An Underwater Thermoelectric Reactor Plant

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A conceptual design is presented for an underwater thermoelectric nuclear power plant capable of producing continuous electric power at a 100-kwe level. The inherent advantage of a self-pressurized, natural circulation, pressurized water reactor (PWR) system is combined with a direct-conversion thermoelectric generator to provide a completely static system. The plant is designed for remote startup and completely unattended operation for over five years. Power is produced directly at 40 v; however, utilization of a solid-state inverter and storage batteries provides a peaking capability of several megawatts(e) at higher voltages. A low enriched core, with an inherently high negative temperature coefficient, is used which allows the control rods to be withdrawn completely at plant startup and to remain static throughout design life. No electronic controls, power monitoring, or feedback systems are required for operation or safety. Segmented thermoelectric elements (PbTe and BiTe) are used to obtain optimized performance over the rather small temperature drop available at the couple junctions. Although system weight is strongly dependent on design depth—80,000 lb for 18,000 ft—advanced pressure balancing concepts would allow weight reductions of 50 to 70% plus higher temperatures for improved thermoelectric conversion efficiencies.

A. Introduction

THE importance of undersea operations is widely recognized. Growing military and commercial applications and their associated electrical power requirements are apparent for remote navigational beacons, deep underwater detection devices, and offshore power supplied for beachhead support, general underwater exploration, and mining operations. Anticipated operational duty cycles, remote environment, and logistic considerations are a virtual mandate for the utilization of nuclear power sources.

Radioisotope thermoelectric power sources are ideal for many applications. They are inherently safe, easily transportable, extremely reliable under adverse environmental conditions, and require a minimum in crew skill and training for servicing and installation. However, such devices appear to optimize at a total output power of approximately 500 to 1000 w. Although multiple units are practical at low multiples of the 500 to 1000-w power levels, it appears necessary to provide a nuclear reactor power source with capabilities in the range of 50 to 500 kwe.

To apply reactors to these operations practically, it is necessary to provide all of the desirable handling and operational characteristics common to the isotope devices. The primary design objective is to produce an inherently safe, reliable, rugged plant that can be remotely activated and left completely unattended for several years. Design and operational simplicity are the keys that couple the long-life, high-power advantages of a reactor power source with the high reliability of a static energy conversion system. A strong contender for this system is a self-pressurized, natural circulation, PWR plant that develops electrical power directly from heat by means of a thermoelectric generator. Such a plant may be designed for complete remote startup and unattended operation.

B. System Description

The powerplant is a self-pressurized, natural circulation, PWR system that develops electrical power directly from heat by means of a thermoelectric generator. The plant is designed for complete unattended operation at depths up to 3000 fathoms. A thermal power of 2.5 Mw is derived from a low enriched, water-moderated nuclear core and rejected to the seawater environment through the thermoelectric elements. A 40-v d.c. potential from the thermoelectric generator is supplied at an average power level of 131 kwe. This is boosted by a d.c.-to-d.c. converter to 100 v and stored as energy in an oversized nickel-cadmium battery bank. Power increments of several (5 to 10) megawatts and at 75 v may be supplied on demand at an average integrated power level of 100 kwe.† The detailed characteristics and operational parameters of the design discussed are summarized in Table 1.

The proposed concept has utilized present-day principles to the maximum. There are no areas where technological breakthroughs are required, and no new concepts have to be developed or proved. In general, the efforts required to make the plant completely operational are engineering or manufacturing extrapolations of past experience. This does not imply that there are no problem areas but indicates that such

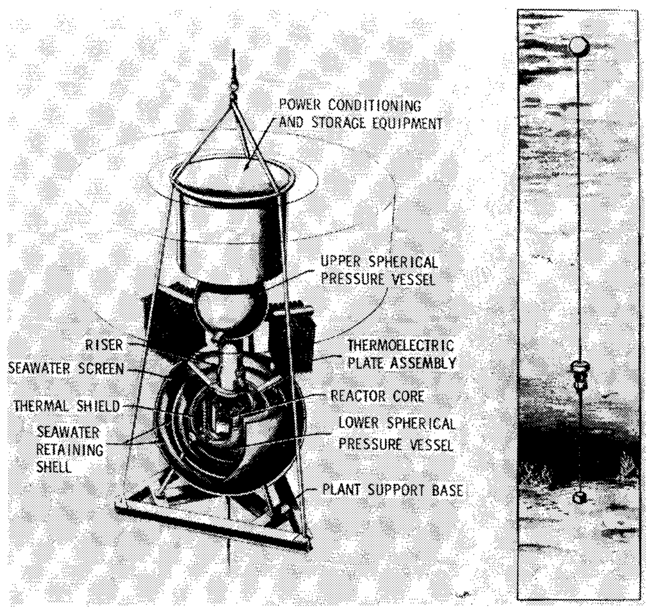

Fig. 1 Underwater plant: 100 kwe.

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† Total electrical power storage capability is 1920 amp-hr.

Table 1 Design and performance characteristics

Plant performance characteristics	
Over-all powerplant	
Maximum peak or pulsed power, Mwe	5 to 10
Time-averaged power, kwe	100
Load voltage, v d.c.	75
Over-all system efficiency, %	4
Reactor-thermoelectric generator	
Reactor core	
Thermal power, Mwt	2.5
Core life, Mw-yr	11.0
Thermoelectric assembly (21 plates)	
Voltage output, v d.c.	40
Current rating, amp	3000
Conversion efficiency, %	6
Design characteristics	
Over-all powerplant	
Design pressure	
External environmental pressure: 3000 fathoms, psia	8000
Maximum coolant operating pressure, psia	2210
Powerplant over-all dimensions, including electrical converter, ft	
Height	28
Width	10
Plant weight,[a] lb	
Total	
Dry	100,000
Submerged	87,000
Dry weight of basic power generator	81,000
Dry weight of electrical energy storage equipment	19,000
Reactor core	
General	
Geometry	Right circular cylinder (approx.)
Equivalent nuclear diameter, in.	27.4
Active core length, in.	28.0
Fuel bundles, no.	12
Control rods, no.	4
Moderator, coolant and reflector	Light water
U-235 inventory, kg	73.0
UO_2 at 8.7% enrichment, kg	967
B-10 inventory: burnable poison only, g	22.4
Fuel bundle data	
Geometry (radial cross section)	Square
Element pitch, in.	0.650
Fuel elements, no.	104
Fuel pin data	
Geometry	Cylindrical rod
Number (core total)	1248
Active fuel length, in.	28.0
Clad composition	750 ppm B alloyed in Inconel
B-10 inventory, g	0.0179
U-235 enrichment, %	8.7
U-235 loading, g	58.6

Table 1 (continued)

Design characteristics (continued)	
Control rod data	
Geometry	Tubular *T*-shaped pattern
Number	4
Absorber length, in.	28.0
Matrix material	Natural B_4C powder
B-10 inventory, g	610
Nuclear characteristics	
Core reactivity, initial, $\Delta K/K$	
At 68°F, core maximum reactivity	0.122
At 650°F, clean core, zero power	0.032
At 650°F, clean core, 2-Mw power	0.029
At 650°F, with equilibrium X-135	0.015
Negative temperature coefficient of reactivity at 650°F, $\Delta K/K/°F$	4.0×10^{-4}
Doppler (power) reactivity coefficient, $\Delta K/K/Mw$	−0.00132
Power peaking factors	
Radial	1.60
Axial	1.40
Over-all	2.24
Thermoelectric characteristics	
P-type element material	
Hot junction	PbTe
Cold junction	BiSbTe
N-type element material	
Hot junction	PbSnTe
Cold junction	BiSeTe/PbSnTe
Element pairs, no.	3570
Series connect paralleled banks, no.	714
Element pairs in paralleled bank, no.	5
End-of-life element junction temperatures, °F	
Hot	545
Cold	140
Voltage output per thermoelectric pair, mv	56.7
Thermal characteristics	
Core flow rate, lb/hr	233,000
In-core coolant velocity, fps	0.90
Coolant cycle time, sec	50
Core heat-transfer area, ft²	386
Core active flow area, ft²	1.91
Core average heat flux, Btu/hr-ft²	22,100
Core peak heat flux, Btu/hr-ft²	88,400
Element average surface temperature, °F	652.6
Element maximum surface temperature, °F	654
Average fuel temperature, °F	1000
Peak fuel temperature, °F	1975
Core pressure drop, psf	1.0
Coolant temperature, °F	
At beginning of life, inlet	615
At end of life, inlet	575
At beginning of life, exit	650
At end of life, exit	610

[a] For 3000-fathom design depth and 1929 amp-hr electrical storage capability.

areas have reasonable solutions. The greatest problem is to prove out the design solutions and demonstrate practicality on the basis of performance, cost, and reliability. Final prototype testing of the over-all system would certainly be required prior to field use.

Arrangement

The basic power system consists primarily of a lower spherical pressure vessel (containing the reactor core), a riser, an upper spherical pressure vessel, three seven-plate assemblies of thermoelectric elements, and the necessary interconnecting piping to complete the coolant flow path back to the reactor vessel. Nuclear heat generated in the lower vessel is circulated by natural convection to the thermoelectric elements. The upper pressure vessel contains sufficient vapor phase space to accommodate volumetric expansion of the coolant over the range of startup and operating conditions. The power produced is stepped up in voltage by a converter and stored in a battery bank located above the upper pressure vessel. This area, as well as that occupied by the thermoelectric elements, is sufficiently removed from the nuclear core to assure neutron and gamma attenuation to an acceptable radiation level.

The over-all system configuration is shown in Fig. 1. The powerplant is shown suspended off the ocean floor and retained in an upright position by means of an anchor and gasoline buoy. Alternate arrangements, depending upon localized

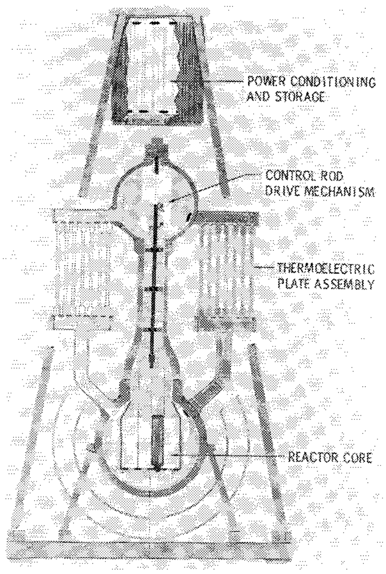

Fig. 2 Thermoelectric generator.

conditions, could be made to allow direct placement of the system on the ocean floor.

The inherent negative coefficient of the core design allows the control rods to be completely withdrawn at start-up and remain fixed throughout design life. Once this rod position is achieved, essentially automatic "nuclear" control is provided, stabilizing the average core temperature regardless of power demand. A design temperature drop of 40°F will occur over the design lifetime to compensate for fuel burnup.

The arrangement of the nuclear power source is shown in more detail in Fig. 2. The principal components of the plant include a reactor core and associated thermal shielding, upper and lower spherical pressure vessels, riser, thermoelectric plate assemblies with associated thermoelectric elements, and the necessary flow plenums and headers to control coolant circulation. Three plate assembly headers, each supplying coolant for seven thermoelectric plate assemblies, extend from the upper spherical pressure vessel at 120° intervals. Similarly, three returns, one from each plate group, carry the coolant back to the lower vessel.

Reactor coolant is cycled through the system by natural circulation. Flow enters at the bottom of the reactor core at a mass flow rate of 233,000 lb/hr or approximately 0.9 fps. At the beginning of core life, the coolant exists from the reactor core at an average temperature of 650°F after taking a 35°F rise across the core. As explained previously, because of fuel depletion and fission product build-up, the average exit temperature will decrease to 610°F at the end of life. The core ΔT will remain approximately constant throughout core life. Because of the relatively low total power generated, the thermal parameters for the core are correspondingly low, i.e., peak centerline fuel temperature is 1975°F; peak heat flux is 88,400 Btu/hr-ft^2.

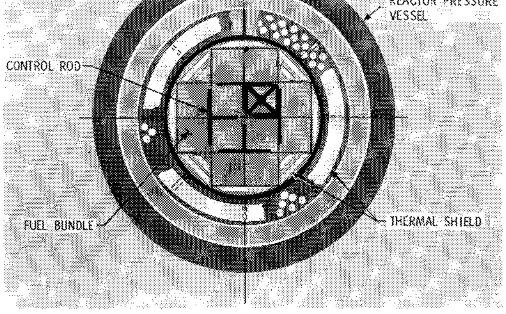

Fig. 3 Core cross section.

Coolant that leaves the core and flows up the riser into the upper volumetric expansion tank is distributed into the three thermoelectric plate assembly headers and into the upper plenums of the individual plate assemblies. The header inlet holes to the individual plenums are orificed to provide a uniform flow distribution through the plate assemblies. Heat flow through the individual thermoelectric elements to the seawater reduces the coolant temperature to 615°F (585°F at end of life). The coolant then flows into the lower plate plenums, the three coolant returns, and finally re-enters the reactor pressure vessel to repeat the cycle. Total coolant cycle time is approximately 50 sec.

Pressure Vessels

The two spherical pressure vessels, riser, and header assemblies will be fabricated from high-strength steel and clad internally with Inconel. The thermoelectric plate assembly, upper and lower plenums, and internal flow plate will also be fabricated from Inconel, thus assuring that all coolant-exposed containment surfaces are highly corrosion-resistant. Inconel provides an added degree of safety over the normally used 300-series stainless steels which is beneficial if a slight amount of seawater leaks into the vessel. The external surface of the containment vessels, connecting headers and plenums, will be thermally insulated from the surrounding seawater and contained in Hastelloy-C for corrosion resistance to the seawater environment. A solid insulation material will be used to withstand the compressive loads imposed by the external water pressure. The insulation will not only reduce heat losses to the seawater, and hence increase the plant efficiency, but will greatly decrease the otherwise severe thermal stresses in the thick pressure vessel walls.

The lower sperhical pressure vessel shown in Fig. 3 contains the reactor core, core shroud, and thermal shields. The pressure vessel itself has a 5-ft $1\frac{1}{2}$-in. o.d. by $4\frac{1}{3}$-ft i.d. It contains four wall penetrations: one for the 16-in. o.d. by 10-in. i.d. riser, and three for the 8-in. o.d. by 4.8-in. i.d. return pipes from the thermoelectric plate assemblies.

The upper spherical pressure vessel has a 4-ft $1\frac{1}{2}$-in. o.d. by $3\frac{1}{2}$-ft i.d. and provides a volumetric expansion space for the reactor coolant during system temperature transitions from 68° to 650°F. Its secondary functions are to provide a plenum for the three thermoelectric plate assembly headers, a surge tank to compensate for small system transients, and a housing for the control rod drive mechanism.

Core Mechanical Design

The core, a typical UO_2 pellet in tube design, is a scaled-down version of the MH-1A[1] basic configuration. It measures 28 in. across the outside flats by 28 in. in height and consists of 12 fuel bundles of square cross section, each containing 104 fuel pins (see Fig. 3). The fuel pins (Fig. 4) are positioned within the bundle on a 0.650-in. square pitch by an upper and lower grid plate. Bundle rigidity is provided by four fuel pins, functioning as tie rods, which extend between the four corners of the grids. Free thermal expansion of the other fuel pins is allowed at the upper grid. Integral with the lower grid is an X-shaped support piece that fits into the core support plate. The shape of the support stand allows for orificed flow to each bundle.

Control is provided by four T-shaped control rods, each consisting of 31-$\frac{1}{2}$-in. o.d. Inconel tubes containing natural boron carbide powder. The T-shape was employed to reduce its over-all dimensions and thus minimize the riser i.d. and its corresponding wall thickness. The poison material was selected for the control rod because of its low cost and the nature of this particular application. Since the plant is operated with the control rods full out, only a small quantity of the boron-10 will be burned. The control rods are used only to hold down the excess core reactivity until the plant has been installed in the desired underwater location.

A core shroud surrounds and supports the core bundles. It aligns the fuel bundles and locks them into position at the lower orifice plate. In addition, the shroud provides partial thermal shielding and directs the system coolant flow from the return inlet plenum to the core inlet. The shroud itself is supported by braces mounted on the inner pressure vessel wall.

Thermal shields are located about the periphery of the core to provide the necessary thermal protection to the pressure vessel walls. Neutron damage is minimized by an imposed total integrated neutron flux limitation of 10^{18}nvt for neutrons with energy levels over 1.0 Mev. Approximately 13 in. of structural steel and water are provided to meet this requirement.

The control rod mechanism is contained within a cylinder supported from the top of the upper pressure vessel. Mechanism actuation is achieved by intermittently deflecting a pressure-sealed flexible plate (Fig. 5) from its midpoint to bottom position. These intermittent plate deflections are transmitted to a jack-type control rod mechanism designed to step the control rods out of the core in small predetermined increments. This mechanism will function only to withdraw the control rods from the core. The reactor can be scrammed at any time during start-up by a rod release device actuated by lifting the flexible plate above its midposition. An operating reactor can be scrammed either by pulling up on the flexible plate or by lifting the plant into a shallower water level and allowing the internal plant pressure to push the plate up. Either method will disengage the control rod drive mechanism and allow the control rods to be driven into the core by scram springs.

Although not required because of the inherent safety of the core design, an added safety device, such as a temperature-sensitive thermal latch, may be incorporated in the actuator rod just above the point where the control rod support members are attached. If a temperature excursion should occur, the latch would release the control rods and allow them to scram the reactor. Other safety features could be added by providing scram action under either high neutron flux (i.e., via a fueled bimetallic strip) or pressure (i.e., via a pressure-sensitive bellows). The reliability of these concepts must be carefully evaluated prior to incorporation in the system to assure that they would make positive gains to the over-all system performance and safety.

The core design is such that initial plant fueling and subsequent refueling can be accomplished through the pressure vessel riser from the top surface of the upper volumetric expansion tank. This minimizes cutting and welding of the containment. It is anticipated that, with a long-lived core, it will be operationally feasible to completely eliminate this refueling operation.

Nuclear Design

With any given geometric configuration of the reactor core, the inventory of fissionable material is determined solely by the enrichment of the uranium in the fuel matrix. By increasing the enrichment and, hence, the loading of U-235 in the core, a greater power lifetime can be obtained. However, this accomplishment costs more than the price of the added fuel inventory, as the reactor is more difficult to control with an increased fuel enrichment. The conflicting objectives of lengthy core life (large energy output) and control capability must be balanced according to the system's specific application and environment.

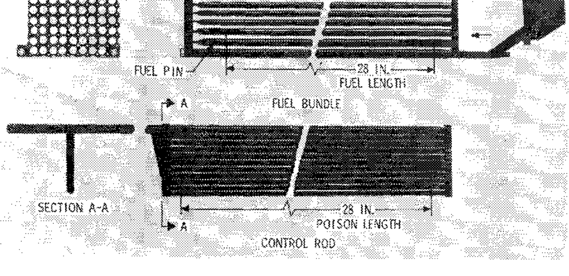

Fig. 4 Fuel bundle and control rod.

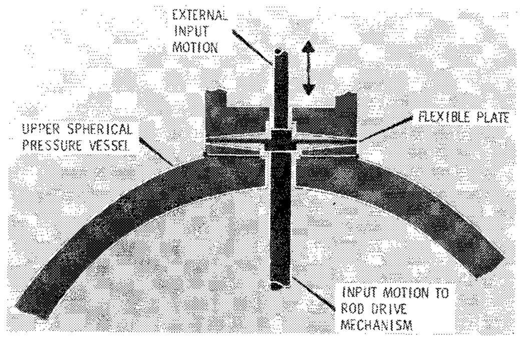

Fig. 5 Control rod drive mechanism.

One predominant environmental factor that must be considered for the undersea nuclear powerplant is its remoteness. This does not allow for maintenance and operational adjustments. The proposed system must be designed for complete unattended operation. Ordinarily, criticality or the power production capability of the core is maintained throughout the life of a reactor by slowly withdrawing the control rods as the fuel depletes. Such adjustments are wholly impracticable for the present application. Servomechanisms and control electronics for automatic rod programing or for remote command control introduce severe reliability problems. Utilizing light water as the moderator material instead of solid moderators gives the core a very large negative temperature coefficient; that is, above the designed operating temperature, the reactor rapidly loses reactivity with any increase in moderator temperature. Conversely, as the coolant temperature is decreased, the moderator density decreases, and the core reactivity increases correspondingly. This is particularly pertinent in controlling the reactor and is used to maintain criticality throughout its life. The control rods are gradually fully withdrawn as the reactor is first brought to power. They are held at this position with criticality being maintained as the fuel depletes and fission product poisons build up, by a slight temperature decrease in the coolant.[2-4]

In this manner, the reactor essentially "rides" the negative temperature coefficient during the life of the reactor through a 40°F decrease in temperature. Should any moderator other than water be used, this temperature decrement would become prohibitively large and cause a severe decrease in the power capability. The effective decrease in the core average coolant moderator temperature as a function of core life (in megawatt-years) is shown in Fig. 6.

The need for unattended safe operation imposes stringent requirements because of the need for inherent design safety.

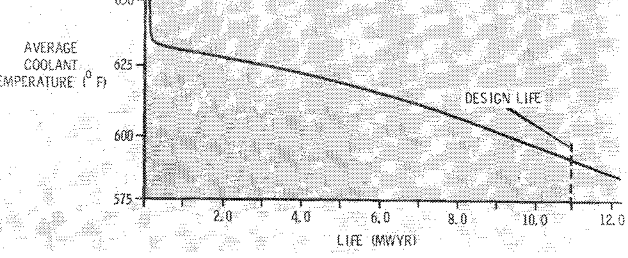

Fig. 6 Core life vs coolant temperature.

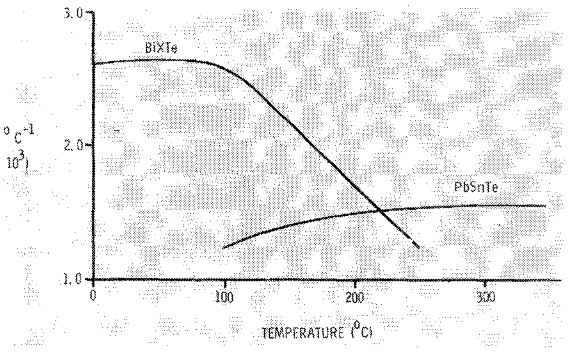

Fig. 7 Figure of merit: *N*-type element.

These requirements are best met with a low enriched fuel reactor. This is because the predominant U-238 isotope has strong parasitic resonance neutron absorption. There is a Doppler broadening of the resonances which increases the net neutron absorption rapidly with fuel temperature, thus contributing immediate damping to an incipient power excursion. Because this effect is dependent on fuel temperature alone, its damping effect is nearly simultaneous with any increase in the fission density due to flux perturbations (power excursions).

With the basic control and safety philosophy established, it becomes necessary to evaluate possible fuel and burnable poison loadings and control rod configurations against core geometric and size restraints. Compromises and tradeoffs are required in each area to provide maximum lifetime along with the necessary control limitations. In the final design selected, the total fuel loading is 850 kg of uranium enriched to approximately 8.7% in the uranium-235 isotope (73.0 kg). The nuclear fuel is in the standard form of uranium dioxide fuel pellets encased in tubular cladding. Inconel is conservatively used for maximum corrosion resistance, although the usual 300-series stainless steel or zircaloy cladding would result in a corresponding decrease in fuel enrichment of approximately 1 to 2%. Natural boron will be alloyed in the fuel pin cladding (750 ppm of natural boron) as a burnable poison to provide shim control and thus permit increased core lifetime. This technique has been used successfully in the Elk River and Indian Point reactors; however, its use with Inconel would first require proof testing.

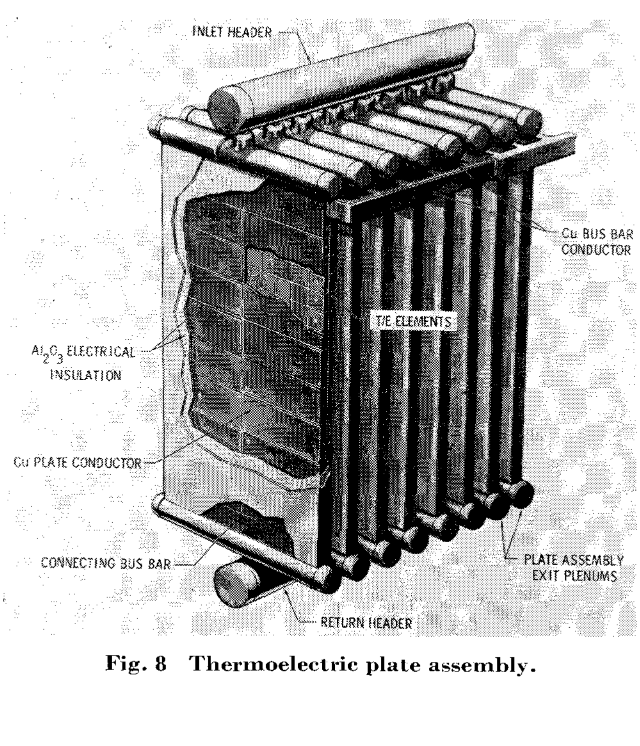

Fig. 8 Thermoelectric plate assembly.

A cold, clean core reactivity of 0.122 $\Delta K/K$ is controlled by four *T*-shaped control rods, each consisting of $31\text{-}\frac{1}{2}$-in. o.d. Inconel tubes containing 3970 g of natural boron carbide powder (610 g of B-10). The resulting core lifetime is 11.0 Mw-yr, and the negative Doppler (power) coefficient of reactivity at operating conditions is approximately -0.00132 $\Delta K/K/\text{Mw}$.

Thermoelectric Elements

The selected pressurized water reactor heat source limits the maximum thermoelectric generator system temperature to approximately 650° F at beginning of life. Because of the control function provided by this temperature, it is necessary to design the thermoelectric couples for the end-of-life coolant temperature conditions of 610°F. Since this temperature is significantly below the present state of the art for thermoelectric generators, the use of segmented thermoelectric elements is proposed in order to achieve a reasonable over-all thermoelectric efficiency. This allows utilization of various thermoelectric materials only over the temperature range that provides optimum performance. Since maximum thermoelectric efficiency is achieved when the average figure of merit for the design temperature range is also a maximum, the value of segmenting two materials at the interesection temperature typically illustrated by Fig. 7 is apparent.[5]

Thermoelectric generator design is an iterative process, since both the heat transferred and the thermoelectric performance are temperature-dependent and interrelated. A hot junction temperature representative of that expected at the end of the reactor core life was chosen as the basis of design. The variation of thermoelectric couple performance as a function of cold junction temperature was then determined. A sharp decrease in the load voltage and efficiency with increasing cold junction temperature emphasizes the need for the most effective heat-transfer scheme at the heat sink. Thus, to reduce the temperature drop to the water environment, the cold junction incorporated a finned design to increase the effective heat-transfer area by a factor of 2.25/1. The resulting iteration provided a thermoelectric hot junction temperature of 545°F at a cold junction temperature of 140°F with a characteristic output voltage of 56.7 mv per *P* and *N* element pair. Thermoelectric conversion efficiency was approximately 6%. (The actual power output required from the thermoelectric generator is 131 kwe in order that 100 kwe can be supplied to the load.) The resulting 40-v, 100-kwe net system has 714 series-connected sets of thermoelectric elements, each set containing five pairs of elements in parallel. A system with five couples in parallel was chosen for reliability purposes and to maintain the thermoelectric element size within the dimension range that has been successfully fabricated.

Thermoelectric elements are contained within 21 plate assemblies. As shown in Fig. 8, each plate assembly is approximately 30 in. wide, 62 in. long, and 2 in. thick. Each assembly contains 34 series-connected sets of thermoelectrics, with each set containing the five pairs of parallel elements (see Fig. 9). Each of the 21 plate assemblies is series-connected.

Copper is used as the electrical conductor at both the hot and cold element surfaces and as electrical leads between plate assemblies. Copper sheets and busbars of large cross-sectional area are used to minimize current densities and hence I^2R losses in the conductors caused by the 3300-amp thermoelectric current. All current-carrying materials are electrically insulated by alumina through the use of either component coating or thin spacers. The plate assemblies are externally clad with Hastelloy-C for protection against seawater corrosion.

Primary coolant flows through each plate assembly in 41 0.444-in.-diam flow channels. These flow channels are contained in a 0.742-in.-thick internal flow plate that is designed to withstand an external pressure up to 8000 psi. Two 3.5-in. o.d. by 2.1-in. i.d. Inconel plenums are welded on each end of the plate assembly to insure uniform coolant flow through the thermoelectric elements.

The P and N type of thermoelectric elements are as shown in Fig. 10. The N type may consist of bismuth telluride (BiXTe) at the cold end and lead tin telluride (PbSnTe) at the hot end or two PbSnTe of different dopants. The cold end segment of the P type of element is bismuth antimony telluride (BiSbTe), and the hot segment is lead telluride (PbTe). Each thermoelectric element is 2.95 in.^{2} by 0.380 in. thick. Approximately 0.020 in. of the thickness consists of barrier and bonding material. Iron shoes are bonded to both the hot and cold element surfaces to prevent poisoning by adjacent materials.

Although elements in the range of interest have been produced and tested, additional concentrated effort will be required. Segmented elements have been fabricated and their worth demonstrated in terms of improved operating efficiency. However, fabrication of large segmented elements on a mass production scale and integration into a large electrical grid have not been accomplished to date. Sufficient operational and reliability data for the statistical evaluation of segmented elements have yet to be obtained.

Composite elements of over $2\frac{1}{2}$-in. diam, containing three segments, have been hot-pressed to shoes and successfully thermal-cycled. Other elements to over $3\frac{1}{4}$-in. diam have been similarly tested. The problem of differential thermal expansion between the thermoelectric and shoe material increases as the element size increases. Adequacy of a close match in expansion characteristics must be demonstrated before the final combination is established. A development effort will also be required to scale the laboratory hot press powder metallurgy process of element fabrication to that of a production procedure. The production elements must be equal in thermoelectric performance and physical properties to the laboratory-produced elements.

Detailed design of a complete thermoelectric assembly plate will require integration of known technology. Adaptation of insulating materials, assembly skills and techniques, electrical connections, and manufacturing processes will be required.

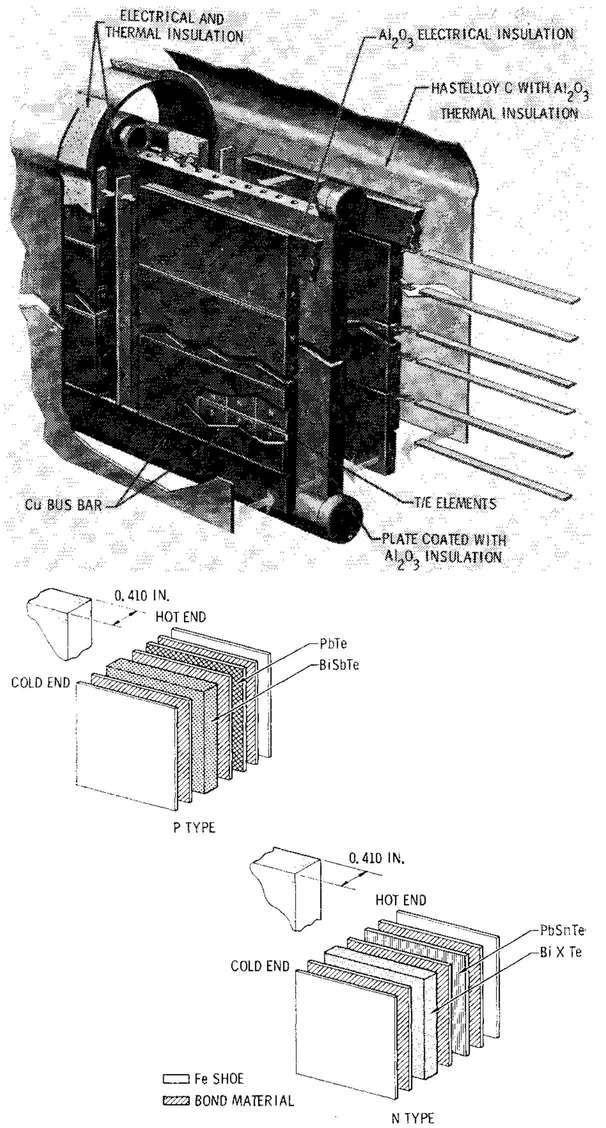

Fig. 10 Thermoelectric plate assembly and element details.

Performance trades between thermal and mechanical design criteria will certainly be needed.

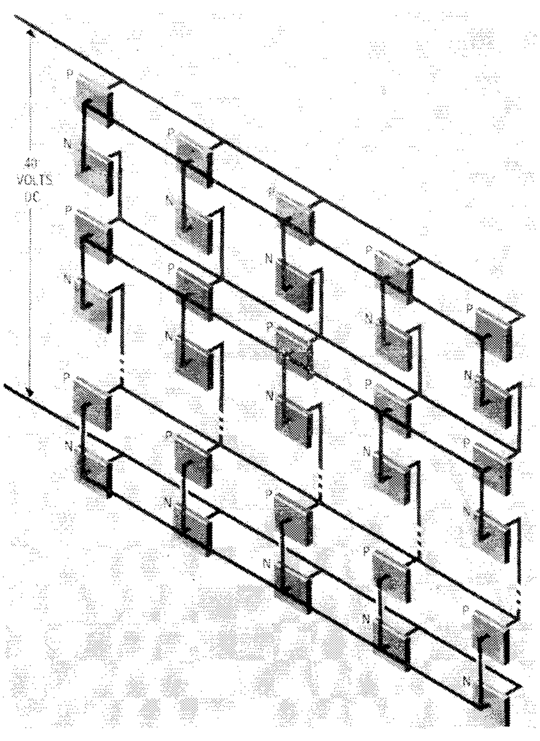

Fig. 9 Thermoelectric elements.

Power-Conditioning and Storage

As shown in Fig. 11, the over-all power system will consist of several components besides the primary energy converter. Such components were desired to condition the thermoelectric power output and to store the energy produced during nonload periods in accordance with the prescribed design requirements.

High-current busbars extend from the thermoelectric system to a complex of 12 parallel-connected independent d.c.-to-d.c. static converter and battery charging regulators. The 40-v d.c. thermoelectric output is inverted to 400-cps square wave although two alternately switched silicon-controlled rectifiers. The 400-cycle power is then transformed and rectified to approximately 120 v d.c., and regulated for charging the batteries. Each of the 12 converter-regulators is rated at 10 kva.

The regulated d.c. outputs are supplied to a bank of independent circuits that provide a nominal 100-v d.c. for charging each of the 12 batteries. In this manner, each of the storage batteries is independently charged and discharged, greatly promoting system reliability, self-maintenance, and

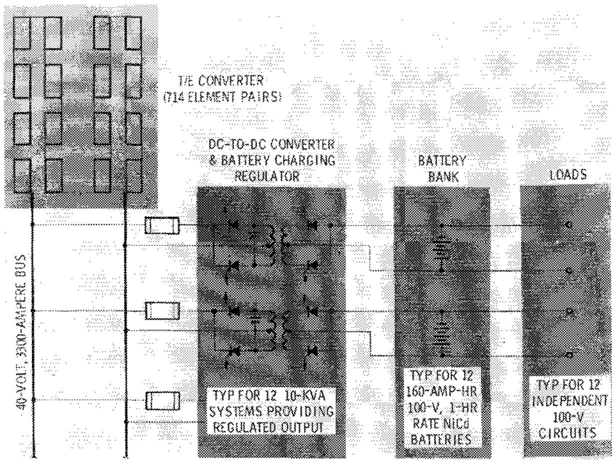

Fig. 11 Power-conditioning and energy storage systems.

cycle life. Each battery (160 amp-hr) consists of 85 sealed nickel-cadmium cells.†

Figure 12 presents the flow of power through the system and summarizes the losses. The reactor produces approximately 2500 kwt, of which 2180 kwt are useful. Approximately 320 kwt are assumed lost to the seawater surrounding the pressure vessels and related coolant pipes.

With a thermocouple conversion efficiency of 6%, 131 kwe are produced, and 2049 kwt are passed, unconverted, through the elements and rejected to the water environment.

At 40 v d.c., the d.c.-to-d.c. converter and battery charging regulator will perform with an efficiency of better than 90%. With 90% efficiency, 118 kwe are delivered to the storage cells, and 13 kwt are rejected.

Under possible high rate discharges from the NiCd batteries, a considerable amount of power would be dissipated in the electrolyte. The storage system in this case has been oversized to minimize these losses, allowing the batteries to function at about 85% efficiency. Thus, approximately 18 kwt are assumed to be dissipated in the cells, leaving a net output of 100 kwe. Since the cells function best at about 77°F, the heat dissipated in the cells will be used to heat the cells above the low ambient temperature.

For packaging the components of the power-conditioning system and storage cells, a cylindrical tank (Fig. 2) is fabricated from carbon steel plate and sheathed externally with Hastelloy-C cladding. The inverter and charging regulator-controlled rectifiers are threaded into heat sink bars welded to the inner surface of the tank. A covering of high dielectric casting resin is applied over the semiconductor rectifiers. The transformers and sealed NiCd batteries are supported within the tank, and the remaining void volume is flooded with oil. A flexible metallic membrane, seal-welded at the top of the container to retain the oil during deep sea submersion, provides for inside-outside pressure equilization.

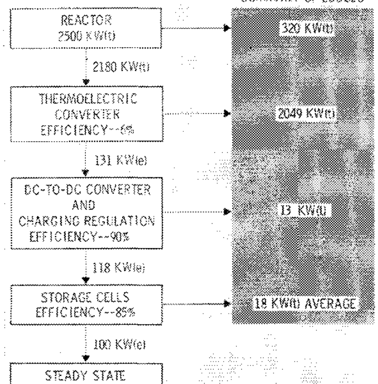

Fig. 12 Power flow.

All components within the tank are designed for the 8000-psi pressure experienced at the maximum design depth. Sealed nickel-cadmium cells are capable of withstanding these external loadings when sealed with a full volume of electrolyte. The sealed tank is located directly above the upper (expansion) pressure vessel.

This concept of power-conditioning and energy storage utilizes apparatus and devices of previously developed technology. The d.c.-to-d.c. converter consists of controlled rectifiers that switch into a 400-cps power transformer. Larger quantities of inverters and converters of this type have been built in the aircraft industry, and recent improvements have been numerous. Also, over the past several years, research and development on sealed nickel-cadmium batteries have well proved the capability necessary for this mission.

Shielding

To provide shielding for personnel handling a shutdown or spent reactor, two shells surrounding the core containment vessel are utilized to retain seawater when the plant is withdrawn from the water. The 2-ft water shield provided by the retained water reduces the dose rate at the external surface of the outermost shell to 1 rem/hr 4 hr after core shutdown. The innermost shell could be designed to accommodate additional lead shot or other temporary shielding material, if desired. However, 1 rem/hr will pose no hazardous biological effect for intermittent handling during system relocation. The entire system could also be retained in outboard fixtures on the ship, holding the reactor below water level.

Water Chemistry

Since the proposed plant utilizes a closed coolant system, water chemistry and crud build-up must be carefully analyzed. The advantages of a closed system are that the need for conditioned reactor makeup water is eliminated and that equilibrium water conditions can be expected to result from the interaction of the driving forces, pressure, temperature, and radiation, on all of the chemical species present. Two solutions to the problem of water coolant chemistry may be considered.

The first and most obvious solution is to provide an initial, large excess of ammonia in the coolant, possibly as a gaseous overpressure. During operation, an equilibrium would be established among the species present (H_2, O_2, H_2O, NH_3, H_2, etc.) to maintain a safe pH level throughout the operating life. Some initial excess hydrogen would probably be beneficial in that the oxide formation during the early period of operation would be minimized by suppressing the radiolytic decomposition of water. There is considerable support in the industry for using a high pH coolant.[6,7]

A second possibility is to provide water of initially high quality and operate the reactor at a neutral pH. The probable sequence of reaction would be an initial attack during which metallic oxides are formed. (The oxides produced would not form a tightly adherent dense film like that formed at high pH.) The aggressiveness of the oxide formation would then decrease with the attendant accumulation of hydrogen and finally reach an equilibrium of relatively low reaction rate. This approach is similar to that used successfully in static autoclaves; however, the radiation environment will tend to raise the initial O_2 level.

In the light of the two approaches, it is not considered necessary to add a coolant purification system. If a purification system is found necessary after careful study of the chemistry of sealed, irradiated water, the incorporation of a practical system into the present design appears feasible. The coolant return flow rates are more than adequate to provide effective water cleanup with demineralizer resins. A side coolant loop could be easily used to provide a lower temperature level at the resin bed. Detailed examination of the coolant chemistry must be made to select intelligently the optimum additives or purification apparatus necessary for the system.

Operation

Reactor start-up will be initiated when the powerplant is at an intermediate water depth as deemed necessary by safety considerations. A built-in pressure switch will prevent accidental control rod withdrawal prior to submergence to this level. The control rods are then withdrawn out of the core at a predetermined rate that will satisfy start-up temperature limitations (thermal gradients). Mechanical activation of the control rod drive mechanism's "flex plate" (previously discussed) is required for each incremental step motion. This is provided by an externally mounted device (removable) activated from the surface by electrical, hydraulic, or direct mechanical linkage techniques.

The rods may be withdrawn by one of two procedures. In one procedure, the rods are completely withdrawn from the core at the predetermined rate. In this case, the reactor coolant temperature will rise to approximately 680°F initially until equilibrium xenon (a fission product neutron poison) builds up to decrease the temperature to the nominal 650°F value. An alternative method would be to withdraw the rods a predetermined number of steps calibrated to suppress a net 2.9% of core reactivity. A much lower rate would then be used to allow the gradual build-up of xenon to compensate for the withdrawal rate. This would hold the moderator/coolant temperature to a maximum of 650°F.

Detailed evaluation of heatup limits and the over-temperature effects will have to be made before the optimum solution is apparent. At present, it appears that the 680°F temperature would be acceptable, thus enabling the faster start-up procedure to be used. Once the control rods are fully withdrawn, the system is fully operational and may be lowered, as required, to the selected final position.

Safety

The proposed design concept is such that the safety problems of plant handling and operation at sea have been inherently satisfied. That is, the basic safety of the selected core concept plus the ruggedness, reliability, and nonskilled operating crew requirements virtually eliminate all operational hazards. However, unique problem areas for this type of undersea application are nevertheless real and must be considered. These will require a detailed examination on the basis of the over-all design and operational concept.

In summary, the safety features of the proposed system are as follows: 1) the reactor design is self-regulating without dependence on safety instrumentation; 2) failure of the system does not expose personnel to any undue hazard; 3) the reactor is capable of deep submergence and start-up without compromising safety; 4) the system is sufficiently rugged and portable that normal handling and transportation are both feasible and safe; 5) transportation, installation, and operation of the system are well within the capabilities normally required of personnel handling technical equipment; 6) the plant can be safety handled by personnel after a 4-hr shutdown period because of its low power output; and 7) the reactor automatically scrams either when raised above a preset depth or when a high coolant temperature occurs.

As adequately demonstrated by extensive use, water reactors are inherently stable and have a high degree of safety. The reactor design proposed for this application improves upon these already acceptable features, as follows:

1) In contrast to existing reactors, the proposed design has no excess reactivity built into the core at operating conditions. The only possible reactivity changes during operation would be caused by coolant temperature changes.

2) The core will be physically smaller than most power reactor cores because of the low power requirement; therefore, the temperature coefficient will be more negative. Increases in water temperature, which accompany higher reactor power production, operate to reduce the reactivity of the reactor and thereby limit its power increase. This self-regulating principle is further enhanced by the prompt negative Doppler coefficient.

3) Accidents such as the loss of coolant, loss of coolant flow, and rod ejection are impossible with this system. The system does not depend upon pumps to establish coolant flow. Since the shutdown rods are removed from the core at start-up, further ejection cannot insert more reactivity into the core. When the plant is operating submerged under external pressure, loss of coolant cannot occur.

Containment of fission products, if they escape from the reactor fuel, would be provided by the corrosion-resistant pressure shell. Even if the fission product release is the consequence of a major powerplant energy excursion, the pressure shell, designed to withstand external pressures of about 8000 psi, would provide containment. In addition, the loss of the reactor in deep water can be tolerated because, even with maximum fission product inventory on board, the release to the environment is estimated to be so delayed and gradual that maximum permissable concentrations of radioactivity in the ocean (10^{-9} $\mu c/cm^3$) would never be attained even at the reactor containment shell release point. Loss in shallow water could be tolerated, at least temporarily, until recovery or transfer to deep water is achieved.[8]

Although the neutron flux at the surface of the pressure vessel will be high and result in considerable activation of the seawater, this problem has been evaluated for a comparable situation in shallow water and shown to be acceptable.[9] Under deep-water application, the problem is further reduced by the absence of food-type marine life.

C. Special Features

Close evaluation discloses many design features that are significant in establishing both system compatibility and over-all concept operability. Besides the basic requirement of supplying power under unattended operation, points of major consideration include those affecting over-all operation (i.e., crew handling, hazards, design lifetime). The following paragraphs summarize the special features of the design which contribute especially to the present application:

1) A large negative temperature coefficient is inherent with the selected core. This allows an acceptable coolant temperature swing to compensate for fuel burnup over the design lifetime and eliminates the need for moving control rods, their accompanying sensing instrumentation, feedback devices, and complicated mechanisms.

2) Reliability is further enhanced by the use of thermoelectric elements for power production. With the elimination of complex instrumentation and control functions, this coupling provides a completely static system requiring no maintenance. Extensive paralleling of circuits within the elements, the static conditioning system, and storage batteries also provide excellent reliability.

3) Operation, by means of the negative temperature coefficient, contributes to system reliability, as the control rods are always fully withdrawn during operation, and no excess reactivity can be added inadvertently by rod motion. Additional inherent safety is provided by utilizing a low enriched core design. The prompt Doppler portion of the temperature coefficient provides immediate curtailment of power excursions. Extensive SPERT tests, where control rods were literally blown out of the core, have demonstrated the built-in stability of this feature. There is no doubt that the natural circulation, temperature-controlled PWR system is preferable to all other state-of-the-art systems, particularly in the safety and reliability areas.

4) Over-all system activation with a PWR system is held to a minimum. With the low natural circulation rate anticipated, irradiation of the thermoelectric region during operations will not be sufficient to affect the operation or reliability.

Other systems, such as a liquid metal, tend to become highly activated, with resulting deleterious effects on system components during operation and portability after shutdown.

5) The basic PWR system is compatible with the natural undersea environment. Nuclear hazards cannot be created by inadvertent contamination with the water environment, nor can operational hazards occur from the coolant and seawater reactions. For potential handling under the adverse environmental condition that frequently exists at sea, such potential hazards cannot be ignored. Early liquid metal concepts for naval use were abandoned, partly because of such considerations.

6) The design is of direct interest for many potential commercial and military concepts. It is based largely upon existing technology, with no basic proof-of-principal developments required. However, quite reasonable extrapolations of current knowledge to that available within the next few years provide even greater possibilities for the planned design. For instance, pressure balancing between the system and its environment could reduce weight by 60 to 75% (and associated cost). Operation at higher temperatures, consistent with the environmental pressure, could double the thermoelectric efficiency. This gain could be translated into either higher allowable power output or lower cost and smaller size by reducing reactor power level and the number of thermoelectric elements. Significant advancements in over-all lifetime are also directly obtainable through improved core designs. In the area of energy storage, developmental systems such as the pile battery offer early potential for weight reductions of over 1000%, plus improved reliability.

D. Potential

In the evaluation of any design concept, more than initial feasibility, development costs and schedule must be considered. Because of the expenditures required for development, growth potential and application to new requirements must also be considered. It is believed that this design provides a firm concept of immediate interest plus excellent potential through advanced development efforts.

The design relies upon developed components to a maximum degree. Many areas exist, however, where technological advancements would contribute significantly. They are mentioned because it may be that their utilization falls within the requirements and/or schedule of a specific application or mission.

The basic size and weight of the power system play an important role not only in shipboard handling but also in storage, logistic support, recoverability, and, finally, cost. Because of the high pressures associated with deep underwater operation, the largest contributions to weight are the main pressure housings. The simplest way to improve this is to balance the internal and external pressures. It not only eliminates a significant pressure wall requirement but enhances reliability and safety because the driving potential for in-leakage is eliminated. A flexible expansion chamber arrangement could provide the balancing principle. Elimination of the pressure requirements would also do away with the need for high-strength structural materials. The materials that require cladding for corrosion protection may be eliminated and solid materials of high corrosion resistance utilized throughout.

Feasibility of the pressure-balancing concept allows the system design operating temperatures to be increased accordingly. This not only allows greater heat rejection from the thermoelectric plate assemblies (along with higher electric power output for a given size) but also significantly increases the basic thermoelectric element efficiency. For example, a system temperature increase of approximately 300°F could almost double the efficiency and, in conjunction with the higher resulting heat fluxes, increase over-all power output by a factor of 3 to 4. Consideration must be given, however, to the effects of higher temperatures on corrosion within the system.

A reduction in the operational depth (3000 fathoms) would considerably reduce over-all plant weight (and cost). For instance, a design for shallow-water application would be at operating pressures of 2210 psi (bursting) rather than 8000 psi (collapsing). This would reduce the basic power generator weight to approximately 50,000 lb and still allow operation up to 1000 fathoms. If credit were allowed for the internal operating pressure, a further increase to 2000 fathoms would be realized.

This core design, with burnable poison added to provide a desired flat reactivity-lifetime curve, will sustain a total thermal power output of 11 Mw-yr. Under an Atomic Energy Commission development contract, cores of over 100 Mw-yr have been designed which are smaller. The flat reactivity required for temperature control alone (rods always full out) would diminish this maximum lifetime value, but it still would be of considerable interest (70 to 80 Mw-yr). This would provide a total core life of approximately 30 years, which is probably well beyond the service life of the system being supported by the plant. This advanced core design effort has included both fuel element manufacturing development and irradiation tests. Its disadvantages include higher initial capital cost and (because of its high enrichment) loss of the prompt Doppler contribution to the negative temperature coefficient. The latter would not significantly affect life but would tend to reduce the inherent safety obtained with a low enriched system.

The basic design concept, once it is critical, is readily adaptable to complete remote power regulation. Although not incorporated into the basic design, a controlled throttle or damper placed in the riser could provide complete power control from zero to 100% of design. The system could remain dormant (reactor hot but at essentially zero power) until the throttle was activated by an external programed signal.

If the load-matching characteristics of the plant can be accepted, virtually the entire power-conditioning system could be eliminated. This potential system simplification would require close coordination with the power requirements for the concept or mission concept under consideration.

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