far higher atom burnup fractions than required in this design and at temperatures from 973 K (1292 F) to 1073 K (1472 F) without noticeably affecting the fuel.

The TFE containment and the driver rod cladding are also shown in the containment diagram on Figure 2.19.

The only emission to the sea water from the NEMO system is the inert gas released from the primary coolant pressurizer directly to the sea during reactor heating and increase in depth of submergence. The two bellows pressurizers in series provide double containment of the primary coolant through this subsystem. The gaseous and liquid activation products of the primary coolant are only removed from the system during periodic inspection of the coolant. The activation of the sea water environment at the surface of the power plant, calculated for still water, is 1.35 times the maximum permissible concentration for exposure of the general public. (Ref. 2.8).

The active pressurizing subsystem assures that primary coolant pressure is independent of the ambient for depths less than the maximum specified depth of service. This provides that the environment of the core will be the same for the development prototype or any system running on land or at the surface as for a system operating at full depth. The primary vessel, piping and auxiliaries are always stressed in tension due to the constant pressurization. The main rupture disc in the primary coolant system will relieve any transient pressure pulse in the primary and the bladder volume compensator in the secondary system is designed with a volume of 0.57 m^3 (20 ft^3) to maintain containment. A rupture disc bypassing the redundant pressure regulator valves on the primary pressurizing system (See Figure 2.18) protects the containments from filling with the charge of the 1000 psi gas bottle if its pressure were imposed in the water by some failure or accident.

Because the primary and secondary water have little volume of gas above them and because the system operates entirely submerged, the occurrence of a leak between containments (or even from the primary to the sea) would not result in draining the core. No account must be made in the design of the reactor for the required (Ref. 2.2) core cooling in the event of "loss" of primary coolant, since it cannot be "lost."

Two independent reactor shutdown systems with different mechanical design principles are used to control the NEMO reactor as required (Ref. 2.2). The eighteen poison-backed drums are used to maintain the desired reactor power level and accommodate changes in reactivity. The three shutdown rods are a backup shutdown control which, independent of the drums, assures that fuel design limits are not exceeded in the event of a system malfunction.

The use of hydraulic pressure to hold out the trip rods provides a safety feature. Automatic insertion will occur in the event of primary coolant overpressure, since the rupture disc in the line to the shutdown rod pistons breaks before the main primary coolant rupture disc (See Figure 2.18) releasing the pressure that holds the rods out. An orifice is placed in the lines supplying the trip rod pistons to limit the rate at which these rods can be withdrawn.

Related to the safety of the system is its reliability as a power plant, since it will be the prime source of power to whatever mission it is applied and the reliable supply of this power will contribute to the safety of the entire operation. The system electrical connection allows the user to have ready access to the individual TFE output busses so that in the event failures occur in the converters, the maximum useful power of the unfailed TFE's is available. A summary of the reactor's safety features is given in Table 2.12.

2.8 VESSEL STRESS ANALYSIS

Sizing calculations for the NEMO reactor vessel were made in accordance with the A.S.M.E. Boiler and Pressure Vessel Code, Section III (Ref. 2.9) requirements for Class 1 components. Because of the unique application some assumptions were required in applying the code. In general a 600 psi operating pressure, a maximum metal temperature of 200°F and a total supported weight of 18,430 lbs. were assumed.

TABLE 2.12

NEMO SAFETY FEATURES

- . Prompt negative temperature coefficient of driver fuel
- . Double containment of primary coolant
- . Double containment of fuel and fission products within TFEs
- . Fission products retained in driver fuel
- . Driver fuel insoluble - demonstrated safety of cladding
- . Coolant pressure independent of ambient
- . Sea water activation is 1.35 of MPC for drinking water
- . Two independent control systems
- . Over-pressure of primary trips shutdown rods
- . Primary, secondary and ambient media are liquid

The ellipsoidal heads were sized to the same thickness as the cylindrical sidewalls, as dictated by Section VIII, Div. I rules, since the Section III recommended guidelines for preliminary analysis are not yet published. All reinforcement calculations used the cross section containing the axis of the shell. The portion of the code relating to openings in cylindrical shells was used at each section. Section VIII, Div. I, was used in analyzing the flange connections with the appropriate modifications from Section III.

A solid flat stainless steel gasket with flat facing was assumed in computing bolt loads. Volumetric expansion of the vessel due to pressure loading neglected expansion of ducts, housings and other irregularities.

The shell and flange for support of the lower external lead gamma shield were sized by trial and error using a discontinuity analysis and comparing the resulting stresses to the yield point. Uniform weight distribution was assumed.

A discontinuity analysis was also used to size the vessel support cylinder. The containment vessel was assumed rigidly connected to the support flange with the combination modeled as a flat plate. The loading was assumed uniform.

Although the period of inspection called for by Section XI of the code, "Rules for Inservice Inspection of Nuclear Reactor Coolant Systems," is ten years, the vessel was designed with weld configurations and assembly techniques which would permit inservice inspection.

Table 2.13 summarizes the thicknesses of the vessel and components for the NEMO.

TABLE 2.13

THICKNESSES OF VESSEL AND COMPONENTS FOR NEMO

Cylindrical Vessel and Ellipsoidal:	
Head (316 SS) Thickness	11.4 mm (0.45 in.)
Control Drum Driver Extension	
Tube (316 SS)	
Thickness	0.51 mm (0.02 in.)
Reinforcement Thickness	6.15 mm (0.242 in.)
Reinforcement Distance	9.5 mm (0.375 in.)
TFE Extension Tube (316 SS)	
Thickness	0.76 mm (0.03 in.)
Reinforcement Thickness	9.8 mm (0.385 in.)
Reinforcement Distance	11.4 mm (0.45 in.)
Flange (316 SS)	
Thickness	51 mm (2.0 in.)
Width	89 mm (3.5 in.)
Bolts (Low Alloy Steel, SA-193)	1-12 UNF
Number of Bolts Required	20
Lower External Lead Support Shell	
(Carbon Steel, SA-537)	
Thickness	6.35 mm (0.25 in.)
Flange Thickness	6.35 mm (0.25 in.)
Flange Width	19.1 mm (0.75 in.)
Vessel Support Cylinder	
(Carbon Steel, SA-537)	
Thickness	12.7 mm (0.5 in.)
Flange Thickness	51 mm (2.0 in.)

2.9 ALTERNATIVE CONSIDERATIONS

2.9.1 Convective System Cooling

The heat exchanger and the seawater circulation loop may be eliminated by transferring the reactor waste heat through the shield water and tank wall to the sea. With this alternate concept the primary coolant water is pumped through a coil of pipe within the shield water. The heat is then convected from the coil to the tank wall and rejected to the sea by natural convection.

The convective heat rejection concept assures complete double containment and permits the primary and secondary containment to be mechanically separated. The primary coolant pump requires more power, approximately 1 kWe, to circulate the primary water through the long coil of piping.

At the thermal power level of 750 kWth convective cooling results in reactor inlet and shield water temperatures on the order of 420 K (296 F). Primary coolant flow is increased to operate the core at higher inlet temperature. A consequence of higher shield water temperature is higher end-of-mission fission product pressure in the interelectrode spaces of the converters. In the TFE designed for NEMO, the temperature of each TFE's charcoal trap determines the fission product pressure in the converters. The traps are located in the upper portions of the TFE where temperatures are in equilibrium with the shield water temperature. Higher pressures in the converters at end-of-mission reduces electrical performance severely, and so TFEs in which fission products and cesium are mixed cannot be used with the alternative cooling system.

2.9.2 Electrical Connection Cables

The alternative electrical connection shown in Figure 2.2 employs individual electrical cables for the connection of each TFE to the user's power conditioning and/or distribution System. The cables contain

two high current power leads and a smaller lead for the cesium reservoir heater current. Cables are neoprene clad. Each cable is terminated by marine-type electrical connectors. The connectors are of the sort used in subsea applications, and in this case are used in a borated water environment.

This alternative eliminates the oil-filled dome of the reference design. Thus, it eliminates the redundant structural support of the TFE shutdown rod and drum drive extension tubes at their upper end. The cables appear to be more expensive than their increased flexibility warrants, and there is a question of the reliability of the marine connectors available. Selection of the type of electrical connection is a decision to be made with potential users.

2.10 DEVELOPMENT AREAS

Several areas appear at the conclusion of this conceptual design study to require development engineering or concentrated analytical effort to demonstrate their reliable function in the NEMO power plant.

2.10.1 LF Series TFE

The LF series fuel element is a test vehicle for new component concepts based on the F series of converters. (The F series design has evolved for six years in the AEC's thermionic reactor development program at Gulf General Atomic.) From the LF development and testing programs, a fuel element design will evolve which contains some if not all of the features of the first LF models. Those features of the first LF series are assumed for the NEMO TFEs. Testing of the first two LF series TFEs will begin in March 1973 and June 1973. Upon completion of these tests the details of a reference design NEMO TFE could be selected.

2.10.2 Borated Shield Water

The selection of the borated solute for the shield water must be based on solubility, electrolytic and corrosion characteristics under the exact condition and design environment of the NEMO. If applicable chemical data cannot be found in a literature search more thorough than the one conducted for this study, then an experimental effort is called for to determine the needed properties.

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3. THERMIONIC REACTOR FOR INSTALLED OCEANIC SERVICE (TRIOS)

The Thermionic Reactor for Installed Oceanic Service (TRIOS) is a self-contained 5 kWe nuclear-electric power source designed for unattended operation on the ocean bottom at depths up to 411 m (1350 ft). It has no moving parts, except for the infrequent actuation of control rods, and is therefore an essentially noise-free system. The design is based on use of the well-proven TRIGA reactor as a driver core for the thermionic fuel elements, resulting in a relatively inexpensive and reliable system. It represents a modest extrapolation of techniques used to test TFEs at Gulf General Atomic in the TRIGA Mark III Thermionic Test Reactor (TTTR). This technology base should eliminate the need for development of a test prototype or an extensive experimental program.

Thermionic fuel elements, qualified for 10,000-hour continuous operation at 0.85 kWe per TFE, should be available by FY 74, and demonstration of a 20,000-hour capability is expected within several years. The present TRIOS design rating is 10,000-hour maintenance-free operation between TFE replacements, and a reactor core life of 50,000 hours using TRIGA FLIP* fuel elements.

Heat transport is accomplished by natural convection in both the primary and secondary coolant loops in order to reduce the auxiliary power requirement and increase system reliability and safety. Double containment design criteria provide protection from release of radioactive materials, and the large prompt negative fuel temperature coefficient of reactivity of the TRIGA fuel provides inherent safety and control stability. Overall design specifications are summarized in Table 3.1.

*TRIGA fuel elements and reactors are discussed in Appendix A.

TABLE 3.1

TRIOS DESIGN SPECIFICATIONS

Thermal Power	600 kW(t)
Net Electrical Power	5 kW(e)
Voltage	Conditioned as Required
Fuel Elements	U-ZrH TRIGA FLIP
U ²³⁵ Core Loading	21.2 kg
Core Reload Period	50,000 hr
Thermionic Fuel Element Replacement	10,000 hr
System Overall Height	9.16 m (30 ft)
Shield Tank Diameter	3.14 m (10.3 ft)
Seawater Shroud Diameter	5.70 m (18.7 ft)
System Dry Weight	29,000 kg (64,000 lb)
Water Shield Weight	20,000 kg (44,000 lb)
Water Coolant Weight	910 kg (2,000 lb)
Submerged Weight	15,500 kg (34,000 lb)
Maximum Surface Dose Rate	44 mrem/hr
Maximum Dose Rate in Controls Compartment	10 mrem/hr
Seawater Activation	Less than MPC

3.1. SYSTEM DESCRIPTION

A layout of the TRIOS system is shown in Fig. 3.1. The power supply consists of the following basic components:

1. TRIGA FLIP core and control rods
2. Thermionic fuel elements
3. Pressure vessel and primary coolant system
4. Secondary coolant system
5. Shield tank
6. Controls and Instrumentation compartment

A standard TRIGA reactor core is used as the nuclear driver for the thermionic fuel elements. Fission heat, generated within the TFE fuel, is converted directly to electricity by the thermionic emission process. Waste heat from the TRIGA fuel elements and TFEs is removed from the reactor core by natural circulation of water in the primary coolant system. The deionized water is heated as it passes through the core and flows up through the core support shroud. This shroud separates the two legs of the thermal siphon and directs the coolant down through the primary heat exchanger located in the annulus inside the pressure vessel. Cooling is also effected by natural circulation of deionized water in the secondary coolant system, and the waste heat is dissipated to seawater in the secondary heat exchanger by natural convection. As no dynamic components are required in this heat transfer system, high reliability and inherent safety are provided. Double containment is employed to minimize the possibility of release of radioactive materials or entry of seawater into the primary coolant system.

The primary and secondary coolant systems are pressurized by gas-actuated accumulators located in the controls compartment. The accumulators compensate for thermal expansion during startup or other transients, and provide the pressurization required to prevent bulk nucleate boiling. Rupture discs and check valves provide for overboard discharge from each

FIGURE 3.1

TRIOS POWER PLANT ELEVATION

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loop in the event of an accidental pressure surge (see Fig. 3.2). Discharge from the primary coolant system is collected in a holding tank to maintain containment integrity.

The radiation shielding is primarily water, which is used to reduce the TRIOS dry weight and simplify transport and handling. The shield tank is hermetically sealed and pressure-equalized. It provides containment for neutron activation products formed in the distilled water, and reduces activation in the seawater to permissible levels. A wire mesh shroud surrounding the shield tank prevents access to seawater areas having radiation levels above 100 mrem/hr. Some lead gamma shielding is mounted on the pressure vessel to reduce the shield shroud diameter to a size which can be easily handled and installed.

The pressure hull welded to the top of the reactor vessel houses controls and instrumentation, control rod drives, switchgear and power conditioning, coolant loop accumulators, and miscellaneous electrical cabling and process piping. An access hatch is provided for maintenance, repair, and refueling operations. The coupling flange located above the access hatch provides a pressure seal mating surface used for temporary connections to a transfer and repair vessel. Maintenance, repair, and refueling can be accomplished on the sea bottom without need for retrieval of the TRIOS.

3.2. REACTOR

The reactor core consists of 106 TRIGA fuel elements, 9 thermionic fuel elements, and six fueled follower control rods fitted inside the 489 mm (19.25 in.) core shroud. The core has a 152 mm (6-in.) water side reflector, and the fuel elements have 86 mm (3.4-in.) long graphite end reflectors in addition to the water cover. The TFEs have 64 mm (2.5 in.) long beryllia end reflectors. A schematic of the reactor cross section is shown in Fig. 3.3. Elements are spaced in a regular equilateral triangular array on centers 39.57 mm (1.558 in.) apart, providing a coolant volume fraction of 25%.

FIGURE 3.2 TRIOS FLOW DIAGRAM

FIGURE 3.3 TRIOS REACTOR SECTION

5

4

BLANK

3

2

1

0

1

2

Upper and lower grid plates are used to locate individual fuel elements in the core. A retainer plate is located above the upper grid plate to hold the elements in place if the entire system is accidentally inverted. Sufficient space is provided below the bottom grid plate to permit full insertion of the control rods, and minimal hydraulic resistance to coolant return flow.

The six control rods are individually operated by separate drives. The drive mechanism contains a rack and pinion to provide vertical movement of the control rods in the core. The control rods are guided through the core inside fixed, stainless steel, perforated tubes.

3.2.1. Fuel Elements

The fuel elements are the standard long lifetime TRIGA-FLIP type, except the active fuel length has been increased to 422 mm (16.6 in.) to match with the TFE. The fuel consists of delta phase uranium-zirconium hydride with a hydrogen-to-uranium atomic ratio of 1.6 and 8.5 wt-% uranium. The average uranium enrichment is 63% U^{235} . Differing enrichments in radial zones may be used to shape the power distribution. A small amount of erbium (1.6 wt-%) is included as burnable poison which maintains the reactivity of the fuel relatively constant throughout the 50,000-hour operating lifetime and enhances the prompt negative temperature coefficient. The fuel element cladding is 0.508 mm (0.020 in.) thick type 316 stainless steel. Fabrication details are shown in Fig. 3.4.

Thermionic fuel element design details* are discussed in Section 2.2.3.

3.2.2. Control Rods and Drives

The control rods are the standard TRIGA Fueled Follower Control Rods which have an overall length of 1140 mm (45 in.) and 34.3 mm (1.35 in.) diameter. The active fueled region is the same as the fuel elements. The neutron absorbing region is graphite containing 25 wt-% boron carbide. These control rods minimize power peaking in the adjacent region when the rod is withdrawn, and maximize control rod worth.

*See also Appendix B, TFE Performance Parameters

FIGURE 3.4 TRIOS FUEL ELEMENT

The control rod drives are mounted on the reactor pressure vessel head near the rod penetrations. Canned-rotor stepping motors are used to drive a pinion gear located in the control rod guide tube extension. The rack and pinion gear set translates the rotary motion into the linear movement required to position the control rods. Position indication is obtained from a linear variable differential transformer (LVDT) mounted at the end of the guide tube. Loss of an electrical signal will release the drive magnetically and allow the rod to move into the core under gravitational and spring force. Each rod is spring-loaded at the top of each tube for positive insertion if the system is accidentally inverted, and is latched during transport. Dash pots are installed to absorb the insertion energy and prevent damage to the control rods and mechanism.

3.2.3. Neutronics

The overall design objective is to use TRIGA FLIP driver fuel elements and thermionic fuel elements in a core configuration which has the following characteristics:

1. Large prompt negative fuel temperature coefficient of reactivity for safety and control stability
2. Reactivity compensation adequate to provide 50,000-hour core lifetime, simplify control requirements, and minimize power peaking
3. Relatively flat radial power distribution in central core region where TFEs are located
4. Moderate fuel inventory
5. Low burnup rate (high thermal efficiency)

One-dimensional transport calculations were performed to estimate fuel requirements and power distribution. The calculated radial power distribution is shown in Fig. 3.5 and compared with experimental measurements in

FIGURE 3.5
RADIAL POWER DISTRIBUTION

the TITR core for 100 FLIP elements. The axial TFE power distribution in the TITR (Ref. 3.1) is shown in Fig. 3.6. The TITR core is similar to the TRIOS with the following basic exceptions:

1. Fuel element spacing is 43.54 mm (1.714 in.)
2. Weight of U^{235} per FLIP element is 136 gm
3. Maximum TFE fuel loading is 600 gm of U^{235} (limited by AEC license agreement)

Using a U^{235} enrichment of 30% in the central 18 FLIP elements and an enrichment of 70% in the outer 94 (including control rod followers) increases the fraction of thermal power in the TFEs, and results in a flatter power distribution in the central core region. The typical TITR operating power required to drive experimental TFEs is 1500 kW(t), as compared with 600 kW(t) for the TRIOS. The fraction of the reactor core thermal power produced in the TFEs is approximately 14% for TRIOS.

Reactor nuclear parameters are summarized in Table 3.2. Neutronic characteristics are sufficiently well defined to establish feasibility of the conceptual design based on extensive experience with the similar TITR core. Additional neutronic calculations and parametric analyses are required to determine detailed specifications and to optimize the design for thermal efficiency, power flattening, minimum fuel inventory, and controllability.

3.2.4. Heat Transfer

Heat transfer in the reactor core occurs by natural convection, and local subcooled boiling in the high heat flux channels. Thermal energy is transported from the core by a gravity thermal siphon (primary coolant system). The water coolant is pressurized to prevent bulk nucleate boiling at the operating temperature. Core heat transfer characteristics are summarized in Table 3.3.

FIGURE 3.6
COMPOSITE AXIAL TFE POWER PROFILE IN TITP

TABLE 3.2

TRIOS POWER PLANT PARAMETERSReactor Core

Mean Diameter	475 mm (18.7 in.)
Active Height	422 mm (16.6 in.)
Number of FLIP Elements	106
Number of Fueled Follower Control Rods	6
Number of TFEs	9
Fuel Element Spacing	39.57 mm (1.558 in.)
U ²³⁵ Core Loading, kg	21.2
Side Reflector Material	H ₂ O
Side Reflector Thickness	152 mm (6.0 in.)
Gross Electrical Power	7.65 kWe
Thermal Power	600 kWth
Power Fraction on TFEs, %	14

FLIP Elements

Outside Diameter	37.69 mm (1.484 in.)
Overall Length	762 mm (30.0 in.)
Clad Material	304 SS
Clad Thickness	0.508 mm (0.020 in.)
End Reflector Material	Graphite
End Reflector Thickness	86 mm (3.4 in.)
Fuel Composition	U-ER-ZrH _{1.6}
U-content, Wt-%	8.5
Average U ²³⁵ Enrichment, %	63.5
Weight of U ²³⁵	124 gm
Erbium Content, Wt-%	1.6
Total Fuel Element Loading, U ²³⁵	13.9 kg

TABLE 3.2 (cont'd.)

Thermionic Fuel Elements

Outside Diameter	38.1 mm (1.50 in.)
Active Length	422 mm (16.6 in.)
End Reflector Material	BeO
Weight of U ²³⁵ , (one element)	800 gm
Total TFE Fuel Loading, U ²³⁵	7.20 kg
Electrical Power	0.85 kWe
Total TFE Thermal Power	84 kWth

Fueled Follower Control Rods

Outside Diameter	34.3 mm (1.35 in.)
Overall Length	1140 mm (45 in.)
Fuel Length	422 mm (16.6 in.)
Neutron Absorber	Graphite-25% B ₄ C
Weight of U ²³⁵	100 gm
Total Control Rod Loading, U ²³⁵	0.60 kg

ElectricalPer TFEPower Plant

Gross Output	0.85 kW	7.65 kW
Lead Losses	156 W	1.4 kW
Power Conditioning Losses at 80% Efficiency		1.25 kW
Net Power		5 kW

TABLE 3.3

CORE HEAT TRANSFER CHARACTERISTICS

Thermal Power	
FLIP Elements and Control Rods	516 kWth
TFEs	84 kWth
Outlet Temperature	416°K (290°F)
Inlet Temperature	389°K (240°F)
Pressure	2.62×10^6 N/m ² (380 psia)
Coolant Flow Rate	18,600 kg/hr (41,000 lb/hr)
Hydraulic Diameter	12.7 mm (0.50 in.)
Coolant Velocity	0.119 m/sec (0.39 ft/sec)
Heat Transfer Surface Area	
TRIGA FLIP Elements & Control Rods	5.57 m ² (60 ft ²)
TFEs	0.455 m ² (4.9 ft ²)
Average Heat Flux	
TRIGA FLIP Elements & Control Rods	9.27 W/cm ² (29,400 BTU/hr-ft ²)
TFEs	18.41 W/cm ² (58,400 BTU/hr-ft ²)
Maximum Heat Flux	
TRIGA FLIP Elements & Control Rods	17.65 W/cm ² (56,000 BTU/hr-ft ²)
TFEs	20.5 W/cm ² (65,000 BTU/hr-ft ²)
Burnout Heat Flux	257.6 W/cm ² (817,000 BTU/hr-ft ²)
DNB Ratio	12.5
Water Saturation Temperature	500°K (440°F)
Maximum TFE Surface Temperature	511°K (460°F)
Maximum TRIGA-FLIP Surface Temperature	511°K (460°F)
Maximum TRIGA-FLIP Cladding Temperature	516°K (469°F)
Maximum TRIGA-FLIP Clad-Fuel ΔT	6°K (11°F)
Maximum TRIGA-FLIP Centerline Temperature	596°K (613°F)

The TRIOS core heat transfer correlation for film temperature drop versus heat flux is shown in Fig. 3.7. The Dittus-Boelter equation (Ref. 3.2) for fluid heating inside tubes was used to calculate the nonboiling region of the curve which extends to a heat flux of about 12.61 W/cm² (40,000 BTU/hr-ft²). Surface boiling heat transfer was calculated using the Jens and Lottes equation (Ref. 3.3):

$$\Delta T_{\text{sat}} = t_w - t_{\text{sat}} = \frac{1.9 (q/A)^{1/4}}{e^{P/900}}$$

and the peak heat flux is obtained from (Ref. 3.3):

$$(q/A)_p = 400,000 V^{1/3} + 4800 (t_{\text{sat}} - t) V^{1/3}$$

where q/A = heat flux, BTU/hr-ft²

P = pressure, psia

V = velocity, ft/sec

t_{sat} = fluid saturation temperature, °F

t_w = surface temperature, °F

t = fluid temperature, °F

Some local boiling will occur on the surface of the TFEs, which have a near uniform heat flux of about 18.9 W/cm² (60,000 BTU/hr-ft²). Few of the FLIP elements and fueled follower control rods will have any regions of local boiling. The volume fraction of water vapor is therefore quite small and will have little effect on the reactivity of the core. Temperatures throughout the core are low and well within corrosion, compatibility, and stability limits of the materials used.

3.3. PRESSURE VESSEL

The TRIOS reactor pressure vessel is nominally a right circular cylinder of 4.37 m (172 in.) overall length (see Fig. 3.1). The central section has a diameter of 700 mm (27½ in.), and the end sections are enlarged to house the primary coolant heat exchanger and core reflector.

FIGURE 3.7

REACTOR CORE HEAT TRANSFER CORRELATION

The lower head is a standard 2:1 semi-elliptical design with a welded closure. The upper head is a dished semi-elliptical design, and is integral with the vessel flange forcing. Penetrations are provided in the upper head for the six control rods and nine TFEs.

The entire vessel is fabricated from Type 304L stainless steel, and will be designed to operate at a maximum external pressure of $4.14 \times 10^6 \text{ N/m}^2$ (600 psia) and 505°K (450°F). Detailed design will be in accordance with the A.S.M.E. Code, Section III, Class I.

The entire weight of the reactor system, and controls compartment is supported by the pressure vessel flange bolted to beams inside the water shield tank. The support flange is located near the system center of mass to minimize transmission of moments into the reactor structure by extraneous lateral accelerations.

3.4 SHIELDING

A diagram of the components of the TRIOS system shielding is shown in Figure 3.8. Shielding is required to reduce radiation levels in the area surrounding the reactor to prevent radioactive contamination by neutron activation of the seawater and radiation exposure of marine organisms. Additionally, radiation levels in the controls compartment must be low enough to permit personnel access for maintenance, repair, and refueling operations. The full-power design doses are (1) 44 mrem/hr at exterior perimeters; (2) on the order of 10 mrem/hr in controls compartments; and (3) MPC (10 CRF-20) of activation products in seawater assuming no dilution. The design objective is to use water shielding to the maximum extent possible to minimize overall system dry weight.

The radial detail of the shield configuration is shown in Figure 3.9. It consists primarily of lead gamma shielding at the pressure vessel surface, a hermetically sealed water shield tank, and a wire mesh seawater shroud. The water shield tank attenuates neutrons to a level which will not produce any significant activation in the seawater surrounding the power supply.

FIGURE 3.8 SHIELDING

FIGURE 3.9. TRIOS SHIELD CONFIGURATION

It is hermetically sealed to contain radioactive activation products formed in the water, and pressure-equalized to reduce the tank weight. Distilled water provides a reasonable sized neutron shield and eliminates the corrosion and solubility problems associated with neutron absorbing solutes such as boron compounds.

Lead is an efficient and inexpensive core gamma shield used to reduce the seawater shroud to a reasonable diameter. The lead shield is clad with Boral to reduce the thermal flux and the production of capture gamma rays in the lead. Seawater shielding is required to attenuate the 2.23 MeV gammas produced in the water shield tank by the $H(n, \gamma)D$ reaction. The seawater shield also reduces the lead capture gammas and reactor core gammas to acceptable levels. The neutron dose at the seawater shroud is negligible. Contributions by the principal gamma sources are:

	<u>Dose Rate (mrem/hr)</u>
H(n, γ)D reaction in shield tank	31
Neutron capture gammas in lead	1
Reactor core gammas	4
TOTAL	<hr/> 44

3.5. PRIMARY COOLANT SYSTEM

The primary coolant circulates in the reactor pressure vessel by natural convection. The driving force for the thermal siphon is obtained from the gravity head between the hot fluid rising from the core and the cold fluid returning from the primary heat exchanger. The two flow channels are separated by the core support shroud. The temperature distribution in the primary coolant loop is shown in Fig. 3.10. The effective height of the thermal siphon, $\bar{y}$, is 1.98 m (6.5 ft) and the driving pressure, ΔP_s , is

$$\begin{aligned}\Delta P_s &= \bar{y}(\Delta \rho) \\ &= 456 \text{ N/m}^2 \text{ (9.52 psf)}\end{aligned}$$

Figure 3.10.. Primary coolant system temperature distribution

PRIMARY COOLANT SYSTEM TEMPERATURE DISTRIBUTION

where $\Delta\rho$ = density differential, 23.47 kg/m^3 (1.465 lb/ft^3). The sum of all pressure drops throughout the coolant loop is equal to 456 N/m^2 (9.52 psf) for thermal-hydraulic equilibrium.

The primary coolant heat exchanger is a single-pass, cross-flow type. Coolant flows across the tube bank which is located in the annulus between the core support shroud and reactor pressure vessel. The tubes encircle the core shroud and are connected to the entrance and exit header for the secondary system. Design specifications for the primary heat exchanger are summarized in Table 3.4. Pressure drops in the primary coolant system are:

	<u>ΔP (psf)</u>	<u>N/m^2</u>
Reactor	2.05	98.15
Heat Exchanger	4.75	227.43
Ducting	<u>2.72</u>	<u>130.23</u>
TOTAL	9.52	455.81

Corrosion-resistant structural materials, water and system pretreatment, and hermetic sealing is used in the TRIOS to avoid the need for continuous primary water treatment. Stainless steels, which have excellent corrosion resistance to high-purity water at the low TRIOS operating temperature, are used throughout the system. Surfaces of the primary system will be cleaned and pretreated, and then treated in situ to de-aerate, deoxygenate, demineralize, and departiculate. The sealed system will then be purged and prepressurized with hydrogen gas to an equivalent partial pressure of several atmospheres of dissolved hydrogen.

Residual dissolved oxygen in the water will initially oxidize surfaces in the system, forming a protective barrier which inhibits further corrosion. The dissolved hydrogen tends to shift the equilibrium so as to enhance recombination rates of the H_2 and O_2 radiolytic decomposition products. A catalytic recombiner should not be required to maintain

TABLE 3.4
PRIMARY HEAT EXCHANGER SPECIFICATIONS

	<u>SHELL SIDE</u>	<u>TUBE SIDE</u>
Fluid	Deionized Water	Deionized Water
Inlet Temperature	417°K (290°F)	325°K (125°F)
Outlet Temperature	394°K (250°F)	367°K (200°F)
Flow Rate	18,600 kg/hr (41,000 lb/hr)	12,380 kg/hr (27,300 lb/hr)
Pressure	$2.62 \times 10^6 \text{ N/m}^2$ (380 psia)	$1.38 \times 10^5 \text{ N/m}^2$ (200 psia)
Pressure Drop	227 N/m^2 (4.75 psf)	182 N/m^2 (3.80 psf)
Heat Transfer Effectiveness		0.45
Number of Transfer Units		1.0
Overall Heat Transfer Coefficient		$965 \text{ W/m}^2\text{-}^\circ\text{C}$ (170 BTU/hr-ft ² -°F)
Shell-Side Heat Transfer Area		14.86 m ² (160 ft ²)
Overall Dimensions		152 x 610 x 1220 mm (6 x 24 x 48 in.)

system pressures within the capability of the pressure vessel during the 10,000-hour maintenance-free operating period.

3.6. SECONDARY COOLANT SYSTEM

Thermal energy is transferred from the reactor vessel to seawater by natural circulation in the secondary coolant system. This auxiliary heat transfer loop provides secondary containment for radioactive contaminants and protection from entry of seawater to the reactor core. A higher reactor operating temperature results from use of a dual loop system; however, the temperature required is well below materials capabilities. Additionally, higher coolant temperatures promote recombination of radiolytic decomposition products and decrease the equilibrium gas pressure in the sealed system.

The deionized water coolant flows through the tube side of the primary heat exchanger, and is transported to the tube side of the seawater heat exchanger by thermal siphon forces. Heat is rejected from the tube surface to seawater by natural convection. Design specifications for the seawater heat exchanger are summarized in Table 3.5. Pressure drops in the secondary coolant system are:

	<u>ΔP (psf)</u>	<u>ΔP (N/m²)</u>
Seawater heat exchanger	2.20	105.3
Primary heat exchanger	3.80	181.9
Piping	<u>1.50</u>	<u>71.8</u>
TOTAL	7.50	359.0

The minimum required height of the thermal siphon, $\bar{y}$, is therefore,

$$\begin{aligned}\bar{y} &= \frac{\Delta P}{\Delta \rho} \\ &= 1.60 \text{ m (5.26 ft)}\end{aligned}$$

where $\Delta \rho$ = density differential, 22.84 kg/m³ (1.426 lb/ft³).

TABLE 3.5

SEAWATER HEAT EXCHANGER SPECIFICATIONS

Fluid	Deionized Water
Inlet Temperature	366°K (200°F)
Outlet Temperature	325°K (125°F)
Flow Rate	12,380 kg/hr (27,300 lb/hr)
Pressure	1.38×10^6 N/m ² (200 psia)
Pressure Drop	105.3 N/m ² (2.20 psf)
Type Heat Exchanger	Single-Pass, Cross-Flow
Seawater Temperature	283°K (50°F)
Heat Transfer Effectiveness	0.50
Number of Transfer Units	0.75
Overall Heat Transfer Coefficient	369 W/m ² -°C (65 BTU/hr-ft ² -°F)
Heat Transfer Area	28.80 m ² (310 ft ²)
Tube Outside Diameter	10.80 mm (0.425 in.)
Number of Tubes	560
Tube Material	90/10 Copper-Nickel
Overall Dimensions	0.914 m dia. x 1.83 m lg. (3 ft dia. x 6 ft lg.)

The tube wall temperature varies from about 305 to 327°K (90 to 130°F) throughout the length of the seawater heat exchanger. Heat transfer experiments in seawater (Ref. 3.4) have shown that marine fouling does not occur on heated metal surfaces above 311°K (100°F), and corrosion scale formation is not greatly affected over the temperature range of 311 to 333°K (100 to 140°F). The heat exchanger is fabricated with 90/10 copper-nickel alloy, which provides anti-fouling protection, is not susceptible to crevice corrosion or pitting, and has a low uniform corrosion rate (less than 0.025 mm/yr, or 0.001 in./yr).

3.7. SAFETY

Safety characteristics of the TRIOS system are summarized in Table 3.6.

The major safety features are: (1) the large prompt negative fuel temperature coefficient of reactivity of the TRIGA U-ZrH fuel; (2) heat transfer by natural circulation in both the primary and secondary coolant systems; and (3) double containment of the reactor core.

During in-pile transient fuel tests, U-ZrH fuel material has been repetitively pulsed to peak adiabatic temperatures of 1100 to 1200°C with complete safety (Ref. 3.5). The maximum fuel temperature during steady-state operation at the design point is 325°C, which provides a large safety margin for an accidental power transient.

The relationships between hydrogen content, temperature, and pressure of ZrH_x have been defined (Ref. 3.6), for example:

	<u>Pressure, atm.</u>			
	<u>1000°C</u>	<u>1100°C</u>	<u>1200°C</u>	<u>1300°C</u>
$ZrH_{1.6}$	20	100	500	2500
$ZrH_{1.7}$	40	200	1000	5000

TABLE 3.6

TRIOS SAFETY CHARACTERISTICS

1. Large prompt negative temperature coefficient of reactivity for UZrH fuel
2. Double containment of reactor core
3. Heat removal by natural circulation in primary and secondary coolant systems
4. Maximum surface radiation dose rate is 100 mrem/hr at full power
5. Maximum dose rate in controls compartment is 10 mrem/hr at full power
6. Neutron activation in seawater is less than MPC, assuming no dilution
7. Low operating temperatures in fuel and coolant
8. Low system pressure and stored energy
9. Fail-safe shutdown

By limiting the composition of the fuel element to the range $\text{ZrH}_{1.5}$ to $\text{ZrH}_{1.6}$ and using 0.020-in. thick cladding material, the hydrogen pressure resulting from a nuclear excursion could be contained at temperatures up to 1100 to 1200°C. Pulse heating to high temperatures (up to 1400°C) has been shown to result in the rapid release of hydrogen without any catastrophic explosion or swelling of the specimens (Ref. 3.7). Physical properties of delta-phase U-ZrH are listed in Table 3.7. The fuel temperature coefficient of reactivity $\delta k/T$, is approximately -1×10^{-4} for the TRIOS.

There are three containment barriers between the fuel and seawater: (1) the fuel element cladding; (2) the primary coolant pressure vessel; and (3) the shield tank, controls compartment or secondary coolant loop. Each of the barriers are structurally independent insofar as containment is concerned. The conventional temperature, pressure, and neutron flux trip signals are supplemented by coolant and shield water radioactivity and salinity trip signals to monitor containment integrity. Remote means of performing a restart sequence is incorporated to counter a spurious trip shutdown without requiring access to the TRIOS. An accelerometer trip signal is also provided to shut down the reactor in the event of high seismic activity or an undersea collision.

Heat transfer is by natural circulation in both the primary and secondary coolant systems, and is therefore not subject to pump mechanical failure. Changes in pressure, temperature, and conductivity (salinity) beyond protective set points will produce trip signals which shut the system down. Convective heat transfer from the surface of the reactor pressure vessel to the shield water tank is adequate to maintain a safe temperature following shutdown.

TABLE 3.7

PHYSICAL PROPERTIES OF DELTA-PHASE U-ZrH

Thermal Conductivity at 500°F	0.21 W/cm-°C (13 BTU/hr-ft-°F)
Thermal Expansion Coefficient	$11.7 \times 10^{-6}/^{\circ}\text{K}$ ($6.50 \times 10^{-6}/^{\circ}\text{F}$)
Density:	
93 Zr-7U (weight percent)	6.8 g/cm ³
93 Zr-7U-H _{1.73} (weight percent)	5.94 g/cm ³
Heat Capacity:	
At 400°F	6 cal/mole-°C
At 1200°F	12 cal/mole-°C
Heat of Formation (δH_{f0298})	37.72 kcal/g-mole
Strength (4, 6-8):	
Elastic Modulus	6.3×10^{10} N/m ² (9.1×10^6 psi)
Ultimate Tensile Strength	1.65×10^8 N/m ² (24,000 psi) up to 922°K (1200°F)
Compressive Strength	4.15×10^8 N/m ² (60,000 psi) at room temperature
Compressive Yield	2.42×10^8 N/m ² (35,000 psi) at room temperature

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- 3.3 Ibid. p. 393.
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- 3.6 W. P. Wallace and M. T. Simnad, Metallurgy of TRIGA Fuel Elements, Gulf General Atomic Report GA-1949, 1961.
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4. PROTOTYPE DEVELOPMENT AND COSTS FOR NEMO AND TRIOS

4.1 DEVELOPMENT PROGRAM

The effort expended in defining the development program and estimating its costs was very limited.

4.1.1 Development Tests

The development effort required to produce a prototype power plant is mainly standard engineering in the adaptation of TFE and TRIGA technology to the product requirements. Some development testing is desirable to evaluate design features of the power plant. The development tests include the following: control mechanism tests; vessel hardware qualification fuel element containment test; pressurizing system testing; critical cell test; and, zero power critical test. These tests are described below.

4.1.1.1 Control Mechanism Tests. The NEMO power system has two kinds of control actuation devices. They are an electrically driven control element drive and a hydraulically driven shutdown rod drive. These drives penetrate the reactor vessel. The actuators are located in the space above the reactor vessel and are sufficiently remote and shielded so that radiation damage to the actuators is not an important design constraint. The development test is to fabricate a single unit of each type and to operate it in an environment that simulates the pressures and temperatures encountered. Each unit is operated for a number of cycles equivalent to its predicted lifetime in service. These tests evaluate the adequacy of the design. The TRIOS system employs a motor-driven, rack and pinion rod. This mechanism is similarly tested.

4.1.1.2 Unique Vessel Hardware Tests. In the NEMO design the TFEs are held onto the vessel with Marman-type clamps sealed with rubber o-rings. The ASME Boiler and Pressure Vessel Code, Section III (Ref. 2.8) permits the use of connections other than bolted flanges in Class 1 applications if a prototype joint has been subjected to performance tests to determine the safety of the

joint under simulated service conditions and if the design provides that separation of the joint is prevented under all conditions of service. Such a demonstration precedes the final design of the NEMO reactor and vessel.

4.1.1.3. Fuel Element Containment. This is a fabrication development test in which the assembly consisting of stainless steel containment, fission gas trap, seals and electrical lead is constructed. Critical joints are then tested by thermal and pressure cycling to evaluate their reliability in service. It is assumed that several TFEs of the reference reactor configuration will be irradiation tested in the TFE development program.

4.1.1.4. Pressurizing System Qualification. Analytical and/or experimental determination must be made of the reliability of the primary coolant pressurizing subsystem. The proposed components are all available commercially. The selection of reference design hardware must be made carefully to assure reliable performance and compliance with the applicable codes and regulations. The selection and qualification must also be made early, since most components approved for nuclear application have long delivery.

4.1.1.5. Critical Cell Test. This is a nuclear experiment in which an assembly consisting of 7 mockup TFEs and 24 FLIP TRIGA fuel elements is installed in a TRIGA core at GGA. The reactor is made critical at low power and the flux distributions measured within the assembly. The information from this test gives needed nuclear design information for calculation of neutron flux spectrum, power distribution and shielding factors in the power reactor under development.

4.1.1.6. Zero Power Critical Test. This test is performed when the components of the power reactor are available, but not assembled. The core is assembled in the open pressure vessel in a shield pool (probably TRIGA Mark F at GGA). The assembly is made critical at low power and reactivity worths of fuel elements and control elements are measured. This allows an opportunity to do reactivity shimming before the reactor vessel is sealed.

Additionally, power distribution measurements are made to evaluate the nuclear design and confirm the distribution of heat dissipation to the coolant assumed in the thermal-hydraulic analyses.

4.1.2 Development Schedule

The development schedule is shown in Figure 4.1. The activities listed result in the production of a prototype plant in a time period of 34 months from the date of initiation of a fully staffed program. Fuel element development is not shown. It is assumed to be supported in the AEC-sponsored development program.

The development programs for the 30 kWe and 5 kWe plants are not now well enough defined to distinguish between them in the total time needed to produce a prototype. The schedule is given in Figure 4.1 applies to both plants.

4.2 COST ESTIMATE

An engineering cost study was performed for each of the two designs presented. The development and recurring cost estimates are given in Table 4.1 and 4.2 for the NEMO and TRIOS, respectively. The recurring cost for each design is also plotted versus electrical power output in Figure 4.2. In the figure the costs are extrapolated to cover the 1 kWe to 100 kWe range for planning purposes. For a comparison of cost with a competitive power conversion concept at the tower levels the estimated cost of radioisotope-thermoelectric generators is also plotted on Figure 4.2. The fuel is SrF_2 at the price advertised by the government with availability in the summer of 1973. The cross-over in cost occurs at a power output level of 2 kWe.

The basis of these cost estimates is the experience Gulf General Atomic has in fabrication of similar components, especially for the TRIGA reactors. Some equipment cost items are based upon vendor prices. The labor estimates are based upon time and services for commercial work rather than for typical space program requirements.

The development costs include all of the activities and procurements resulting in the final assembly of a prototype power plant. They do not include shipping or testing of the device. The training costs listed are

FIGURE 4.1 DEVELOPMENT SCHEDULE

TASK	MONTH	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
1. <u>REACTOR ENGINEERING</u>																			
- NUCLEAR ANALYSIS																			
- THERMAL-HYDRAULIC ANALYSIS																			
- MECHANICAL DESIGN & ANALYSIS																			
- CONTROL ANALYSIS																			
- HAZARDS ANALYSIS																			
2. <u>PLANT DESIGN</u>																			
- INSTRUMENTATION & CONTROL																			
- HEAT TRANSFER LOOP																			
- WATER CHEMISTRY																			
- SHIELDING																			
- PLANT LAYOUT																			
3. <u>DEVELOPMENT TESTING</u>																			
- CRITICAL CELL																			
- VESSEL HARDWARE TESTING																			
- TFE CONTAINMENT																			
- PRESSURIZING SYSTEM QUALIFICATION																			
- ZERO POWER CRITICAL																			
- CONTROL DRIVE & SHUTDOWN ROD																			
4. <u>SAFETY REPORTS</u>																			
5. <u>FABRICATION AND PROCUREMENT</u>																			
- REACTOR HARDWARE																			
- SHIELD																			
- PLANT COMPONENTS																			
- FUEL ELEMENTS																			
6. <u>FINAL ASSEMBLY AND CHECKOUT</u>																			

TABLE 4.1
NEMO COST ESTIMATE

Costs are given in thousands of 1972 dollars
and include no fee or profit.

<u>HARDWARE</u>	<u>Development</u>	<u>Recurring</u>
Thermionic Fuel Elements	997	997
TRIGA Fuel Elements	159	159
Uranium - 235*	437	437
Mechanical Control Hardware (Shutdown Rods & Drive, Control Drums, Shaft Assy's Motors)	80	80
Reactor Vessel & Internals	20	20
Shielding Components	21	21
Instrumentation & Control (Neutron Source, Detectors, Electrical Reactor, Process & Rad. Monitor)	165	165
Coolant Loop(s) (Pumps, Heat Exchanger, Piping, Specialties)	139	139
Structure and Miscellaneous	30	30
QA & QC	50	50
Hardware Subtotal	2098	2098
<u>SOFTWARE</u>		
PSAR Reactor System	125	---
PSAR Critical Experiments	104	---
FSAR	100	---
Operating Manual	150	---
Software Subtotal	479	---

If the reactor is built for the U. S. Government, the cost of uranium-235
is specially accountable.

TABLE 4.1 (continued)

<u>DEVELOPMENT TESTS</u>	<u>Development</u>	<u>Recurring</u>
Control Mechanism Test	200	---
Fuel Element Containment	63	---
Critical Cell Test	138	---
Zero Power Critical	90	---
Vessel Hardware Testing	100	---
Pressurizing System Qualification	50	---
Development Test Subtotal	641	---
 <u>LABOR</u>		
Engineering	750	25
Management	200	50
Assembly & Checkout	125	125
Training	105	105
Labor Subtotal	<u>1180</u>	<u>305</u>
GRAND TOTAL	4398	2403

TABLE 4.2
TRIOS COST ESTIMATE

Costs are given in thousands of 1972 dollars
and include no fee or profit.

<u>HARDWARE</u>	<u>Development</u>	<u>Recurring</u>
Thermionic Fuel Elements	311	311
TRIGA Fuel Elements	207	207
Uranium - 235*	265	265
Mechanical Control Hardware (Control Rods, Drives, Motors)	40	40
Reactor Vessel & Internals	58	58
Shielding Components	26	26
Instrumentation & Controls (Neutron Source, Detectors, Electrical, Reactor, Process & Rad. Monitor)	92	92
Coolant Loop(s)	50	50
Structure & Miscellaneous	70	70
QA & QC	37	37
Hardware Subtotal	1156	1156
 <u>SOFTWARE</u>		
PSAR Reactor System	125	---
PSAR Critical Experiments	50	---
FSAR	100	---
Operating Manual	150	---
Software Subtotal	435	----

*If the reactor is built for the U. S. Government, the cost of uranium-235 is specially accountable.

TABLE 4.2 (Continued)

<u>DEVELOPMENT TESTS</u>	<u>Development</u>	<u>Recurring</u>
Control Mechanism Test	100	---
Fuel Element Containment	63	---
Zero Power Critical	90	---
Pressurizing System Qualification	50	---
Development Tests Subtotal	303	---
 <u>LABOR</u>		
Engineering	600	25
Management	200	50
Assembly & Checkout	100	100
Training	105	105
Labor Subtotal	<u>1005</u>	<u>280</u>
 GRAND TOTAL	 2899	 1436

FIGURE 4.2

THERMIONIC UNDERSEA POWER PLANT COST ESTIMATE (RECURRING COST, 1.372\$)

the estimated cost of instruction and do not include support of the trainees.

Remote restart of TRIOS may require a digital data acquisition and control computer. This equipment is not included in the listed costs.

APPENDIX A

TRIGA FUEL ELEMENTS AND REACTORS

The TRIGA^{*} fuel elements have a record of proven performance and demonstrated safety based on the experience of over 300 reactor-years of operation. As the driver elements of underwater thermionic reactors, they provide for the inherent safety of the reactor. The TRIGA reactor's inherent safety is due to the large prompt negative temperature coefficient of the uranium-zirconium hydride fuel. This negative coefficient provides that power rises initiated by the rapid insertion of large amounts of excess reactivity are automatically suppressed without external controls and the reactor immediately returns to normal operating levels.

TRIGA reactors were developed to provide a safe nuclear reactor especially suitable for use by universities, industrial laboratories, and medical centers. Since the program was initiated in 1956, forty-four TRIGA installations have been placed into operation on five continents. Forty-two TRIGAs are now operating and seven more are under construction. The continuing improvement in design has brought about the TRIGA-FLIP fuel. (The name of the FLIP fuel comes from the Fuel Lifetime Improvement Program.) This fuel contains more U-235 and has erbium burnable poison to allow burnup of core loadings to ten megawatt years. The addition of the small amount of erbium has no effect on the fuel's mechanical or chemical properties which contribute to its safety features, and enhances the prompt negative temperature coefficient

^{*}TRIGA is a registered trademark of Gulf Oil Corporation.

The TRIGA fuel has high fission product retention within the U-ZrH without swelling. The fuel is strong in compression, under thermal stress exhibiting radial cracking which does not disturb the radial heat flow. The U-ZrH is relatively insoluble in water.

TRIGA reactors are pool-type water cooled cores. Fuel element separation is 6mm(0.239 in.). Natural convection core cooling is employed in all TRIGAs installed to date since they are all designed for a steady state thermal power. For steady-state power levels in the range from 3 to 10 MW, forced flow core cooling is provided.

The Thermionic Test Reactor (TTTR) at Gulf General Atomic has been operating since January 1966 with thermionic fuel elements (TFEs) on-test in the core. The TTTR operates now with the FLIP fuel elements and up to ten TFEs (or equivalent experimental capsules) included in the core. The reactor power level is now nominally 1.5 MW.

APPENDIX B

TFE PERFORMANCE PARAMETERS

The electrical outputs of the NEMO and TRIOS designs are based on nominal TFE operating conditions. Power output of a TFE is sensitive to the current density, which is a function of the electrical load and to emitter temperature.

In Figure B-1 the electrical power output of the 6F series TFE is plotted as a function of current, emitter temperature and thermal input power of the TFE. This figure indicates how the operating parameters will affect the power output of the TFEs in an undersea thermionic reactor.