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AI-AEC-13069, VOL I

SNAP 4 SUMMARY REPORT
VOLUME I. APPLICATIONS AND SUMMARY

AEC Research and Development Report

Atoms International Division
Rockwell International

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VOLUME I. APPLICATIONS AND SUMMARY

J. R. WETCH

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CONTRACT: AT(04-3)-701
ISSUED: JULY 20, 1973

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ABSTRACT

The AEC-sponsored SNAP 4 Program provided the basis for the conceptual design of a compact reactor system employing uranium-zirconium hydride for fuel and moderator, beryllium reflectors for control, and forced-convection boiling water for cooling. The completely self-contained, compact, multipurpose, automatically-controlled, transportable nuclear reactor was directly coupled, through a steam separator, to a high-speed, hermetically sealed, turbine-generator unit. The turbine exhausted to a compact high-pressure condenser, and small steam driven turbo-pumps returned the condensate to the reactor. The complete system, which could be designed and built for a specific power rating in the range from 400 to 4,000 kwe, is adaptable to marine or terrestrial, surface or submerged, fixed or mobile, and arctic or tropic environment.

The report demonstrates that the SNAP 4, or COMPACT, reactor may be of even greater significance today than when it was conceived in the early 1960's.

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I. INTRODUCTION

This report summarizes the design and research effort conducted by Atomics International which has resulted in a Compact Multi-Purpose Auto-matic-Controlled Transportable (COMPACT) nuclear power concept. The AEC-sponsored SNAP 4 reactor experiment research and design has provided a basis for this work. The concept consists of a uranium-zirconium hydride alloy fueled and moderated, beryllium reflector controlled, forced convection boiling water cooled, compact reactor. It is directly coupled, through a steam separator, to a high-speed hermetically sealed turbine generator unit. The turbine exhausts to a compact high-pressure condenser, and small steam driven turbo-pumps return the condensate through the system to the reactor. The resulting hermetically sealed compact system may be air or water cooled, and completely contained.

A single, low cost, 4-year basic hardware design and development effort will provide a prototype 2000-kwe unit, that, with minor modification and tailoring, can fulfill a significant fraction of the nation's power needs in the 400- to 4000-kwe power range. The shielded unit weight is comparable to unfueled industrial and marine diesel-generator weights of several thousand kilowatts output. The power production costs of the volume-produced COMPACT power unit could be comparable to diesel power costs in the U. S., and could be markedly lower for remote or ocean environment applications.

The unit will be air transportable in four to six packages, depending upon requirements. It is adaptable to marine or terrestrial, surface or submerged, fixed or mobile, and arctic or tropic environments. The COMPACT power unit is inherently stable, automatically controlled and self-diagnosed, and represents the safest mobile nuclear reactor design currently known. The technology and technical requirements are known, and final engineering and development can proceed from the existing SNAP 4 research and design program.

II. SUMMARY

The COMPACT power system described here will produce 12 Mwt and 2 Mwe for a 1-year (or 500 kwe for 3 years) per core loading, at a total shielded operating system weight of 90,000 to 150,000 lb, depending upon operating environment (land or sea, desert or arctic, manned or unmanned), and at 400 or 60 Hz frequency output. To generate the same amount of electric energy for 1 year by means of diesel equipment would require about 12 million pounds of fuel at the surface, or 40 million pounds of fuel and oxidizer in submerged or buried operation. Nearly twice as much fuel consumption would be required for open-cycle gas turbines. Therefore, COMPACT power has of the order of a 100 to 1 logistics advantage in the first year of operation, compared to chemically fueled systems.

Marine and industrial diesel electric generators weigh 50 to 300 lb/hp; the "shielded" COMPACT electric generator weighs from 35 to 100 lb/hp (depending on usage); consequently, in the few thousand horsepower output range, COMPACT power often can result in comparable installed weight to diesel power, even before diesel fueling. Further, it can be broken into packages for air transport. COMPACT power will excell in weight over gas turbine power, after only 2 to 3 days operating time, including fuel, and it is ideally suited to submerged or "buttoned up" hard-base operation, which is not possible for air breathing engines.

On land, the COMPACT system can be placed in remote locations at the point of usage, thus reducing the need for overland transmission or fuel transport. It can, in the future, serve as an "energy depot" or mobile fuel station by charging batteries or decomposing a chemical compound (such as H_2O , to form H_2 and O_2) for use in fuel cells to power smaller vehicles. It can also power large overland vehicles, "off road trains," railroads, etc, directly.

More than 1000 diesel engines at > 600 hp output, including over 400 diesel engines > 1000 hp output, are built in the United States each year for marine and industrial use.

Most diesel units, in peacetime, produce power at costs ranging from 20 to > 200 mills/kwh, due to the high cost of diesel fuel in some remote or mobile situations. The cost of remote power in time of war is incalculable.

Diesel power has enjoyed a near monopoly for small and remote site power generation for many years. Yet, nearly half of the world's land mass is relatively inaccessible by sea, rail, pipeline, or highway. Consequently, it has not been economical to explore or extract resources from much of this area, due to a lack of economical fuel transportation facilities.

It is evident that even excluding ASW and military uses, a substantial non-military market could develop for a safe nuclear unit that meets or excels the diesel engine weight, if costs can be reduced by production standardization.

In the long range, regardless of war or peace or current economic standards, it must be recognized that 70% of the world's surface (16 times the lunar surface) and its potential resources are submerged under the oceans. This leads us to consider how these resources can be tapped; and it becomes evident, as demonstrated by the nuclear submarine, that nuclear power is the only practical means of accomplishing sea floor exploration and extraction. Due to large pressures, compactness is of prime importance at great depths, and COMPACT power can give birth to an entire new industry and source of national wealth.

Thus, much of the promise of nuclear power is as yet untapped. However, for compact multipurpose nuclear power to be useful and to fulfill these potential needs, it must produce power at reasonable costs; it must be inherently safe to be transported and operated around the world under adverse conditions (mobile accident, battle damage, etc.). It requires semi-automatic and/or automatic control to reduce operator and operator training requirements. It must be extremely reliable, and require only occasional periodic service or maintenance by an air transportable service team. It must be hermetically sealed and fully contained, to prevent radioactive waste dispersal or the entrance of foreign materials.

To achieve these objectives, the compact multipurpose nuclear power system must be a standardized machine that can be put into volume production to achieve low cost and high reliability.

III. BACKGROUND AND APPROACH TO CONCEPT

In 1951 and 1952, Atomics International considered various types of reactors, but found that no suitable power reactor concept existed that would make compact multipurpose nuclear power feasible. Concurrently, the company researched and built the homogeneous water solution type research reactor, to gain experience in "small" reactor physics, control, gas handling, and later, production. It was soon learned that homogeneous water solution reactors would not become power producers, because they could not easily overcome elevated-temperature corrosion problems, as was demonstrated by the Homogeneous Reactor Experiment in Oak Ridge.

In 1953, the company funded its first formal study in its quest for a compact multipurpose power system. The impetus for this study was provided by the Rand Corporation's early studies, indicating the need for nuclear power in space satellites. The conclusion was reached that, for reasons of safety and economy, some form of thermal reactor was required. It was also concluded that, to achieve mobility and transportability as well as economy and safety, a small ($\sim 1 \text{ ft}^3$) high-power-density, high-energy-density reactor core was required. To achieve this goal, it was observed that the entire core should serve as "fuel element," in order to provide maximum heat transfer surface per unit volume, and to provide maximum possible dilution of fission products to minimize overall irradiation damage. Only a "fast" reactor or a hydrogenous-homogeneous reactor could have these features. Figure 1 illustrates the comparison of various types of reactors, and shows that only these two types can meet the criteria for mobility. The "fast" reactor was not favored, because of safety and cost.

In 1953 and 1954, Atomics International determined the thermodynamic equilibrium dissociation pressures and basic composition data of zirconium hydride.

Also in 1953, the first promising solid zirconium hydride bodies were formed. With this information and the pressure-temperature-composition data and the physics and control data from the homogeneous solution type reactor, Atomics International considered dispersing uranium fuel uniformly throughout

Figure 1. Compact Reactor Heat Source - 12 Mwt for 1 Year

the metal hydride, to evolve the first homogeneous metal hydride fueled and moderated, beryllium reflected, compact thermal power reactor. However, the concept, as evolved at that time, was still not adequate to meet the goals of compact multipurpose nuclear power, because the powder metallurgical bodies with dispersed UO_2 lacked adequate thermal conductivity, strength, and thermal shock resistance.

In 1954 and 1955, the ANP program resolved how to form low hydrogen density ($N_{\text{H}} = 4 \times 10^{22}$ H atoms/cc) massive zirconium hydride which had high strength, thermal conductivity, and thermal shock resistance.

This new accomplishment, coupled with the 1955 data that hydrogen diffusion through metal at elevated temperatures was drastically reduced by an oxide film, provided the impetus needed to proceed further with the evolution of compact multipurpose nuclear power. A study of the solid-state physics and

metallurgy indicated that it should be feasible to alloy zirconium and uranium; and, by massively hydriding slowly at high temperature, and holding composition constant during cooling by simultaneously varying pressure with temperature, one could then massively hydride to a high N_H of 6 or 7×10^{22} H atoms/cc. Then, by cladding the metal hydride fuel with oxide-coated steel, one could achieve the required core compactness and high power density in a thermal reactor at elevated temperatures. This approach was proposed in 1955 to the Air Force and the AEC, in competition for development of Nuclear Auxiliary Power for Space Satellites, and won the competition. The Systems for Nuclear Auxiliary Power (SNAP) Reactor Development Program was then initiated.

Operation in space required the use of high temperatures, and liquid metal coolants and working fluids, in order to radiate cycle waste heat at high temperatures. In 1956, at the beginning of the SNAP Program, plutonium and U^{233} fuels, and other hydrides (YH_2 , CaH_2 , TiH_2 , and LiH_2) were further evaluated, along with fast oxide-fueled cores. The homogeneous uranium-zirconium hydride alloy thermal reactor was again confirmed as being the safest, most reliable, and least-cost approach. At that time, various thermodynamic cycles were again reviewed, including the Brayton gas turbine cycle, the Sterling cycle, and the Rankine vapor cycle. It was again demonstrated that the Rankine liquid-vapor cycle was the best thermodynamic cycle for small, compact, automatic-controlled power systems. Due to the high temperatures in space, the mercury Rankine cycle was selected for space operation.

By 1957, forced convection boiling water experiments conducted for the AEC indicated that surface boiling heat transfer rates of $> 10^6$ Btu/ft²-hr were achievable. The fact that the reactor was moderated by the hydrogen in the zirconium hydride fuel element, indicated that the reactor could use various coolants, and led to the decision to cool the reactor with forced convection boiling water. Water worth, void coefficient, and preliminary control worth measurements were made in the first SNAP critical assembly in 1957, to confirm the control and stability feasibility of this decision.

However, it was recognized at the outset, in the summer of 1957, that available steam power generating equipment was excessively heavy and expensive. It was also recognized that a major weight contributor was the condenser

and the last stages of the steam turbine, because of the normal commercial practice of expanding to low pressure (1 to 2 psia). By boiling at high pressure (1200 psia) directly in the reactor, it was possible to achieve good thermodynamic efficiency with high turbine outlet pressure (5 to 20 psia). The size of the low-pressure equipment is inversely dependent upon the square of the exhaust vapor density. Thus, this higher exhaust-condenser pressure permitted shrinking these components by a factor of 10 in size. In 1957, it was also established that another high weight and cost contributor was the low-speed (1200 to 3600 rpm, 60 Hz) generator. It was apparent that, by increasing frequency to 400 Hz at 12,000 rpm or higher, this component could be decreased in size by a factor of 5 to 10.

Other high weight contributors in conventional steam equipment are valves and pumps. Thus, Atomics International, assisted by Rocketdyne Division of North American Aviation, Inc.,* examined the suitability of low-weight, hydraulic-actuated, high-pressure valves and turbo-pumps used in aircraft hydraulic control systems and rocket engine fuel and oxidizer lines. It was evident that, not only could weight be reduced by several factors, but that the extremely high operating reliability being developed for aircraft and missile flight systems would more than meet the requirements of a compact multipurpose automatic-controlled nuclear power system.

In 1958, Atomics International, with Rocketdyne support, undertook a conceptual design study to bring together all these concepts into one integrated system design. It was then recognized that a mobile system could not tolerate either the weight or the maintenance difficulties associated with conventional motor pumps, feedwater makeup, radioactive gas venting, steam loss, bearing lube oil cooling and separation, and air in-leakage to the system. Consequently, Atomics International drew upon the SNAP 2 Program, wherein the turbine generator was directly connected on one shaft, and suspended upon working fluid (mercury) lubricated bearings. In this case, water was to be used, rather than mercury. By that date, the use of water-lubricated bearings had been well established, with the canned rotor coolant pumps developed for the Pressurized Water Reactor Program. This approach permitted a completely welded

*Now Rockwell International Corporation

hermetically sealed water system, to prevent steam loss, oil contamination, feedwater makeup requirements, radioactive waste disposal, etc, and eliminated the excess weight, cost, maintenance, and operating requirements associated with such auxiliaries. Figure 2 is a simplified schematic of the resulting concept. One additional fundamental system problem remained. The hydrogen and oxygen formed from radiolytic decomposition in the reactor core had to be recombined in the sealed system, and water purity and chemistry control had to be accomplished. Here, it was found that the static-operated, platinized alumina, catalytic hydrogen-oxygen recombiner that was developed at Atomics International for the water solution type reactors could be utilized with modification. A low-temperature filter and deionizer, operating in the condensate loop, was found to be adequate for water purity control.

Figure 2. Sealed Single-Loop System

Heat rejection to air in land or mobile systems was accomplished by means of air forced through compact aircraft-type gas heat exchanger cores by motor driven fans. Due to the high condenser temperature ($\sim 200^{\circ}\text{F}$), this component is reasonable in weight and cost. Thus, the total system concept was basically evolved, and was integrated into a preliminary design for a truck-mounted mobile unit.

IV. SUMMARY TECHNICAL DESCRIPTION

The objective of the COMPACT development effort was to provide a multipurpose compact nuclear power system. To be truly multipurpose, the system had to be readily transportable by air, land, rail, or water, and had to be compatible with all terrestrial environments, either water or atmospheric. It had to be easily adapted to various uses with a minimum of equipment or packaging changes, and be sufficiently compact to permit mobile use or total unit assembly and shipment. The complete power system had to be capable of unattended remote operation, and automatic startup and shutdown. Unattended, remote, or long-endurance applications, as well as economics, dictated that the system and components had to be highly reliable. The demonstration of the required degree of reliability would be one of the most difficult problems, following initial development. In the event of piping rupture as a result of physical accidents, overall system containment had to prevent any spreading of contamination beyond the containment boundaries, especially when the physical accident was accompanied by the maximum credible nuclear accident. Basic shielding had to prevent activation of structure and environment, and ensure adequate protection of radiation-sensitive components. Maintenance and handling access requirements would vary with specific applications; thus, biological shielding became one of the custom engineering tasks in the application of the COMPACT power system. A final consideration in the criteria for the COMPACT power system was economics; the military forces had to be able to buy the number of units needed without placing an undue burden upon the overall military budget; and the cost of power had to be comparable to, or better than, other methods of providing power, including the cost of logistic support.

The COMPACT power system was designed to meet these criteria, at a nominal power of 2000 kwe and over a potential adaption range of 400 to 4000 kwe. The system incorporated a homogeneous zirconium-uranium alloy hydride fixed-moderator fueled, boiling water cooled, 1 ft³ reactor core in a direct-cycle saturated steam power conversion system. The compact, high-speed, 12,000 rpm turbine-generator equipment produced 400 Hz. The reactor and water purification and circulation modules could be connected to a heavier, lower speed (60 Hz) turbine-generator unit, or a marine propulsion turbine-shaft, at a sacrifice in weight, cost, and mobility (Figure 3). Specific dimensions

Figure 3. Multipurpose Power Conversion

and weights of the system were a function of the application, and are discussed elsewhere in this report.

A. REACTOR DESCRIPTION

The COMPACT reactor was designed for a nominal thermal power of 12 Mw, a life of 12 Mwt-years, and was reflector controlled. The core occupied a volume of $\sim 1 \text{ ft}^3$, and had a length-to-diameter ratio of 1.5. The core contained 583 stainless steel clad, 0.440-in. OD, cylindrical fuel rods with 17 in. of active length. Minimum spacing of 0.022 in. between adjacent fuel elements was maintained under operating conditions by spirally wrapped wires on alternate rows of fuel elements. The reactor core was designed to facilitate handling by dividing the core into seven fuel element clusters. Thirty-seven shim rods in the central cluster were readily exchangeable, for criticality adjustment prior to operation. In addition, the entire 2-ft diameter reflector-control assembly was removable into a shipping cask for maintenance or replacement.

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Figure 4. COMPACT Reactor

A cutaway view of the reactor and core is shown in Figure 4. Figure 5 is an engineering drawing of the reactor assembly.

Radial and axial power flattening were accomplished by the incorporation of a nuclear poison, hafnium, in the fuel alloy prior to hydriding. The fuel rods were segmented within the cladding to permit axial flattening. By varying the composition of fuel and poison in two regions within the core, a peak-to-average power ratio of 1.3 could readily be obtained. Flattening the power enhanced the worth of the reflector control elements, permitting a higher average core power density, and resulting in better overall fuel utilization. Burnable poison (hafnium) was also used to reduce reactivity swing due to burnup to $< 2\% \Delta k/k$ over the core life. Table 1 lists design and operating characteristics of the reactor.

An additional 2 to 3% $\Delta k/k$ was required for complete shutdown xenon override. The ability of the reactor to accomplish this was dependent upon when in the core life the requirement occurred, and the power output during xenon burn-out depended upon results of final critical tests.

Reactor control was accomplished by simple rotation of twelve, 4-in. diameter reflector drums which consisted of a 2/3 beryllium segment and a 1/3 segment of hafnium hydride, canned together in Type 347 stainless steel. Each control drum was held in axial alignment by water-lubricated ball bearings, and in rotation position by an electromagnetic clutch against a spring that would scram the reactor upon signal or power failure. All control-actuating mechanisms were sufficiently shielded from the core radiation to permit access and maintenance during reactor shutdown.

The entire core, reflector, controls, control actuators, thermal shield, and top activation shield plug were contained in a 1-1/8-in. thick stainless steel vessel, 2 ft in diameter and 6-1/2 ft long. This vessel was insulated and shielded with 4 in. of lead, as required to meet air transportation requirements after long-time operation and after core removal. An additional 4 in. of lead, weighing 7,000 lb, was required to transport the reactor with hot fuel in place, after activation shield water had been drained from the shield containment vessel.

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Figure 5. Reactor Vessel Cross Section and Nozzle Arrangement

TABLE 1
CHARACTERISTICS OF THE COMPACT REACTOR

Operating Power (Mwt)	12	Heat transfer area (ft ²)	95
Core Life (Mwt-yr)	12	Average heat flux (Btu/hr-ft ²)	431,000
Core Volume (ft ³)	1.07	Maximum heat flux (Btu/hr-ft ²)	560,000
Core Configuration		Burnout safety factor (minimum)	3
Effective diameter (with cusps) (in.)	11.77	Average power density in fuel (Mw/ft ³)	15.7
Active length (in.)	17	Coolant mass velocity (lb/hr-ft ²)	2.85 x 10 ⁶
Number of fuel rods	583	Coolant passage hydraulic diameter (in.)	0.0937
Fuel diameter (in.)	0.410	Reactor pressure drop (psi)	22.8
Cladding thickness (in.)	0.015	Reactor pumping power (water hp)	21.7
Fuel element diameter (in.)	0.440	Nuclear Control Requirements (% Δk/k)	
Pitch of triangular lattice (in.)	0.462	Minimum shutdown margin	2.0
Rod separation (at closest approach) (in.)	0.022	Transition from cold to hot-and-boiling (core N _H change)	4.81
Core Composition		Transition from cold to hot-and-boiling (axial reflector)	0.50
Fuel volume fraction	0.714	Doppler effect (core resonance absorption)	0.57
Coolant volume fraction	0.180	Fuel element elongation	0.16
Cladding volume fraction	0.106	Grid plate expansion	0.12
U ²³⁵ loading (fully enriched) (kg)	20.7	Thermal flux spectrum temperature shift	0.04
Zirconium loading (kg)	112.0	Fuel element cell effect	(negligible)
Burnable poison		Hydrogen loss from fuel	(negligible)
Hafnium (kg)	4.8	Equilibrium xenon poisoning (mid-life)	2.0
Europium oxide (gm)	160	Burnup control requirement	1.4
Hydrogen density in fuel (atoms/cc fuel)	5.35 x 10 ²²	Total	11.60
Hydrogen density in cold, flooded core (atoms/cc core)	5.02 x 10 ²²	Nuclear Control Availability (12 reflector drums)	
Average hydrogen density in hot, full-power core (atoms/cc core)	4.42 x 10 ²²	Cold	12.50
Burnup (peak) (metal at. %)	2	Hot	13.2
Reflector Composition		Coefficients of Reactivity (Reactor operating conditions)	
Axial Stainless steel (in.)	1		$\frac{\Delta k/k}{^\circ F}$ $\frac{\epsilon}{^\circ F}$
Water - bottom plenum (in.)	10	Fuel elongation coefficient	-0.20 x 10 ⁻⁵ -0.025
Water-steam - top plenum (in.)	4	Core coolant expulsion coefficient	-0.57 x 10 ⁻⁵ -0.071
Radial Control drum diameter (in.)	3.95	Neutron spectral coefficient	-0.03 x 10 ⁻⁵ -0.004
Thickness of beryllium (in.)	2.80	Doppler coefficient	-0.54 x 10 ⁻⁵ -0.069
Thickness of poison zone (in.)	1.15	Net prompt coefficient	-1.3 x 10 ⁻⁵ -0.17
Cusp and filler material	Nickel	Lower grid plate coefficient	-0.055 x 10 ⁻⁵ -0.007
Operating Conditions		Upper grid plate coefficient	-0.133 x 10 ⁻⁵ -0.017
Coolant flow rate (lb/hr)	4.1 x 10 ⁵	Power coefficient	-0.0044 k/k-Mwt, 55 ε/Mwt
Coolant inlet pressure (psia)	1235	Steam void coefficient	-0.165 k/k-sec
Coolant outlet pressure (psia)	1212	Core hydrogen concentration coefficient (N _H in terms of 10 ²² H atoms/cc)	0.09 Δk/k-ΔN _H
Coolant inlet temperature (°F)	540		
Coolant outlet temperature (°F)	570		
Recirculation ratio	10.1 (10% exit quality)		
Average cladding temperature (°F)	667		
Average fuel temperature (°F)	879		
Maximum fuel temperature	1056

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Figure 6. System P&I and Heat Balance Diagram

The reactor was cooled with 430,000 lb/hr of 1200 psia recirculating water. Steam was formed at a rate of 43,000 lb/hr, to form a 10% exit quality mixture. The mixture exited the core at a 50/50 volume ratio, and flowed through the top shield plug labyrinth to an annulus inside the core vessel and out the 6-in. diameter center pipe to the adjacent steam separator. The mixture was separated by gravity, a demister, and centrifugal action. The water was drawn from the bottom of the separator vessel to the steam turbine driven recirculation pump suction, and discharged to the reactor inlet through a float check valve to the outer annulus of the concentric nozzle to the annulus formed between the thermal shield and the inside of the reactor pressure vessel. The return water flowed downward around the reactor, cooling the pressure vessel and the thermal shield, and reversed direction at the bottom to flow upward through the reflector core to complete the circuit.

The entire high temperature-pressure, insulated, hermetic-sealed water circuit was contained within the cold water filled primary shield containment vessel. Thus, if any leaks or pipe breaks should ever occur, the hot steam and water could do no more than raise the shield water temperature 15° F, still below atmospheric boiling temperature. Likewise, the entire shield water inventory was available to cool the reactor after-glow heat, should a line break occur. Isolation valves in the main steam exit and water return lines would close upon loss of pressure in the external steam loop. An auxiliary natural circulation shutdown decay heat loop was valved to the main internal recirculation stream, to be utilized in case of a leak in the main external steam system. The shield water was externally cooled. Figure 6 is a system P&I H at Balance Diagram.

The primary containment tank was 8 ft in diameter, and 8 ft high without its flanged polyethylene-filled cover dome, which would be airshipped separately. The vessel was fabricated of reinforced 5/8 in. 52S aluminum, to minimize weight. This primary shield was adequate only for prevention of equipment activation and for close-approach shutdown contact maintenance. In many undersea applications, no further shielding is required. In other fixed installations, earth or ice shielding is available. In open or mobile applications, further lead and water or polyethylene shielding must be provided, in accordance with operating access requirements.

TABLE 2
APPROXIMATE REACTOR AND SHIELD WEIGHTS

Objective	Reactor Module Only (tons)		
	Dry System	Water Shield	Operation Total
Fixed-Plant Air Transportable Site			
Biological Shield Water Equipment			
Activation Protection			
Nonrelocatable	9	14	23
Relocatable	14	14	28
Relocatable 2 weeks (dry) with full in-place ICC shipping regulations	18	14	32
Truck or Rail Mounted			
2.5 to 5 mr/hr at 500 ft operating, immediate shutdown maintenance access and ICC shipping regulations shutdown (<24 hr) dry	20	17	37
Mobile operating, additional control cap shielding	10		47
Ocean Bottom Installed			
Naval marine activation specification, nonretrievable (less depth containment)	8	10	18
Retrievable for direct maintenance	17	14	31
With 1000-fathom pressure hull	22	14	36
Surface Ship Installed	25	40	65

TABLE 3
APPROXIMATE SYSTEM MODULE WEIGHTS

Power (Mwe)	Core Life 70% Plant Factor (year)	Water Process Module (tons)	Power Conversion Module (tons)		Heat Rejection Module (including condenser) (tons)		Electrical and Controls	
			400 Hz 25 psi	60 Hz 10 psi	To Water 10 psi	To Air 25 psi	400 Hz (tons)	60 Hz (tons)
0.5	3-1/2	4-7	4	10	3	6	6	7
1	2	5-8	5	12	4	8	6	8
2	1-1/2	6-9	6	15	6	12	7	9
3	1	7-10	7	18	8	16	8	10

Fuel changing equipment - 4 tons, core shipping cask - 9 tons, Installation and Assembly Tools and Materials - 5 tons.

B. PROCESS SYSTEM

The COMPACT system was simplified, to permit early development and more versatility in application. The simplification primarily consisted of removing the pumps from the combined rotating unit (CRU) shaft. They were turbine driven, by prime reactor steam from the main primary steam line. The steam was exhausted to a feedwater heater to provide regeneration. In this way, the system could be designed and operated more independently of the turbogenerator. Consequently, the same reactor-pumping system and water processing system could be used with either a 400-Hz turbine-generator set, a 60-Hz turbine-generator set, or a marine propulsion turbine. In addition, the 400-Hz turbine-generator shaft was thus shortened, and could shrink in diameter to bring the water bearing speeds to nearly state-of-the-art levels. Likewise, easier system control was provided, by varying the steam flow to the turbine-driven pumps rather than throttling the water flow, as before. The penalties paid by this approach were: (1) two separate pumps (within the state-of-the-art), (2) $\sim 1\%$ efficiency loss, and (3) slightly less compact system arrangement. The penalties were overshadowed by the simpler development and added versatility of valving and control.

The primary recirculation pump was included in the reactor package. The remaining water process system components, including the condensate-high pressure feed pump, the deionizer and filter, the hydrogen-oxygen eductor and recombiner, the regenerative heat exchangers, the water accumulator, and a safety poison injection system were placed in a separate package. The turbine-generator, the condenser, and the turbine bypass valves were placed in a third package (Figure 7). All packages were designed for complete containment and aircraft shipping requirements. In the low exhaust pressure, 60-Hz turbine-generator systems, the condenser might have to be put in a fourth package, to meet a 20,000-lb load limit.

Tables 2 and 3 present the approximate weight of the reactor, shield, and system modules.

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Figure 7. Power Conversion Equipment

V. APPLICATIONS

A. GENERAL APPLICABILITY

A review of national energy requirements in 1970 indicates a fuel usage distribution as follows:

1) Electrical generation	23%
2) Industrial heat and power	29%
3) Residential and Commercial heat	21%
4) Transportation	26%

An advantage of compact nuclear power is the ability to locate it in small packages near the load requirement, without a significant logistics penalty. Consequently, it is particularly suitable for application in "Total Energy" systems, wherein waste heat is put to useful service. If it is assumed that the vapor evaporation cycle is used for refrigeration and air conditioning, the heat temperature requirements for waste heat application are shown in Table 4. As an example of energy use patterns, Table 4 shows the energy use breakdown for Residential and Commercial Sector.

TABLE 4
ENERGY USE PATTERN FOR RESIDENTIAL AND COMMERCIAL SECTOR

	Trillion Btu/year	Required Temperature (° F)
Space Heating	6,700	120- 200
Water Heating	1,700	140- 200
Clothes Drying	210	140- 200
Air Conditioning	500	180- 240
Refrigeration	700	180- 240
Cooking	650	240- 600
Electrical	<u>1,240</u>	450-1000
Total	11,700	

Consequently, it is observed that 85% of the residential and commercial energy consumption could be satisfied by the waste heat temperatures from compact power systems.

A significant fraction of industrial and electrical energy requirements can also be supplied by smaller decentralized packages as, of course, already occurs in ships, railroads, mining, and other heavy diesel applications.

As electric or fuel cell transportation vehicle power systems are developed, the compact power system will further contribute to transportation energy demands, through the "Energy Depot" concept.

Compact power can aid the nation's energy dilemma in critical periods of national emergency, by reducing logistics and by reducing imported and export oil dependence, as follows:

- 1) By powering military communications, surveillance, command, and strategic missile sites and hardened bases
- 2) By powering public communications, transportation, and medical-hospital centers
- 3) By powering strategic food and materials stockpile centers
- 4) By powering barge and rail materials transportation systems
- 5) By powering water and pipeline pumping distribution systems, and and sewage treatment facilities
- 6) By powering strategic industries and processes
- 7) By powering overseas military operations — air bases, command and communications, and vehicles (by means of energy depots, utilizing fuel cell or advanced battery power supplies)
- 8) By providing military and strategic ship propulsion for extended-range cruise operating mode
- 9) For propulsion of antisubmarine warfare small submersibles, and powering underwater sonar surveillance systems.

Compact power can further reduce world shipping requirements, and enhance development of isolated regions and islands by providing reliable energy for

tourism, food processing and preservation, and initial industrial development. The relocatable feature of the plant permits adoption of more economical power as energy demands grow and develop, to where large power plants can be justified.

B. SPECIFIC APPLICATIONS STUDIES

Through liaison with potential users, and brief design, configuration, weight, and safety studies over 5 years, Atomics International has reached the design and package concept previously described. Some compromises must be made to the optimal design for each application, to do the jobs with a single reactor design and a single development program. However, these sacrifices are overshadowed by the decreased cost, maintenance, and operator training requirements that can be achieved by utilizing a single approach.

The applications considered include:

- 1) Fixed installation packaged transportable units
 - a) Bureau of Yards and Docks
 - (1) Advanced base units (2000 kwe — 60 and 400 Hz)
 - (2) Antarctic units
 - (3) Small ship- and barge-mounted units
 - (4) Disaster recovery
 - b) Army second-generation package power (1000 kwe — 60 Hz)
 - (1) Air transportable
 - (2) Antarctic and tropic
 - c) Air Force and Office of Civilian Defense
 - (1) Deep underground hard-base command and communications centers (2000 kwe — 400 Hz)
 - d) Canadian remote northern radar and missile base power (2000 kwe — 400 Hz)

Figure 8. COMPACT Power System Applications

- e) Industrial development of northern Canadian interior, Brazilian interior, and other remote mining or extractive industries (2000 kwe — 60 Hz)
- 2) Land mobile units
 - a) Truck-mounted (2000 kwe — 60 or 400 Hz) units for Army and OCD application (nonoperating during transit)
 - b) Low-power (300 to 500 kwe — 400 Hz) truck-mounted system for Army Combat Support and ADS-70
 - c) Nuclear locomotive (2000 to 3000 hp)
- 3) Mobile marine units
 - a) Large ship electrical power generators (1000 to 2000 kwe)
 - b) Ship long-range cruise propulsion power
 - c) Small submersible (untethered variable depth sonar) propulsion (1000 to 3000 shp)
 - d) Department of Interior Research Submarine propulsion (2000 kwe — 400 Hz) or (2500 shp)
- 4) Fixed, sea-bottom-installed marine units
 - a) ASW — fixed sonar barriers and networks (100 to 1000 kwe)
 - b) Ocean-bottom extractive industries (1000 and 2000 kwe — 400 Hz)

Figure 8 illustrates many of the applications listed.

Surveys made indicate that the greatest demand for compact nuclear power will be in marine applications, until costs are decreased to the volume production level. Details of these surveys are not provided, because they are incomplete at this time.

The conclusions that may be drawn are:

- 1) Many of the discussed applications will never come to pass, unless a suitable power unit first exists.
- 2) Several of the applications, as currently foreseen, cannot individually justify a nuclear power unit development.

- 3) Several important systems that could be better accomplished with compact nuclear power are not willing to jeopardize their own progress by depending upon a nuclear power plant that does not as yet exist.
- 4) If this country is to realize the benefits of its leadership and investment in nuclear power, and especially its compact SNAP power technology, the government should and can immediately undertake to final design, component test, fabricate, and operate a first-prototype COMPACT power system, to provide the required stimulus for widespread adaptation of the compact energy of the atom.

C. FIXED TERRESTRIAL AND TRANSPORTABLE POWER SYSTEM

1. Bureau of Yards and Docks (Figure 9)

The Bureau of Yards and Docks, U. S. Navy, is responsible for disaster recovery, and for nonpropulsive Naval Nuclear Power Development. The power area showing most need and promise for nuclear application is in the 1 to 2 Mwe

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Figure 9. Power Barge — COMPACT Power System

power range. This power is required at advanced base complexes (usually established at overseas locations) in the initial stages of construction, and for the base operation in time of war. Fuel supply for conventional plants imposes a severe load on logistic support facilities. A plant is being sought that is relatively compact, and is truck-, air-, and landing-craft transportable before and after operation at 30,000 lb per package. The units must be capable of rapid field assembly and disassembly at a remote site with limited logistics support. The method of rejecting heat to the surroundings would normally be to an air-cooled heat exchanger, to allow independence of water-supply sources. An erection crew of about 10 to 20 men is permissible, depending on site requirements. The plant could be maintained and refueled in the field, and should have a minimum core life of at least 5000 hr. The general characteristics are shown in Table 5.

TABLE 5
GENERAL CHARACTERISTICS OF THE 2-Mwe, 60- AND 400-Hz SYSTEMS

Power	2 Mwe, 60 Hz	2 Mwe, 400 Hz
Number of Packages	6	5
Total Weight of System (lb)	140,000	90,000
Fuel Handling Equipment and Shipping Cask (lb)	26,000	26,000
Reactor Access After Shutdown (hr)	6	6
Cost After Development		
Power system	\$1,729,000	\$1,439,000
Fuel	250,000	250,000
Installation	<u>388,000</u>	<u>388,000</u>
Total	\$2,367,000	\$2,077,000
Operation (mills/kwh)	31	29

2. Hardened Bases (Figure 10)

The Strategic Air Command, U. S. Air Force, must have the ability to maintain positive communications with field forces, during and after a sustained thermonuclear attack. To meet this requirement, the Air Force has given serious consideration to deep underground facilities which will function as

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Figure 10. COMPACT Facility (Hardened Base)

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Figure 11. COMPACT Power Plant for Remote Operation

command and control centers. One of the problem areas which can be defined is that of providing a reliable, highly regulated, electrical power supply in the facility at all times.

The base must be provided with a power source that is economically attractive during normal operation. The power plant must be suitable for construction and operation in deep underground tunnels, and power must be continuously available during long periods (months) of complete isolation from the surface.

3. Army Second-Generation Packaged Power (Figure 11)

The general technical objectives of the Army Reactor Branch Program include: (1) increasing power and life of nuclear reactor cores, (2) simplification and ruggedization of components, (3) reduction of crew size and improvement of system reliability and safety, making plant operation as nearly unattended as possible, (4) continued improvements in plant transportability, mobility, and relocatability, (5) reduction of on-site construction effort, time, and costs, (6) achievement of as high a degree of standardization as possible, and, very importantly, (7) reduction of initial and operating costs to a minimum.

As a result of experience to date, especially with the PM-1, PM-3A, and PM-2A, there is an urgent need for fewer packages, more rapid field assembly and checkout, more reliable and less complex operation, and lower costs. As an example, PM-3A at McMurdo Sound required 57 packages, and an estimated \$10 million final plant cost, including installation. Operational and control problems plagued the plant during initial operations.

Atoms International conducted extensive analysis and design studies on a hydride moderated boiling reactor, COMPACT, to determine how well it met the needs of the Army Reactor Branch. Results of Atoms International's efforts indicated that there was no doubt as to the ability of the COMPACT reactor system to fulfill or better the requirements of a second-generation portable package power plant. The COMPACT plant would require six packages, and each package would weigh <20,000 lb, except the reactor module, which would weigh <30,000 lb. This module could be reduced to 20,000 lb at the expense of increased site fabrication costs and reduced plant reliability, or sacrifice of the ability to relocate the reactor after a period of use. Neither appears to be desirable or required. Total system weight would be ~120,000 lb, plus

~25,000 lb for spent fuel handling and shipping equipment. Erection time is ~2 weeks, requiring 12 men and only limited site excavation. The system is adaptable to air-cooled condensers and/or water-cooled condensers, and can be air transported with final positioning by skids. The cost of the system f.o.b. factory should be approximately \$2 million in initial production, and less later. Shipping, installation, and operation costs will be small, compared to other systems, and perhaps the single most important conclusion is COMPACT's unique standardization approach. Costs, training requirements, and spare parts maintenance will be reduced with the increased potential of stock piling, relocating, changing site, or application after manufacture.

4. Nuclear Power for Civil Defense

The Office of Civil Defense (OCD) must have the ability to maintain positive communications with regional offices which, in turn, must communicate with designated areas before, during, and after a sustained thermonuclear attack. Many difficult technical, economic, and operational problems arise when one considers establishment of facilities to fulfill this requirement. Again, as in Air Force hardened bases, one important problem is that of providing a reliable, highly regulated, electrical power supply at all times.

Consideration of the power needs of the OCD indicated that they could be subdivided into three general areas, as follows:

a. Command and Control Headquarters

One important facility is the Command and Control Headquarters of the Office of Civil Defense. The base must be provided with a power source that is economically attractive during normal operations, yet it must be compatible with DOD weapons systems and objectives of the National Plan. The power plant must be suitable for construction and operation in deep underground tunnels, and power must be continuously available during long periods of isolation from the surface, as in Air Force hardened bases.

b. Communications Within Regional Areas

A second important portion of the network is the electronic equipment required to transmit, receive, and/or relay signals within the regional areas. Usually, this equipment is located at a strategic site; and in many cases, these

locations are in remote, inaccessible regions, such as on mountains, in line with canyons, on islands, etc.

The electronic system must be able to operate unattended for long periods of time, and under severe environmental conditions. A reliable power source is one of the most critical portions of the system. Here, very small nuclear power plants could be used which are capable of operating for several years without refueling. Such plants must be completely automatic, and have inherently high reliability.

c. Civil Defense Groups

Civil defense groups are somewhat decentralized; and, especially after an attack, these groups will be autonomous for varied periods of time. Therefore, it is imperative that each regional area be self-sufficient. It would be advantageous to have multipurpose energy sources available that are free from logistics support and readily transportable. A compact mobile nuclear system fulfills this mission. Also, as with warning and communications nuclear power systems, these multipurpose plants should lend themselves to the capability of full-time utilization during normal periods, as well as during emergency conditions. This type of operation is desirable due to the capital investment involved.

The COMPACT system has been presented to the Director of Communications and Warning, Office of Civil Defense, and Office of Emergency Planning, for consideration in resolving certain power problems. The Deputy Director, Special Assistant of the Office of Civil Defense, and personnel from the Office of Emergency Planning expressed interest in the COMPACT system for Office of Civil Defense application.

The briefings revealed that there are many advantages for using a COMPACT system for Civil Defense needs in the 0.5- to 2-Mwe power range. Some of these:

- 1) Compactness
- 2) Relocatability
- 3) Mobility
- 4) Safety

5) Economy

- 6) Versatility — the same basic plant could be built for various modes of operation: (a) shipboard or barge mounted with saline water distillation and water pumping equipment, (b) truck mounted for off-road utilization, (c) rail mounted, and (d) air transportable for rapid transportation.

The safety, economy, mobility, and versatility provides OCD with the possibility of subsidizing commercial or civic groups for normal use, rather than just outright procurement for emergency use only.

5. Nonmilitary Utilization (Figure 12)

Diesel engines, fossil fired boilers, and in some locations, hydro-plants, supply industry with small blocks of power for either electrical production or

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Figure 12. Remote Industrial Utilization — COMPACT Power System

industrial heat. The first two systems rely on a supply of fossil fuel, while the latter system is restricted to specific geographic locations. As the location of the power user moves away from the source of fossil fuel or a natural hydro location, the cost of power rises rapidly.

The volume-produced COMPACT unit would be competitive with the diesel at the source of fuel, and would become a significantly cheaper source of power at a remote location because of its independence from fuel supply. The COMPACT system is therefore ideally suited to help countries penetrate their undeveloped areas. For example, the COMPACT unit can be located to produce economic power at remote natural resource exploration sites. Such power would be produced until a large central station power system was justified, or until economic consideration dictated otherwise. In either case, the COMPACT unit would be moved to another site requiring a small block of power.

A number of Canadian government agencies have expressed interest in the COMPACT system. They let a contract to determine the extent to which Canadian industry could provide the power conversion and packaging portions of the plant. They considered undertaking a cost-sharing program with the U. S. government for the development of the COMPACT system (known in Canada as the HMBR). Among these agencies were the Canadian Department of Trade and Commerce, Department of Defense Production, and Atomic Energy of Canada Limited (AECL). AECL expressed interest and belief in the feasibility of COMPACT. In northern Canada, diesel power is generating electricity at 30 to 35 mills/kwh. The hydro-plant at Mayo produces electricity at 23 mills/kwh. As the development of more remote areas in Canada and elsewhere increases, the cost of conventional power will rise even higher. The Canadian Government is acutely concerned about how to develop its northern interior. In several instances, the required in-flow of fuel oil to operate mines exceeds the ore outflow. Secondly, Canada's role in NATO and Continental Defense includes their operation of northern radar and missile sites, and their participation in Arctic ASW. They recognize the potential advantages of applying compact nuclear power to solve these problems. The market potential for volume-produced COMPACT units is therefore very promising, especially when

Figure 13. Total Annual Cost for Nuclear and Diesel Plants (Transport and transport distance)

Figure 14. Land Mobile Unit — COMPACT Power System 7564-0210

we consider that the rejection heat from a reactor can be used for space heating in northern locations. Such utilization of the waste heat would reduce the power cost ~ 4 mills/kwh, assuming $23\text{¢}/10^6$ Btu.

The Asimow Project at the University of California (UCLA), sponsored by AID, is concerned with the development of the interior of Brazil and other underdeveloped countries. This project has recognized its power problem, when trying to develop the interior. The project has expressed its desire to determine how COMPACT power can help solve these problems.

Figure 13 shows the total annual cost for 2000-kwe nuclear and diesel plants for various modes of transport and transport distance. Zero distance costs include amortized plant cost, maintenance and operating cost, and base fuel cost of $18\text{¢}/\text{gal}$ for the diesel plant.

6. Truck-Mounted Transportable Power (Figure 14)

a. High Power

One of the main objectives of the Army Nuclear Power Program (ANPP) is the development of truly mobile nuclear power plants for field use for a variety of purposes. These power plants must eventually be capable of operation while in motion, at power levels from 1 to ~ 3 Mwe, for a variety of applications. The long-range development of these unit transportable power plants is expected to produce the capability for such eventual applications as a propulsion power source for an overland train or other vehicle.

The general technical objectives of the ANPP in developing nuclear power plants for this application must include compactness, safety, simplification, light weight, economy, and minimum operating and maintenance requirements.

The COMPACT power plant could meet the requirements of the Army program for a mobile compact reactor nuclear power system. The compact, lightweight, modularized arrangement of the components, and the inherent safety of the boiling water system, are ideal for installation as a truck-mounted system. The mobile 2-Mwe system will weigh ~ 53 tons, not operating, and a total operating weight (including shield water) would be ~ 70 tons. About 10 tons of this weight could be on a separate electric equipment and control truck. In this regard, advances in the state of the art in wheeled-vehicle construction,

especially in the field of earth-moving equipment, leads to the consideration of a land transport configuration for the COMPACT system that would have high mobility in both off-road and on-road utilization.

For early application of off-road trains, the drive could be diesel, or diesel-electric with individual electric drive in each wheel, as in large earth-moving equipment, and the system would be ready for full-power operation upon arrival on station. The eventual use of the electric power output of the nuclear power plant to propel the vehicle in transit has many operational advantages, though it represents a substantially more difficult safety and shielding problem. The self-propelled plant would have complete logistics independence during the life of the reactor core. Surplus power during transit would be used to drive the wheels of attached vehicles on a land- or snow-train configuration. Proper selection and design of the cars on such a land train could provide a logistically independent offensive and defensive capability for an Army combat unit. The system would be self-propelled to near its action point. The train would carry troops, vehicles, missiles, guns, ammunition, and stores. When stopped, the nuclear power would be used for radar, fire control, and communications. Eventually, the Army hopes to use the power as an energy depot (mobile fuel supply), by charging lightweight batteries for battery-powered combat vehicles, or to electrolyze water into hydrogen and oxygen to supply fuel-cell-powered vehicles.

Figure 14 shows a possible arrangement of the COMPACT unit as a vehicle-mounted system.

b. Low Power

In the lower power ranges, the Army Nuclear Power Program has as its objectives the development of mobile nuclear power for the support of combat units and other requirements. The same general objectives of safety, simplification, etc, are as important in this development as in the higher power ranges.

The COMPACT unit, at ~40 tons transportable weight, and producing 500 kwe, could readily meet the requirements of the ML-1. It could use the same reactor and recirculation loop as the higher-powered units. However, it would use smaller power conversion and air-heat rejection system components,

specifically designed for the low-power operation. Under these conditions, the COMPACT core would have ~ 5 full-power years of operating life. Due to the type of service these plants would see, it is doubtful whether the core need ever be replaced during the system's operational life.

7. Locomotive Propulsion (Figure 15)

An application for nuclear power that has been considered in the past is its use in locomotive propulsion. Previous evaluations did not have available a compact thermal reactor upon which to be based. Diesel electric locomotives weight from 200,000 to 750,000 lb. The COMPACT air-cooled shielded system can easily meet the weight and space requirements for locomotive use. However, for locomotive use, economics and mobile safety must also be achieved. In this regard, the Association of American Railroads has been following the development of nuclear power with interest. Their reasons for doing so are that nearly 25% of the electrical power generated in the United States is consumed by railroads, which produce a major share of this power by means of diesel-electric locomotives in the 500- to 5000-hp range. The cost of U. S. diesel-electric railroad power ranges from 25 to 45 mills/kwh, considering diesel maintenance, fuel storage, handling, and distribution costs. The costs in India, Canada, Australia, Africa, and South America are often higher, due to the remoteness of their interiors and the low skill level of personnel. These areas are almost totally dependent upon rail transportation, and diesels are extremely expensive to maintain and rebuild. The development of a reliable, low-cost, automatic-controlled, nuclear power engine for their use would be of great long-term advantage to world rail transportation.

The Denver and Rio Grande Western Railroad Company had been working with the Long Range Planning Service of the Nuclear Division of Stanford Research Institute, to determine what advancements have been made in the field of nuclear energy that might be applicable to their proposed usage. Discussions with D & RG management, relative to the possible application of the COMPACT nuclear power system to their needs, had resulted in a renewed interest in this possibility on their part.

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Figure 15. Nuclear Locomotive - COMPACT Power System

The COMPACT power system incorporates many features in its basic design that are required in an application of this type. The lightweight, compact, modularized arrangement of the components, and the inherent safety of the boiling water system, coupled with the three degrees of fission product containment, results in a system with a high degree of safety under most of the credible accidents that could be postulated. This, coupled with the potential economics of the volume-produced COMPACT system, indicates that this application warrants a new study and evaluation.

Figure 15 shows an artist's concept of the COMPACT power unit adapted to locomotive propulsion.

Units of this type could serve dual purposes. They not only could furnish motive power for the railroads (especially in mountain areas), but could serve as a source of standby power when required in disaster areas. If the applications studies of the COMPACT system appear promising, the Nuclear Research Board of the American Railroad Association has expressed interest in approaching the AEC and the OCD for potential aid in the development of the COMPACT-powered locomotive.

D. MARINE

1. Nuclear-Powered Research Submarine (Figure 16)

The Department of the Interior expressed interest in nuclear-powered research submarines. The vessels would be used jointly by the Bureau of Mines and the Bureau of Commercial Fisheries. The Bureau of Commercial Fisheries wants a vehicle capable of tracking schools of fish for considerable distances at relatively high speeds, to ascertain migratory habits. The Bureau of Mines wants to be able to observe, photograph, and map deposits, to recover samples from the ocean floor, and to drill core-sampling holes of at least 1000 ft in depth.

Plans for a vehicle are still fluid; but, in general, it should be ~150 to 200 ft long, and powered by a 2500- to 3000-hp nuclear power plant. It should provide for direct ingress and egress by SCUBA divers. It would have a 1000-ft depth capability, and should provide for a technical staff of 10 to 12, as well as the ship's crew necessary for a few weeks at sea. Most significantly, it should be able to remain resting on the ocean floor for periods up to 2 to 3 weeks, while drilling test holes in deposits.

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Figure 16. Research Submarine – COMPACT Power System

Figure 17. Ocean Bottom Drilling and Mining

Nuclear propulsion for submarines satisfies the requirements for long range and underwater endurance. Current nuclear power plants used in submarines meet these requirements; however, they are quite large, heavy, and costly for research vessel uses. The correlation between size and cost has led to the consideration of small submarines for research.

The COMPACT power plant would be uniquely adaptable to power a vehicle of this type, and possesses many advantages for this application which are not attainable in other power systems. The low specific weights of the COMPACT hermetically sealed power system, combined with its capability for generation of electrical power, makes possible the design of a research submarine that will meet the requirements of size, range, and endurance desired by the Department of the Interior. Since the requirements for performance of the small research submarine are very similar to those of drone sonar, it will be possible to use a "standardized" COMPACT power module for both applications.

2. Ocean-Bottom Drilling and Mining Exploration and Extraction (Figure 17)

The mineral content of the ocean appears to be virtually inexhaustible. Sea water contains trace elements which comprise billions of tons of potentially valuable minerals. Marine beaches are a source of ilmenite, rutile, and other sands which contain industrial minerals, such as titanium, zirconium, and iron. The continental shelf and slope areas hold vast deposits of oil, coal, gas, and sulphur, as well as mineral-bearing terrigenous sediments and phosphate rock. The deep sea itself contains valuable sedimentary deposits, hardrock, and ore bodies which, in certain areas, are found as "nodules" of manganese, cobalt, nickel, and copper, formed by precipitation and other chemical reactions.

Beach sand deposits and ocean water magnesium and bromine extraction is being exploited around the world by shore-based plants. Shallow areas of the continental shelf are currently being tapped for oil, gas, and sulphur. However, there have been no known commercial operations in the outer reaches of the shelf and slope areas, or in the deep-sea regions. Development and operating costs with conventional surface dredging and mining equipment, logistical support, power requirements, and surface platform stability problems are a few of the reasons why deep ocean mining has not yet become commercially attractive to industry.

The use of nuclear power in marine mining could provide the key to surmounting some of these problems, because of its ability to operate on the bottom on a stable platform, free from weather, sea conditions, and logistic support. Many applications of the COMPACT reactor system to marine mining and dredging could be postulated. Many potential schemes have not been exploited, because no such reactor power system has been available at reasonable cost. Atomics International has been receiving a limited number of inquiries from industry concerning the use of COMPACT power for such applications, as knowledge of COMPACT's existence has become known to industry through classified channels.

3. Anti-Submarine Warfare Ocean Surveillance (Figure 18)

The threat that the Sino-Soviet submarines present to the defense of our country, commerce, and allies, stems from their seclusion under the ocean's surface. Modern long-range and high-resolution radar, coupled with surveillance aircraft, satellites, and ships, has illuminated the air and ocean surface spaces, such that relatively straightforward defensive and evasive tactics may be employed against surface craft. However, the opaqueness of the sea to electromagnetic radiation leaves us virtually blind below the ocean surface. The Navy, the National Science Foundation, and many universities and contractors have for several years been making every effort to learn how to illuminate the ocean.

In past conflicts, our submarine enemy has been tied to the surface. He had very little submerged endurance and speed; thus, when he was detected on the surface, while cruising or charging batteries, he was often quickly tracked and destroyed. The later, more sophisticated, snorkling submarines were usually detected by hydrophones, due to their high noise output. Consequently, current hydrophone surface or near-surface limited-detection techniques will continue to be in use for some years to come. It is known that the potential enemy is rapidly increasing his nuclear submarine force strength. Nuclear submarines can run deep, fast, and quiet for a long time. As a result, sound echo ranging (active sonar) is one known reliable detection and tracking method available. Normally, surface-deployed sonar is limited to a range of a few miles. Only in very unusual ocean conditions is this range significantly increased.

Figure 18. Anti-Submarine Warfare Ocean Surveillance

Oceanographers and sound experts have theorized that, at great depths [~ 2000 fathoms (12,000 ft)], depending upon latitude, season, etc., the speeds of sound equals the speed of sound at the surface. Thus, a sound channel would exist between these depths. When a sound source is placed deep, the sound emanating from it should refract and reach the surface about every 35 miles. If the sound source is placed at $\sim 12,000$ ft, it should form a wall of sound, shaped like a bell, with a 35-mile diameter at the surface. If the sound source is powerful enough, the second ring at the surface would be >100 miles in diameter.