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NUCLEAR POWERPLANTS FOR MOBILE APPLICATIONS

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Abstract

Mobile nuclear powerplants for applications other than large ships and submarines will require compact, lightweight reactors with especially stringent impact-safety design. This paper examines the technical and economic feasibility that the broadening role of civilian nuclear power, in general, (land-based nuclear electric generating plants and nuclear ships) can extend to lightweight, safe mobile nuclear powerplants. The paper discusses technical experience, identifies potential sources of technology for advanced concepts, cites the results of economic studies of mobile nuclear powerplants, and surveys future technical capabilities needed by examining the current use and projected needs for vehicles, machines, and habitats that could effectively use mobile nuclear reactor powerplants.

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Summary

Mobile nuclear powerplants for applications other than large ships and submarines will require compact lightweight reactors with especially stringent impact-safety design. For civilian nuclear power in general, a broadening role is indicated by the increasing orders for land-based nuclear electric generating plants and the awakening multicountry interest in the potential economy of nuclear ships. This paper examines the technical and economic feasibility that this broadening can extend to compact, lightweight, safe mobile nuclear powerplants. The paper discusses direct technical experience, identifies potential sources of technology for advanced concepts, cites the results of economic studies of mobile nuclear powerplants, and surveys future technical capabilities needed by examining the current use and projected needs for vehicles, machines and habitats that could effectively use mobile nuclear reactor powerplants.

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The technology sources discussed are land-based electric generating experience, advanced marine reactor systems for merchant shipping, space nuclear power systems, including the SNAP programs, and analytical and experimental feasibility studies of lightweight, safe, and long-life airborne nuclear reactors.

The applications discussed include vehicles for international cargo transportation (ships, submarines, air cushion vehicles (ACV's), airships, and aircraft); submersibles for underwater prospecting, research, construction, mining, farming and ranching; habitats and energy depots (small central power stations) under the oceans and in the Arctic; and machines for underwater mining and underground tunneling. The reactor thermal powers that would be needed range from under 0.1 MW for small work submersibiles and small habitats to several megawatts for research submersibles, tunneling machines, and large habitats to hundreds of megawatts for ships, submarines, ACV's, and deep underwater shaft mining to thousands of megawatts for very large aircraft and ACV's.

Introduction

During the past two decades two situations have arisen that could be effectively served by mobile nuclear powerplants. First, a world economy highly dependent on international trade has developed. The projected growth of this economy (fig. 1, from ref. 1) will require a new international cargo-transportation capability with higher speed and higher productivity than at present. Because this new capability will require much more energy per vehicle than present chemically-powered vehicles, nuclear-powered cargo vehicles should receive increased emphasis.

Second, the world faces a dilemma of resource depletion versus both increasing population and increasing per capita resource consumption. Furthermore, projections of these conditions (fig. 2, from ref. 2) indicate that the seriousness of this dilemma will not only increase, but will do so at a higher rate than in the past. Perhaps the most obvious, easily implemented and hence likely-to-be-used way to ease this dilemma (at least temporarily) is to increase our discovery, extraction, and transportation of raw materials.

During the last several years the abundant resources of the oceans and the oceans' important role in the natural processes of the earth have been increasingly appreciated. A number of studies (e.g., ref. 3 and 4) have identified the many facets of the oceans' potential effect on man. A number of instruments (using the word instruments in a broad sense to mean vehicles, remote stations, and machines) have also been proposed and some demonstrated on a small scale that would allow man to open both the oceans and the Arctic for exploration and development of resources.

The performance likely to be required of these instruments will make them candidates for mobile nuclear powerplants. However, most of the civilian instruments needed for resource development and cargo transportation that could effectively use nuclear powerplants must first probably be justified, built, and used in their chemically-powered form, if they haven't been already. But as the new capabilities become more necessary and require more energy, the utility of the instruments using chemical fuel may then be improved markedly through the use of mobile nuclear powerplants (MNPs).

Many of the advantages of nuclear fuel over chemical fuel for mobile applications arise from the difference in energy density. One pound of uranium has the energy equivalent of about 1.9 million pounds of oil (about 6000 barrels).

Because of its energy density, nuclear fuel provides an energy autonomy which offers: (1) nearly unlimited vehicle range and endurance without refueling, (2) a larger "revenue-cargo" volume (which would have been taken up by chemical fuel) as the vehicle energy requirement gets larger, (3) surface- and weather-independence for undersea instruments, and (4) energy independence and reserve endurance in remote areas.

The purpose of this paper is to identify the indications of technical and economic feasibility of mobile nuclear reactor powerplants (hereafter referred to as MNPs) and instruments (vehicles, remote stations, and machines) that could effectively use them.

The lowest power need identified in this paper is about 50 kWt. Seaborg[5] states that undersea power needs above about 10 kilowatts electric (kWe) could be provided by small reactor powerplants. With dynamic energy conversion at 30 percent efficiency, the reactor thermal power would be about 35 kWt.

It is beyond the scope of this paper to arrive at or compare detailed costs, systems designs, or configurations for equivalent chemical powerplants or for alternative nuclear powerplants. However, the paper will discuss direct technical experience, identify potential sources of technology for advanced concepts, cite the results of economic studies of nuclear powerplants, and survey the future technical capabilities needed by identifying nonspace instruments with high power needs.

How Mobile is Mobile?

Within this paper mobile will mean readily transportable as a unit either when integrated as a propulsion and power supply in a host vehicle or when simply moved about for temporary use at various locations. Portable will mean transportable in sections. Land-based will imply built at and occupying a permanent site.

Nearly all existing mobile reactors are ship-based. They include: (1) those that power naval vessels, mainly submarines, (2) those that have operated in prototype merchant ships, for example, the Savannah (U.S.), the Otto Hahn (West Germany), and soon the Mutsu (Japan), and (3) the MH 1-A which is installed onboard, but does not power, a converted World War II Liberty Ship, the Sturgis.

An example of a portable reactor is the PM 3-A which has supplied power and heat for scientific base at McMurdo Sound, Antarctica, since 1962. This reactor powerplant produces about 5 MW (thermal) (5 MWt), weighs about 400 metric tons, had to be delivered in 33 packages, and took 80 days to assemble and test.[6]

However, other smaller reactors have been under investigation for marine and airborne applications. For marine use the Consolidated Nuclear Steam Generator (CNSG)--a pressurized water reactor--developed by Babcock and Wilcox and is described in Refs. 1, 7, and 8. A first generation CNSG (shown in fig. 3) is used by the N. S. Otto Hahn; the fourth generation is under development.[1] For airborne use technology studies described in Refs. 9 to 15 permit a preliminary conceptual design of a gas-cooled thermal reactor (fig. 4) that is much lighter and more compact than the CNSG reactor.

A comparison of various powerplants illustrates the potential compactness of mobile reactors. First is a comparison of the cross section of a CNSG reactor vessel to conventional oil-fired boilers (fig. 5). Each of the two boilers shown produces 60 000 shaft horsepower (shp); the CNSG would produce 120 000 shp plus auxiliary power from a reactor power of 314 MWt. Note that neither the biological shield for the reactor nor the fuel oil tanks for the boiler are included.

Second, the two mobile reactor concepts (marine and airborne) at 300 MWt are shown in Fig. 6. The CNSG IV reactor system (actually producing 314 MWt) would have a volume of about 1800 cubic meters and a weight of 500 tons, excluding the biological shield. With the biological shield the CNSG reactor system would weigh about 2000 metric tons. In contrast, the conceptual gas-cooled airborne reactor would have a volume of about 100 cubic meters and a weight of 210 metric tons, including the biological shield. For the CNSG reactor the radiation dose rate is about 1 millirem per hour at the outer surface of the shield. For the compact airborne reactor the dose rates are about 4.5 millirem per hour just outside the shield (radius 2.9 m) and about 0.25 millirem per hour at 9.15 meters from its spherical center. However, in fairness it must be pointed out that this marine reactor is on the verge of construction while the "much-lighter-weight" airborne reactors are still in the early conceptual stages.

As a third comparison the dimensions of 1000 MWt conceptual airborne reactor are compared to an equivalent power, conventional land-based reactor in Fig. 7. In each case the shield reduces the dose rate at the outer shield surface to that rate permissible for the general population (0.25 mrem/hr). This dose constraint is one-tenth of the exposure limits set for radiation workers and is derived from quarterly dose constraints set forth in Title 10, CFR, Part 20.

Are Mobile Nuclear Powerplants Technically Feasible?

Marine nuclear powerplants (mainly pressurized water reactors) seem clearly technically feasible for widespread application to merchant shipping. Navy nuclear submarines and surface ships, the Russian navy's nuclear ships and icebreaker Lenin, the German Otto Hahn, the Japanese research ship Mutsu, and the U.S. nuclear ship Savannah are all propelled using a pressurized water reactor with engineering variations to suit the particular application.

Hence, the question of technical feasibility of MNPs is really directed toward reactors for instruments having much more stringent limitations than surface ships and submarines. Such instruments will fall in two broad categories: (1) submersibles and habitats that will need reactors of lower power, and smaller size and weight than present marine reactors, and (2) airborne vehicles that will also need smaller and lighter weight reactors but which must have higher power and be able to safely withstand higher-speed impacts.

The purpose of this section is to identify some of the sources of technology for lightweight MNPs. It is beyond the scope of this section to provide an exhaustive survey of all pertinent work on the variety of reactor concepts.

The technology for more compact, lighter weight, lower power MNPs for marine use (mostly undersea) may come from several sources: (1) advanced marine reactor systems for merchant ships, (2) low-critical-mass studies at Los Alamos, and (3) the U.S.A.E.C. SNAP (Systems for Nuclear Auxiliary Power) programs.

The Nuclear Propulsion Program of the U.S. Maritime Administration (MARAD) should produce an advanced pressurized water marine reactor system-a fourth generation CNSG.

The purpose of this program is to develop a nuclear propulsion system of the CNSG type and to construct a fleet of at least 3 commercially viable ships that would provide the at-sea, in-service demonstration of technical and economic performance by 1982.[1,16] This program will draw information from (1) the design and operating experience of the N.S. Savannah, (2) the pressurized light water technology and components developed and proven in the cental station nuclear industry in the past 15 years, and (3) operating data from the N.S. Otto Hahn (to which the U.S. has access).

Application of low critical mass studies (theoretical and experimental) to reactor design has produced the concept described in Refs. 17 and 18. This small pressurized water reactor would produce 300 kWt for one year. The reactor vessel would be cylindrical, about 1.2 meters high and 0.86 meters in diameter, excluding any shielding. This conceptual reactor, specified from basic neutronic considerations, is based on 20 years of design and materials experience.[17] It has simple geometry and uses familiar materials.

Wetch[19] discussed the applicable technology from various types of small fueled-hydride reactors being developed under the SNAP programs in 1966. The present technology as it has evolved from the SNAP 8 and 10A programs is described further on in this section. In particular Wetch described two mobile nuclear powerplant concepts. One concept, called NEPTUNE, would have a reactor thermal power of 400 kWt. This concept would combine thermoelectric technology from SNAP 10A and reactor technology from SNAP 8. The other concept, called COMPACT, would have a reactor thermal power of up to 25 MWt. This concept would draw on SNAP technology to minimize the shielded volume.

It is not clear yet what the best reactor concept is for airborne use, in contrast to the prevalence of pressurized water reactors for present and planned marine use. However, civilian studies have tended to favor the gas-cooled reactor concept, with liquid metal cooling being the next choice. The technology for these reactors may also come from several sources: (1) high-temperature, gas-cooled land-based power reactors, (2) advanced space nuclear power systems, some of which are outgrowths of SNAP programs, and (3) technical feasibility studies of airborne nuclear reactors.

A high-temperature, helium-cooled thermal reactor (300 MWt) for airborne use[9,10] might have a reactor coolant outlet temperature of about 940° C and a helium pressure of about 1070 newtons per square centimeter (1500 psi).

Some of the high-temperature materials and gas-cooling system technology may come from land-based electricity generating plants which entered the commercial market in 1971. The twin reactors (from Gulf General Atomic) for a Philadelphia Electric power station will have core outlet temperatures of about 765° C and a gas pressure of about 500 newtons per square centimeter (700 psi)[20]; each reactor will have a thermal output of 3000 MW.

Space nuclear reactor power system, which include the even-numbered SNAP systems such as 10A and 8, have had development goals of compactness, light weight, and long-term reliable, unattended operation, some of which are even more stringent than for nonspace mobile applications. The SNAP 8 program has evolved into a zirconium hydride (ZrH) reactor program (with thermoelectric power conversion) at Lewis Research Center under the joint support of NASA and the AEC (administered by the Space Nuclear Systems Office). A technology base for the thermoelectric power conversion system has been provided by the SNAP 10A program. This ZrH reactor (NaK coolant, thermal spectrum) would produce 100 kWt and generate 5 kWe from the thermoelectric elements.

An advanced power reactor (lithium coolant, fast spectrum) is also being investigated at Lewis with the experimental criticality work being done by Atomics International. A reference design of this reactor calls for a 2 MWt output for 50 000 hours.[21] Efforts are underway in materials compatability and irradiation effects, bearings and seals, reactor physics and reactor control.

Investigations of airborne nuclear powerplant technology at NASA Lewis Research Center has stressed long-life fuel pins and heat exchangers, optimized shield design, and impact and meltdown safety. Its status is described in Refs. 9 and 10. From this program the lightweight/compactness feasibility of an airborne nuclear powerplant has been suggested by analytical studies which indicate that current ship reactor weight may be reduced by at least a factor of 10 and that the reactor and shield could be enclosed in a spherical containment vessel less than 9 meters (30 ft) in diameter[11-15] (figs. 4, 6 and 7).

The safety problem of preventing radioactivity release as a result of an impact accident is a critical one. There are two stages of an accident. First, the kinetic energy of the reactor-shield-containment vessel (RSCV) system must be absorbed during the impact without rupturing the containment vessel. Second, after the impact, the thermal energy from decaying fission products must be transferred from the RSCV system without rupturing the containment vessel. Safety during an accident will also require prevention of uncontrolled criticality. This might be accomplished by designing the reactor so it can be made subcritical by poison addition or moderator removal. Radar sensing of impending impacts would automatically activate these safety measures as well as close and seal all penetrations of the containment vessel.

Two techniques for kinetic-energy absorption have been examined in the technology program at Lewis. One technique would surround the containment vessel with material configuration that are highly energy-absorbing such as balsa wood, frangible tubes, or metal or plastic honeycomb. This technique appears reasonable for impact velocities up to about 100 meters per second (180knots).[10] Above this speed another technique may be necessary.

The other energy-absorbing technique examined has been simply the deformation of the containment vessel itself. In fact, the reactor shield-containment vessel system (RSCV) would be designed so that all parts of the RSCV system would serve multiple purposes, one of which would be to absorb kinetic energy. Simulated RSCVs (two-foot-diameter valveless models weighing about 450 kg (1000 lb) each) have impacted concrete at velocities of 195, 320, and 332 meters per second (640, 1055, and 1090 ft/sec) without rupturing. Earlier tests at lower velocities are described in Ref. 15.

After an impact the second stage of the accident safety problem would occur. To overcome this the reactor and safety system must be designed so that the heat from decaying fission products will not melt through the containment vessel. One approach to this problem is to provide enough impact energy absorber around the RSCV to ensure that the shutdown cooling system will function after an impact. Another approach is to design a RSCV which will permit the core to melt without melting through the containment vessel. Preliminary studies indicate either of these approaches is feasible in principle.

Until this point this paper has discussed the feasibility of reactors. Another important part of a power system, of course, is the subsystem that converts the reactor heat to a more usable form, electricity or shaft rotation, for example. Again, the requirements of space power systems, compactness and light weight, may make their technology useful for mobile nonspace nuclear power systems.

Coupled with the ongoing space reactor development at Lewis is the development of dynamic power conversion systems. The status of several of these systems is given in Ref. 22. One important aspect of these dynamic power systems is that they are capable of providing electrical power over a broad range, a few kilowatts to thousands of kilowatts. They are also efficient, which will contribute to low fuel needs and hence compactness and light weight of the reactor system.

The Brayton power conversion system seems particularly attractive because of its versatility and its technical status as described in Ref. 23. An overall efficiency of 30 percent appears readily attainable for Brayton power systems of 10 kWe output and above. "...in comparison with competitive power systems, the Brayton system offers the best chance for a successful reactor because of its low demand for heat, the high fuel-volume fraction that is possible, the simple reactor construction, the tolerance of fuel swelling, and even the comparatively low reactor-fuel temperature."[23]

"It is important to recognize that the Brayton-cycle technology derived from the NASA program is broadly applicable to undersea and terrestrial applications as well as space missions."(23) (The reactors being developed by NASA for space missions might well have a similar applicability.)

The major components of three power conversion systems for space reactors have successfully operated for several thousand hours. For the SNAP mercury-Rankine conversion system, every major component has successfully operated for at least 10 000 hours; the complete conversion system was tested for 7320 hours without replacement of any of its components. A 10 kWe Brayton rotating unit (turbine, alternator, and compressor) recently completed a 10 000 hours endurance run; for over 9000 of these hours the test had no one present and was controlled by a computer. As for static energy conversion the SNAP 10A thermoelectric system was ground tested for 10 000 hours (during 1965-1966) without failure.

To summarize this section: On-going development programs for space power conversion systems will provide a solid technology base for nonspace mobile nuclear power systems. But mobile reactors to generate the power are a much tougher problem. Much work must be done to establish the relative technical (and subsequently economic) feasibilities that pressurized water, liquid metal, gas or some other reactor can solve the substantial problems of impact safety and high power but small size and weight.

Is Mobile Nuclear Power Commercially Feasible?

The capital costs of a nuclear powerplant are higher than for an equivalent fossil power plant (land-based or marine). But nuclear fuel has become cheaper than fossil fuel per unit of energy, enough that the nuclear system total life cost can now be lower than the cost of the fossil system. Furthermore, as the power level increases, the nuclear system increases its economic advantage over the chemical system because of the increasing importance of fuel costs and the greater "economy of scale" (that is, the cost per unit of output power decreases as the total output power increases) offered by nuclear power.

This section summarizes three sources of information relating to nuclear power costs. The first is the growing number of land-based nuclear powerplants (built and ordered). Although not a mobile use of nuclear power, this example shows that at least for the less-technically-demanding, stationary land use, nuclear fueled power is not cheaper than fossil-fueled power (above some minimum power level that depends on several factors). Reference 24 discusses the trends in nuclear powerplant costs.

The second source is recent detailed economic studies for merchant shipping.(1,16,25,26,27) Several developments have brought about a substantial improvement in the economic attractiveness of maritime nuclear propulsion as compared to the picture as recently as 5 years ago. From Ref. 16: "The growth in population and in the volume of world trade has brought about a parallel and dramatic growth in ship sizes and propulsion power levels. The growth will accelerate...At higher power levels, nuclear powerplants for ships become more economical. Concurrent with the increase in power levels, there has been a continued increase in the price of fossil fuels and a growing uncertainty regarding fuel availability. Meanwhile, as a consequence of the maturation of the central station nuclear electric power industry and advances in nuclear technology, the cost of nuclear fuel has decreased significantly in recent years."

In fact the fuel costs are the "swinger" in making nuclear power cheaper than fossil-power for merchange ships as they are for land-based powerplants. The next three figures (8 to 10) taken from Ref. 1, provide a graphic summary of the role that fuel costs play in merchant ship economics. Figure 8 compares the average annual costs of two equivalent-cargo and -speed container ships powered by nuclear and fossil fuel. The nuclear ship power is 120 000 shaft horsepower (shp) and the fossil ship power is 128 000 shp, reflecting the penalty of the weight and volume of the fuel oil. Because the nuclear fuel cost is only one-fourth of the fossil fuel cost it offsets the higher capital and operating costs of the nuclear ship. Actually, it more than offsets them; it provides a net cost savings of more than a million dollars per year (about a 6 percent reduction in total annual cost).

Figure 9 shows the even greater cost advantage of nuclear power as the power level increases or as the fossil fuel cost increases. And Fig. 10 shows that trends in fuel costs have been to make the fossil fuel increasingly more expensive than the nuclear fuel.

This potential economy of nuclear power for merchant shipping has given rise to the Nuclear Propulsion program of MARAD[1,16] and the projection of the Japan Atomic Industrial Forum that there will be 280 nuclear container ships by the year 2000.[28]

The third source of information is from cost studies of conceptual vehicles - large air cushion vehicles and very large aircraft powered by MNPs. Comparison of costs for nuclear versus chemically fueled air cushion vehicles (ACVs) appears in Ref. 29; a comparison for aircraft appears in Ref. 30. These results are summarized in Fig. 11. With chemically fueled airborne vehicles the range strongly affects the costs. The reason for this is that the chemical fuel displaces a sizable amount of revenue-earning payload. For example, a chemically fueled ACV on trans-Atlantic and longer voyages, has 50-80 percent of its payload taken up by fuel (fig. 12) according to studies described in Ref. 29.

In fact, Fig. 12 shows that for ranges beyond about 2000 miles a nuclear ACV would carry more payload than a "current-technology" chemical ACV of the same gross weight. The difference between the two would increase as the range increases so that at a transatlantic distance (3500 n mi) the nuclear ACV would have twice the payload of the chemical ACV. At a transpacific distance (6000 n mi) the nuclear ACV payload has four times the chemical ACV payload.

For a container ship at 30 knots, about 25-30 percent of its payload is fuel for propulsion.[26] A tanker at 16 knots would use from 3-10 percent of its payload as fuel for propulsion depending on its size.[1,26]

A comparison of nuclear airborne vehicles to nuclear ships is shown in Fig. 13. Note that large airborne vehicles could be competitive in cost for some types of cargo. They are also faster than ships and can serve different ports because of the aircraft's inland accessibility and the ACV's coastal mobility.

Another aspect of commercial feasibility is market demand. Given that nuclear powerplants are more economical than chemical powerplants above certain power levels will enough powerplants be needed to make it worthwhile to manufacture them?

A MARAD study[1,25] projects that in the year 1990 there will be a need for a worldwide shipping fleet of 500 ships over 100 000 shp and 2500 ships over 40 000 shp (fig. 14). The MARAD economic studies have indicated that nuclear power for merchant shipping is presently economically competitive with oil-fired power above 100 000 shp.[22] They also suggest that by 1978 nuclear power can be competitive at 40 000 shp and above. Thus there is a large worldwide market potential for marine nuclear powerplants. This market demand is supported by the projection by the Japan Atomic Industrial Forum that there will be 280 nuclear container ships on the high seas by the year 2000.[28]

Market demand for other uses, underwater, in the air or on land, are not so easily determined. Until now few instruments have needed so much power. However, future propulsion and power capabilities to meet the technical and economic needs of international cargo transportation, resource development, and scientific research may be outlined and that constitutes the remainder of this paper.

What Instruments Have Sufficiently High Power Needs?

The instruments that might require MNPs are categorized as vehicles (cargo transportation, research, exploration, and work), stations (underwater habitats, remote bases (Arctic), and energy depots) and machines (underwater mining and pumping equipment and underground tunneling devices).

Vehicles

Ships-existing nuclear powered merchant ships are the Savannah (21 knots, 22 000 shp, 74 MWt reactor), the Otto Hahn (15 knots, 10 000 shp, 38 MWt reactor), and soon the Mutsu (16.5 knots, 10 000 shp, 36 MWt reactor) and the Enrico Fermi (22 000 shp, 80 MWt reactor).[26]

The next generation of container ships will be represented by 33 knot, 120 000 shp vessels. Eight of these ships (all chemically fueled (oil-fired)) have been ordered by Sea-Land Service, Inc.; the first was to be delivered in August 1972.

As for tankers they "do not have the same requirement for high speeds (as container ships), and so even 250 000 ton tankers rarely need shaft horsepowers greater than 35 000...However, a tanker of 400-500 000 tons is on order in Japan and tankers of this size would need 60-70 000 shp."[26]

But there is one situation in which high speeds for tankers might be desirable and hence in which higher power might be needed. This situation is outlined in Ref. 1; most of the remainder of this paragraph is excerpted from Ref. 1. Usually comparisons are made one-for-one, that is, a nuclear-fueled ship of a given size is compared to a fossil-fueled ship of the same size and service. Another approach is to compare several high-speed nuclear ships with a larger number of slower-speed fossil ships (table I). Historically, tankers travel at 15-16 knots because of economics. At this speed tankers use anywhere from 3-10 percent of their payload as fuel for propulsion. Any significant speed increase would require a substantial power increase (power increases as the cube of the speed) and would seriously reduce the tanker's payload capacity. At 25 knots, 40 percent of the payload capacity could be required for ship propulsion purposes. For a nuclear tanker of 120 000 shp, the nuclear powerplant would take up less volume than two 60 000-shp fossil boilers (fig. 5) and would not require any fuel volume. Thus five nuclear tankers traveling at 24 knots could do the job of eight fossil tankers traveling at 15.5 knots. The capital cost of the five nuclear tankers would be about the same or less than the eight fossil tankers, and the annual fuel savings might be $5-6 million for the nuclear ships.

The power needed for large fast container ships will range between 80 000 and 150 000 shp for cargo deadweights between 20 000 and 40 000 tons and speeds between 25 and 33 knots.[26] At 30 percent efficiency the reactor power will range from 200 to 380 MWt. The power needed for large oil tankers (with 16 knot speed) will range from 35 000 shp for a 250 000 deadweight ton (dwt) capacity to 70 000 shp for a 400 000-500 000 dwt capacity. These shaft powers will require a reactor thermal power output of 90-180 MWt.[26] For large tankers (250 000 dwt) with higher speeds (24 knots) the power requirements will be about 120 000 shp or 300 MWt reactor power.[1]

Submarines

At higher speeds (above 20-30 knots depending on the vessel size) and in rough seas, submarines are more efficient than surface ships because they do not create waves when underwater. But submarines are generally more expensive to build than surface ships. Thus unless there are geographic or topographic restrictions to surface ships, submarines are not competitive with them.[31]

One region where surface ships are severely restricted is the Arctic. In fact, most of the studies of commercial nuclear submarines have been directed toward their use as crude-oil tankers for transporting Arctic oil to North Atlantic ports.[31,32]

Nuclear submarines might also be used to carry ore from the Arctic or containerized cargo under the North Polar Pack between North Atlantic and North Pacific ports.[32]

The precedent was set in 1958 when the nuclear submarine Nautilus crossed under the North Pole. However, as discussed in Ref. 32, the present maritime Law of the Sea could be invoked to prevent passage of submerged cargo carriers through the ice-covered Bering Strait.

The power needed for large cargo submarines would range from 27 400 shp (42 000 metric ton displacement, 20 knots) to 218 000 shp (104 000 metric tons displacement, 37.4 knots).[33] The corresponding reactor powers would be 70 to 560 MWt. From Ref. 31, a 75 000 shp Arctic oil submarine tanker powered by a 250 MWt reactor could have either a cargo deadweight of 170 000 metric tons and speed of 19 knots or a cargo deadweight of 250 000 metric tons and a speed of 17 knots.

In considering high underwater speeds, Van Driest[34] has calculated that to move a submarine of the Thresher class (about 85 meters long, 10 meters in diameter) at 100 knots, 4.5 meganewtons (about 1 million pounds) of thrust would be needed. This thrust would be generated through an underwater steam-powered rocket nozzle; the power would be provided by a 12 500 MWt reactor.

Air Cushion Vehicles (ACVs)

The ACV provides a step increase in surface mobility over present vehicles. It needs no surface contact; it glides on a cushion of air over water, ice, snow, mud, sand or any relatively flat surface. The ACV is a relatively new vehicle. In 15 years it has gone from "table-top" demonstration to commercial vehicles carrying more than a million passengers each year. By the end of the century its mobility and speed could dramatically affect world trade and the distribution of people on the earth.[35]

Small ACVs up to about 200 tons have been used all over the world for ferry service, coastal patrol, river exploration and equipment transporter for Arctic oil fields. Much of the operating experience of the larger ACVs has come from the SR N4[36] which has provided English Channel Ferry service since 1968. The SR N4 weights 150 metric tons, moves at 65 knots, and can carry 250 passengers and 30 cars. A 225-metric-ton ACV transporter (non-self-propelled) for carrying oil field equipment is now operational in the Arctic; a 2700-metric-ton transporter for a similar purpose is nearing the construction stage. ACVs of 1000-2000 metric tons would be large enough to effectively use a nuclear powerplant.

Conceptual designs and the economical potential of large multithousand ton nuclear ACVs are described in Refs. 37-40. An artist's rendering of a conceptual nuclear-powered ACV freighter (4500 metric tons) is shown in Fig. 15. Nuclear ACV freighters could have a flatbed design that would permit them to carry containers, vehicles, and even modular housing, as cargo.

Missions and implications of large ACVs have been discussed in Refs. 35, 40 to 47. Three particular missions are described below because their implications are sufficiently important and far-reaching to stimulate the development of large ACVs, the growth of a large-ACV industry, and the demand for a lightweight MNP.

For nearly 500 years seafaring nations of the North Atlantic have searched for a Northwest Passage between the Atlantic and Pacific Oceans. Nuclear-powered ACV freighters could open a Northwest Passage (through the Canadian Arctic Islands) or other Arctic passages across the North Polar Cap to commercial traffic in the time period 1985-2000.[47] As described in that reference, a nuclear-powered ACV freighter could provide (1) a shortcut trade route between most of the major industrial and population centers of the world, (2) competitive cost with conventional displacement ships for container and roll on/roll off cargo, (3) independence from the Panama and Suez Canals, and (4) all-season Arctic-wide mobility.

The possibility of using ACVs configured as tankers to carry oil over the polar ice from the North Slope of Alaska around Point Barrow and south to be transshipped to a displacement tanker waiting in ice-free water has been described.[46] Large ACV tankers will not likely compete economically with oil tanker or bulk ore carriers on open sea routes from present sources. But from Arctic sources they may. ACVs, with their potential Arctic-wide, year-round mobility, could provide an economical means of moving raw materials from remote ice-bound mines and wells to ice-free ports where the cargo could be transshipped to conventional displacement tankers, bulk carriers or pipelines.

The presence of vast mineral and fuel resources in the Arctic plus its potential (using ACV freighters) as a trade route between ports of the North Pacific and North Atlantic Oceans may be the prelude to settlement and development of the Arctic. The nuclear ACV would provide the heavy-duty transportation needed to develop or operate in this remote and hostile region.

The mobility of the large ACV would not only permit new transportation routes but it would also provide a totally new geographic freedon in locating ports and laying out a port-city.[35] By the 1980's fleets of large ACV freighters could begin to carry ocean-going cargo. The mobility of an ACV fleet would allow hoverports to be located away from present crowded areas. Such hoverports would provide new transportation nodes and thus could support new business, industrial and population centers. New cities could arise along shallow or reef-bound seacoasts and rivers just as cities once arose around deep water seaports. There are already many reasons why new cities should be built. The large ACV and hoverport offer economic incentives for building them: Competitive operating costs of ACV freighters, use of cheap land requiring little preparation, early economic strength as a trade center and creation of new jobs.

ACVs of 1800 metric tons gross weight and a speed of 100 knots would require a reactor power of about 460 MWt.[29] ACV's of about 9000 metric tons would require 2300 MWt for a 100 knot speed[29] and about 900 MWt for a 60-knot speed.[46]

Airships

The lighter-than-air craft (airship) has enjoyed a recent revival in interest. In fact, a new West German dirigible recently began service for a European sky-advertising company and there are orders for more.(49) Although the use and performance of the airship may be limited by the weather, its low power needs and prospects for low cost are especially attractive. Hence, the use of dirigibles for advertising is only a first step. The builder of the small advertising dirigible (198 feet long, 62 mph, 1.5 metric ton payload) expects to begin building (in 1974) larger cargo airships (396 feet long, 87 mph, 30 metric ton payload). Their cost would be a little over $1.5 million compared to $25 million for an aircraft of the same payload and, of course, much higher speed. Even several airships, to provide the same productivity, would cost less than half of the single aircraft cost.

Furthermore, because of increasing cargo traffic congestion and depletion of energy resources, conceptual designs of airships much larger and much safer than those of the 1930's have been advanced from several sources. In England, Cargo Airships, Ltd. has been formed by the Manchester Liners Group of Companies to actively explore a transport concept (by M. J. Rynish) called the Merchant Airship Cargo Satellite System. Rynish envisions an efficient system of 100-knot cargo airships, continually orbiting the earth at low level, relaying world trade in much the same way communications satellites are now relaying the world's messages.(50)

For an airship nuclear power would have an additional advantage. For long range the nuclear airship would not have to continuously adjust the ballast to account for the continuous (and finally substantial) reduction in fuel weight. In the U.S. at Boston University, Morse has designed a conceptual nuclear airship.(51) The reactor would be a scaled-down version of a liquid metal-cooled reactor system (200 MWt) built and tested by Pratt and Whitney for the Aircraft Nuclear Propulsion program. The advantages of using this airship for oceanographic work have been described in Ref. 52.

The power needed for nuclear airship would be about 6000 shp for an 85 knot, 80 metric ton payload, 340 metric ton lift capability.(51) The reactor power would have to be about 18 MWt. A conceptual airship, the Europa,(53) that would have the same productivity as the Boeing 747F would require 16 100 hp (a reactor power of about 40 MWt).

Aircraft

The large aircraft of today (the Lockheed C5A and Boeing 747) weigh about 380 tons; growth versions of these aircraft will approach 500 metric tons; and the next generation of large aircraft may approach 1000 metric tons. These coming aircraft will be large enough to accommodate a nuclear powerplant (with a power density of 3 MW/ft^3). In fact, according to Ref. 54, in their present size the C5A and the 747 could accommodate a high-power density (13.5 MW/ft^3) reactor.

The Boeing Company has considered a conceptual aircraft to be used for resource transport, particularly oil.(55) This vehicle would have a gross weight of 1600 metric tons, a payload of 1050 metric tons, a speed of 400 knots, and would be powered by twelve 50 000 hp engines. This resource transport vehicle considers only chemical fuel but the conditions of large size, high power needs, and the need for high utilization make a nuclear powerplant (with its long time between refuelings) an attractive alternative.

What nuclear aircraft potentially offer in a civilian capacity are almost unlimited endurance for inflight experiments and scientific observations,(56) nonstop flights between any two airports on earth, and very low cost for fast cargo transport.(30) With low cargo hauling costs and unlimited range, nuclear aircraft freighters would permit inland cities (such as Denver, or Geneva, Switzerland) to become international ports. Inland cities could become as important in international trade as coastal seaport cities are now.

A nuclear powered C5A would require 200 MWt.(54) From Ref. 30, the power required for a subsonic aircraft ranges from about 800 MWt for 907 metric tons gross weight to about 2700 MWt for 3630 metric tons gross weight. A bulk oil carrier of 1600 metric tons(55) would need a reactor of about 2000 MWt.

Submersibles. - For man to develop the resources of the oceans, underwater vehicles of various types will be needed. This section will use the term "submersible" to include (1) tracked vehicles for use on the ocean floor, (2) submarines for research or exploratory use, and (3) underwater "work boats" or mini-subs, for smaller, one- or two-man tasks. Submarines large enough for cargo transport were considered earlier.

The beaches, continental shelves, and slopes of the oceans may be developed by sea bed vehicles. One such manned sea-bed crawler, the Sealbeaver, has been built for use in the North Sea but it is now mothballed because of company financial problems.(57) The Sealbeaver's ability to withstand strong currents, avoid surface waves, provide a refuge for divers make it an ideal vehicle, for work in the North Sea off-shore operations. However, the Sealbeaver is confined to one end of an umbilical from a parent surface tender and hence can only operate when the tender is able to withstand the North Sea conditions. Nuclear power for sea bed crawlers would offer autonomous power and life support and therefore independence from surface support.

For local work tasks, such as construction, digging, and underwater drilling, sea-bed crawlers will be useful. But the mobility needed for exploration, prospecting, and research throughout the ocean volume and over the entire sea floor will require submarines.

Submarines for research might be the largest of the submersibles. They must be large enough to accommodate scientists and their instruments, and will require extra power for the instruments and experiments and endurance for prolonged sampling and experiments. "Nuclear power will inevitably send research craft along the axes of the great submarine trenches and the flanks of the mid-ocean ridges. The potential is too great to ignore."(5) Also from Ref. 5, J. Madell of Argonne National Laboratory has reported the design of a 7.75 MWt pressurized water reactor that would supply 2000 shp to drive a 100 foot oceanographic research submerisble. One nuclear powered civilian submersible has already been built and launched. The NR-1, launched in 1969 for undersea scientific and rescue missions, is about 150 feet long and weighs about 400 tons.

Reactors of 0.3 MWt to 8 MWt will be needed for research submersibles.(5,19) Smaller submersibles for prospecting, surveying, mapping, or search missions may require reactors of 100-400 kWt.(19)

Still smaller submersibles, with one or two men, could have a variety of duties. These minisubs or underwater "work boats" could be used for localized exploration, mining, salvage, construction, or rescue. They would have manipulators, external power tools, television cameras, lighting and sampling systems. Their power needs would range from 50-200 kWt.(19,58)

Small submersibles could also be used for stalking, tracking, and observing ocean fish and mammals so that man may learn to breed, feed, protect, and harvest desirable species for his needs. Later submersibles will be needed for ranching and roundup. Deep water submersible trawlers may be used for harvesting tuna, hake, anchovy, and squid. Ocean shelf farming of oysters, scallops, lobster, shrimp, crab, abalone, eel and various kelp species will require sea floor harvesters and marine farming equipment analogous to land farming equipment and perhaps processing equipment. Direct harvesting of algae and plankton will require pumps and processing equipment.(19) Small submersibles for underwater farming and ranching will require powers of 50-100 kWt.(58)

Remote Stations

Two types of remote stations might require a nuclear reactor powerplant. One type, which includes underwater habitats and Arctic bases, requires large amounts of energy for life support. The other type is simply an energy depot - essentially a small, remote central power station.

Habitats

Much of the experience with mobile or portable nuclear powerplants has come from U.S. military use. Those reactors that have not been used for propulsion have ranged in power from about 500 kWt to 30 MWt and have been used to supply base power and heat in Greenland and Antarctica, for example.(6)

An example from the Soviet Union illustrates several other advantages of nuclear powerplants for these applications.(59) Several reactors will be used for each of several electric power stations that will serve mining operations in Siberia. Each station will be equivalent to 50 000 tons of coal and will provide heat and electricity for a settlement of 3000-5000 people and as well as providing heat for the mines. Present electric power stations in the Northern Soviet Union ran on diesel oil and coal which must be transported during the brief summer months at a cost of about $168 per ton of coal.

Underwater habitats would be needed for a farming or ranching village or agriculture experiment station, a prospecting or scientific laboratory, or a mining, drilling or pumping station. Habitat power will be needed for tools, instruments, lighting (inside and out), heating, air conditioning, hydrogen-oxygen separation to provide breathing atmosphere. For simple manned work platforms or single small habitats the power level would range from 100-500 kWt.(19,60) For more sophisticated or larger habitats or groups of habitats (villages) the power level would range from 1-10 MWt.(19)

The idea of a land-based mobile energy depot has been discussed in Ref. 6. One use for an energy depot would be for local chemical fuel production. Presently, chemical fuel is transported worldwide over long supply lines from its natural source ultimately to a location where it is used. By using local constituents and the energy from mobile nuclear reactors, chemical fuel such as hydrogen or ammonia could be produced where it is consumed.

A mobile energy depot could also be quite useful in situations in which normal power is disrupted for a prolonged period or in which power is needed for a temporary project. One example is emergency power for disaster areas; mobile power supplies might be carred by ship to coastal sites, such as the MH 1A on-board the Sturgis could be.

The ACV could carry power to sites on shallow coasts, up rivers, and even inland for some distance. In fact, to put it more generally, the ACV can become a mobile power source with unusual mobility. Instead of carrying cargo the ACV would carry energy in immediately usable form (heat, electricity, or turbine gas).

Machines

Dredge ships are presently used for ocean floor mining. The dredge techniques, controlled from the surface ship, are either bucket ladder, grab bucket, dragline, or suction (air-lift). Needless to say, even with good weather, dredging from the surface in 6-kilometer deep water has its drawbacks, especially for ores that occur in discreet form, such as the manganese nodules.

Completely underwater extraction and transportation to the surface might be performed by mechanical conveyors and air or water lift shafts. Dredge techniques, controlled from the sea floor, could also be used. These would allow deliberate collection or ores in contrast to the almost random collection when controlled from the water surface.

Completely submersed shaft mining (ore collection and transport of the ore from the sea floor to the surface) will require powers of 1-4 MWt for depths less than 300 meters.[5] Between 300 and 7000 meters the power needed could range between 4-350 MWt.[5,19]

As for underwater oil wells, and pumping stations, a gathering center and wellhead equipment along with pumps and storage might require 2-7 MWt.[19]

On land the energy requirements for tunneling offer a possible application for MNPs. New ground transportation in metropolitan areas will require extensive tunneling because of aesthetics, safety and economic and social problems in removing existing above-ground structures. Unfortunately the present construction costs of tunnels and underground terminals is high, so that new, cheaper tunneling methods are needed.

One new, experimental method of tunneling is by thermal disintegration, raising the temperature of the rock so high that it breaks by differential expansion or that it melts.[61] Lasers are being investigated as one approach[62,63] by using them to heat-weaken or score the rock face ahead of the cutter blades on the boring machine. Although it is too early to know how much of the rock face must be heat-weakened or what the specific energy for weakening is or how much must be scored, estimates are that for a 6 meter diameter tunnel a 0.5-1 MWt laser will be needed.[61,62] For a thermal to electrical conversion efficiency of 30 percent and an electrical to laser conversion efficiency of 50 percent[64] a reactor would need 3.5-7 MWt.

Summary of Power Needs

This section merely collects and arranges by power level the applications previously discussed (table II). Most of the reactor powers listed are approximate and are based on 30 percent thermal to electrical conversion efficiency. For some applications a range of power is given, for others only a single power level is appropriate or could be found.

Table III lists the instruments that may require MNPs and the range of power that may be needed for varying sizes and capabilities.

Concluding Remarks

The technical feasibility of pressurized water reactors for marine use has been clearly demonstrated. Other reactor concepts that are more compact, lighter-weight, and impact-safe at high speeds appear feasible from initial studies (conceptual, analytical, and experimental) and from reactor development programs.

Although nuclear powerplant capital and operating costs will likely remain higher than fossil plant costs (for both stationary and mobile reactors) the trend of relatively decreasing nuclear fuel cost has made nuclear power economically competitive at increasingly lower power levels. In this paper a number of instruments, requiring a wide range of power levels, have been identified that could effectively use mobile nuclear powerplants.

The order of development of nuclear powered instruments will depend on need, economic feasibility, and social acceptability as well as the technological readiness of the instrument and the technical feasibility of the powerplant. The nuclear aircraft will likely be the most difficult to achieve, both technically and socially. An easier application, with exciting and prolific possibilities for its use, is the air cushion vehicle.

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TABLE I. - EQUIVALENT TANKER FLEETS[1]

Example	Fossil steam propulsion	Nuclear steam propulsion
No. of ships	8	5
Speed, knots	15.5	24
Shaft horsepower (shp), each	35 000	120 000
Dead weight ton (dwt), each	250 000	250 000
Percent fuel volume	2-6	0
Annual fuel costs, millions $	10-12	5-6

TABLE II. - MOBILE NUCLEAR POWERPLANT APPLICATIONS

Application	Description[a]	Reactor Power Requirements (megawatts thermal)	References
Underwater work boat	small, 1-2 man submersibles	0.05-0.075	58
Exploration sub	deep submergence vehicles	0.15-0.35	19
Single habitat	underwater work platforms	0.15-0.35	19,60
Mining conveyor	depth to 300 m	0.5-3.5	58
Large habitat	living quarters, energy depot	1.5	19
Habitat village	groups of habitats	1.5-7	19
Oil well	gathering and pumping stations	1.5-7	19
Laser tunneler	6 m diameter	3.5-7	61,62
PM-3A	base power, McMurdo Sound	5	6
Research Sub	deep submergence, 30 m long	8	5
Large base	remote settlements (Arctic)	0.5-30	6
Shaft mining	water or air lift (deeper than 300 m)	15	19
Airship	380 mtg, 90 mA, 85 kt	20	51,52
MH-1A	installed on Sturgis	30	6
Mutsu	researc ship, 16.5 kt	36	26
Otto Hahn	ore carrier, 15 000 dwt; 15 kt	38	26
Airship "Europa"	conceptual, 630 mtg, 270 mt, 108 kt	40	53
Savannah	9500 dwt, 21 kt	74	26
Enrico Fermi		80	26
Cargo sub	40 000 mtg, 20 kt	70-100	33
Container ship	20 000 dwt, 24 kt	80-100	26
Supertanker	250 000 dwt, 16 kt	90	26
Mining	water or air lift (>300 m)	100-350	5
Cargo sub	50 000 mtg, 22 kt	100	33
Supertanker	400-500 000 dwt, 16-18 kt	150-250	26
C5A	350 mtg, 13.5 MWt/ft^3	200	54
Submarine tanker	170 000 dwt, 19 kt; 250 000 dwt, 17 kt	250	31
Container ship	40 000 dwt, 33 kt	300	1
Supertanker	250 000 dwt, 24 kt	300	1
ACV	1800 mtg; 900 mt; 100 kt; 3 MW/ft^3	460	29
Cargo sub	100 000 mtg; 37 kt	550	33
Aircraft	900 mtg; 150 mt; 400 kt, 3 MW/ft^3	800	30
ACV	3600 mtg; 2000 mt; 100 kt, 3 MW/ft^3	900	29
ACV	9000 mtg; 5400 mt; 60 kt; 3MW/ft^3	900	46
Aircraft	Boeing Resource Transporter 1600 mtg; 1050 mt; 400 kt, 3 MW/ft^3	2000	55
ACV	9000 mtg; 5400 mt, 100 kt	2300	29
Aircraft	3600 mtg; 1100 mt, 400 kt	2700	30
Submarine	high speed-100 knot Thresher class	12 500	34

[a]Payload for ships is in deadweight (long) tons (dwt)
Payload for air vehicles is in metric tons (mt)
Gross weight or displacement is in metric tons (mtg)
Cruising speed is in knots (kt)

TABLE III. - INSTRUMENTS AND THEIR POWER NEEDS

Instrument	Reactor power level (megawatts thermal)
Submersible	0.05-8
Habitat(s) Energy depot	0.15-30
Mining machines	0.5-350
Tunneling machines	3-50
Airship	20-40
Existing ship	36-80
Future merchant ship	80-300
Cargo submarine	70-550
Air cushion vehicle	200-2300
Aircraft	200-2700

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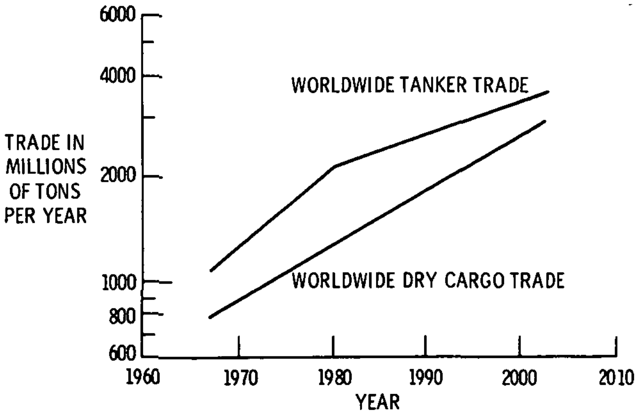

Figure 1. - Worldwide trade forecast (from ref. 1).

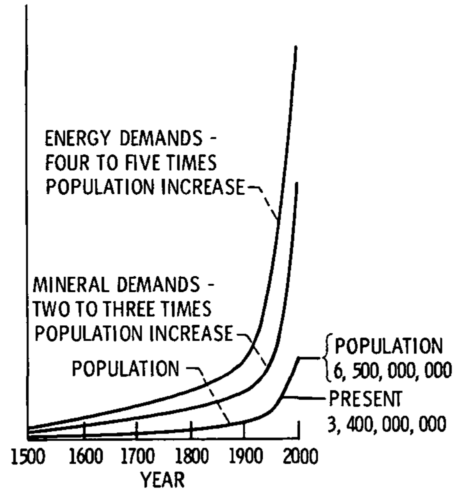

Figure 2. - Projection of population and mineral and energy demands (from Welling, ref. 2).

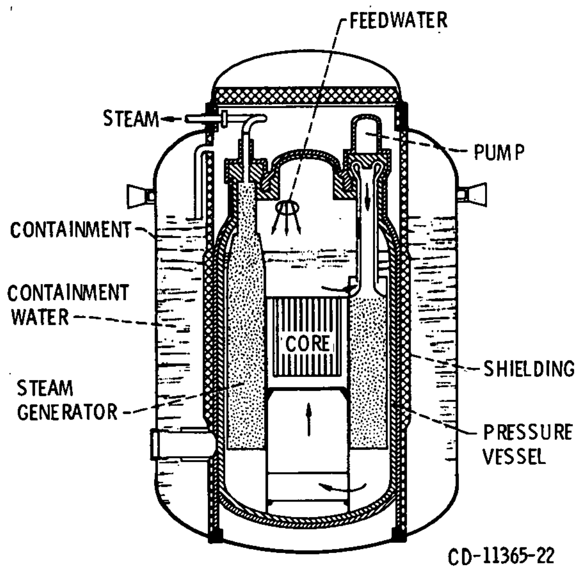

Figure 3. - First Generation CNSG General arrangement (from ref. 7).

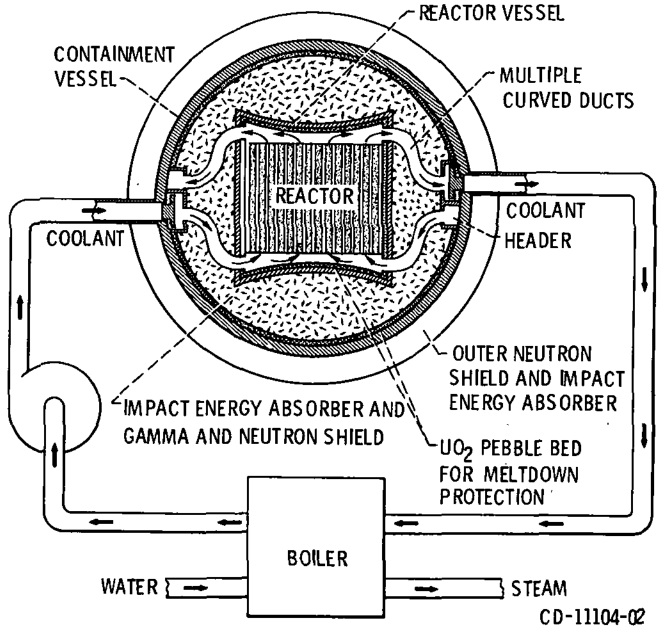

Figure 4. - Lightweight, compact mobile nuclear reactor concept.

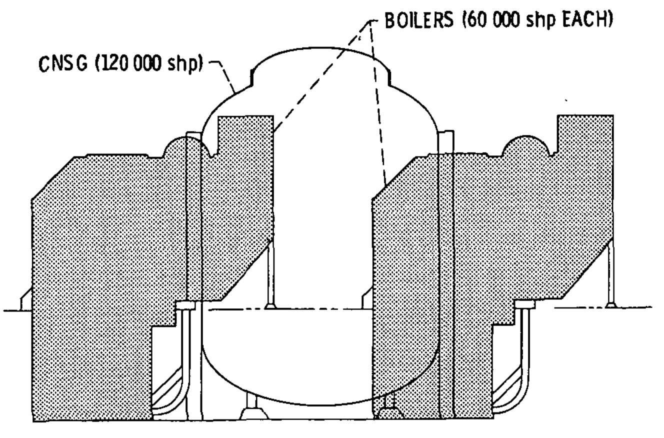

Figure 5. - Comparison of boilers with CNSG (from ref. 1) (power output 120 000 shp).

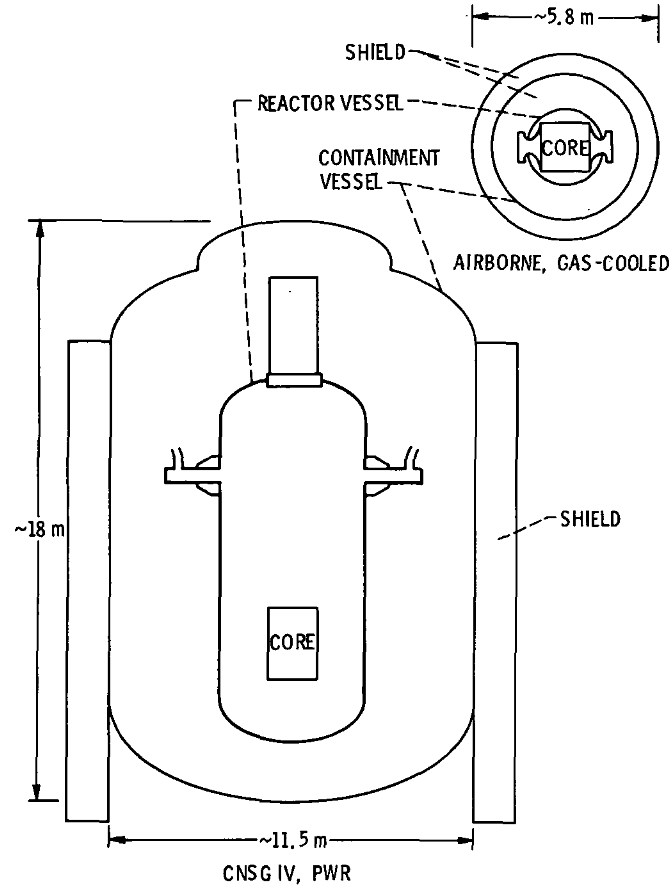

Figure 6. - Comparison of mobile reactor concepts at ~300 MWt.

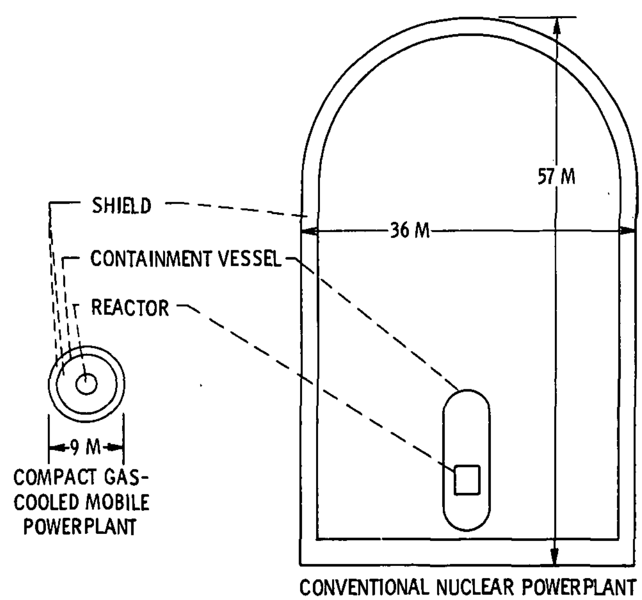

Figure 7. - Contrast of reactor sizes at 1000 MWt (shielded for 0.25 MR/hr at the outer shield surface).

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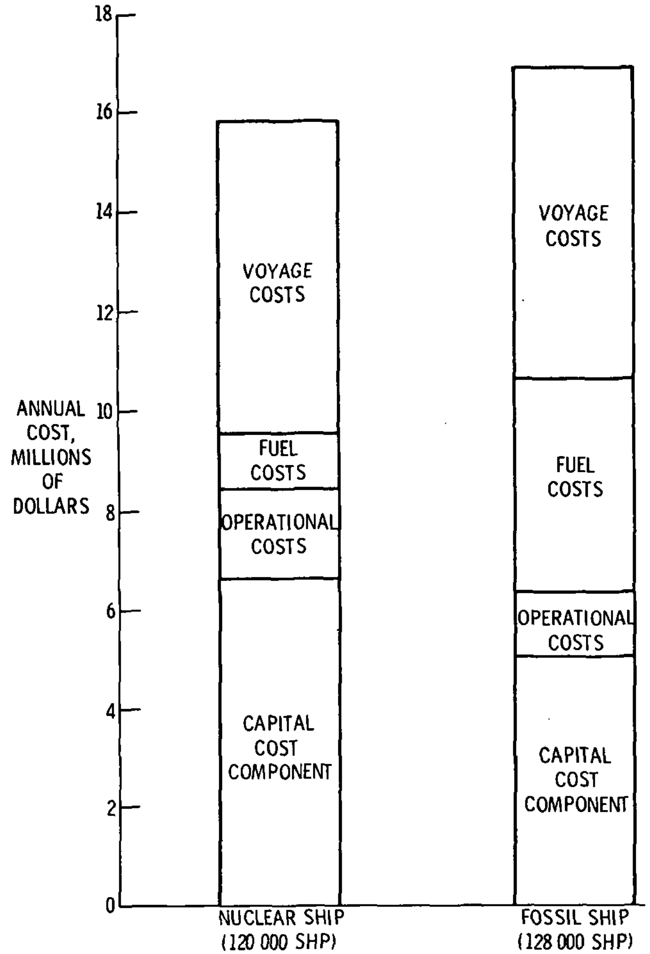

Figure 8. - Average annual cost - nuclear versus fossil ship equivalent cargo capacity (from ref. 1).

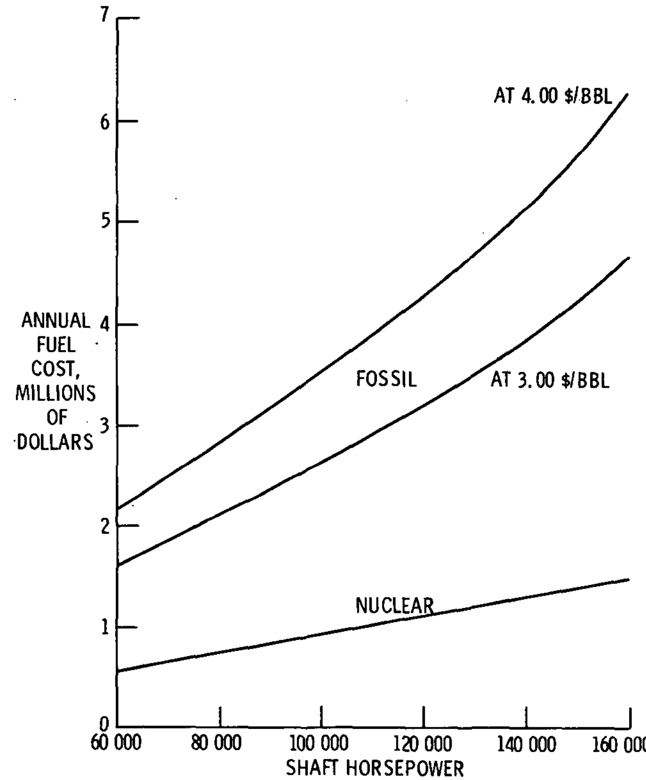

Figure 9. - Fossil and nuclear annual fuel cost (from ref. 1)

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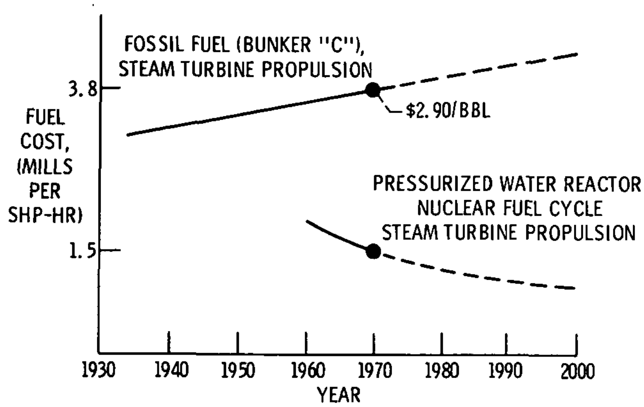

Figure 10. - Trends in ship propulsion fuel cost fossil fueled and nuclear powered ships (120 000 SHP)(from ref. 1).

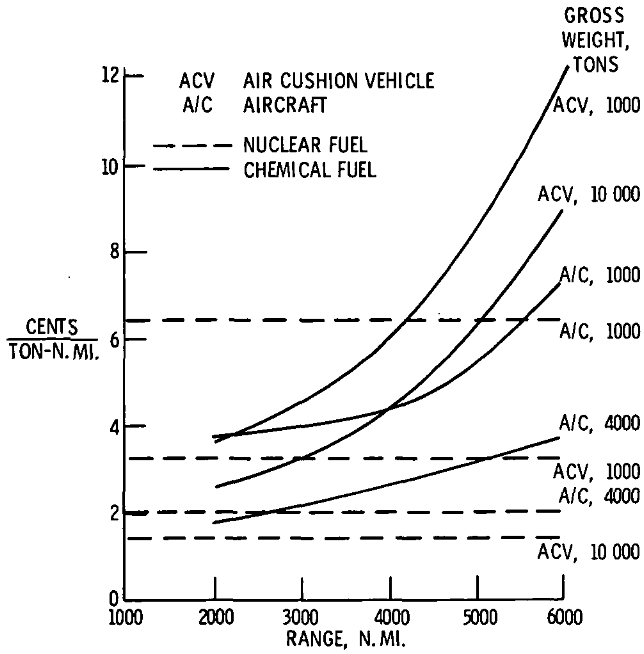

Figure 11. - Direct operating costs for airborne vehicles (data from refs. 25 and 26).

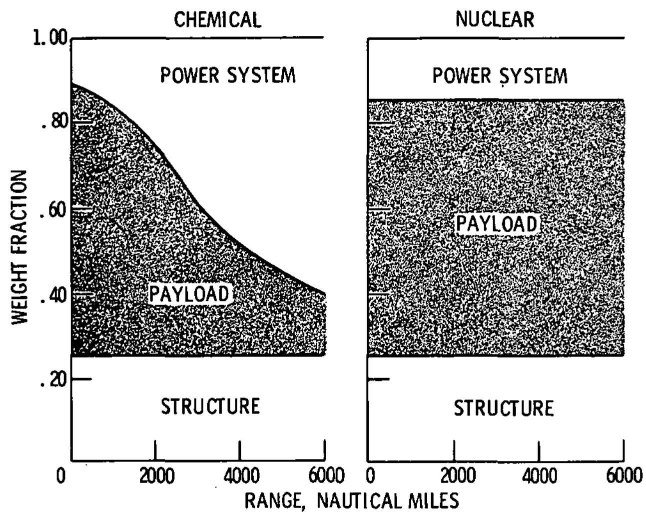

Figure 12. - Payload for 10 000 ton ACV.

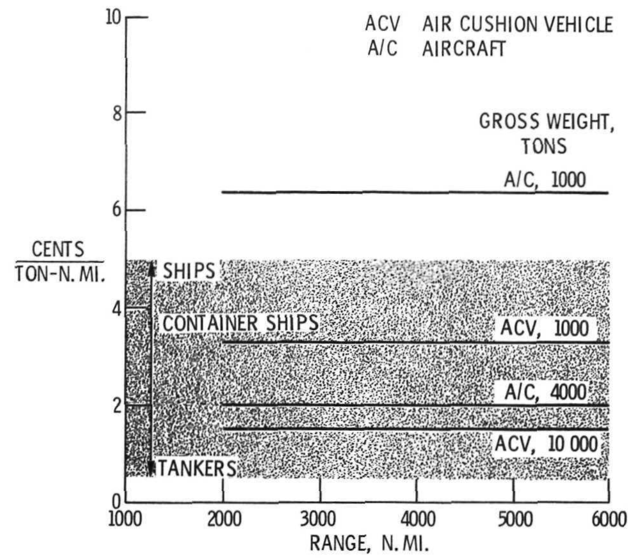

Figure 13. - Estimated operating costs for nuclear vehicles (data from refs. 29 and 30).

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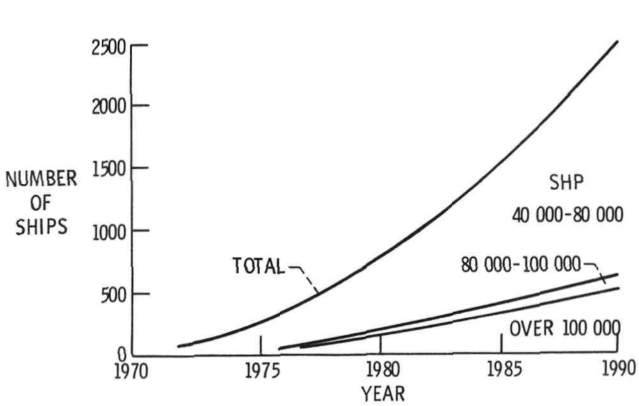

Figure 14. - Projected worldwide requirement for high powered ships (power above 40 000 SHP) (from ref. 1).

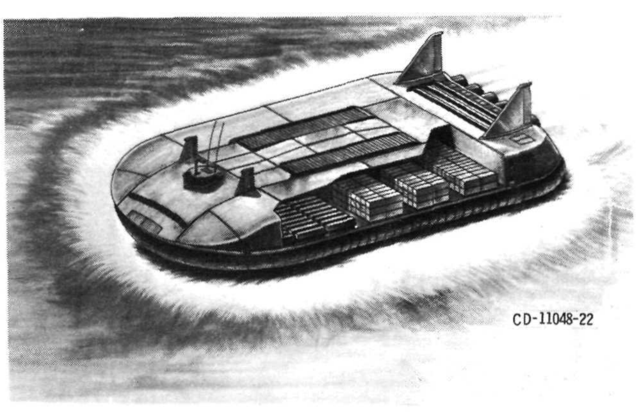

Figure 15. - 4500 metric ton nuclear ACV freighter.