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ASSESSMENT OF LIGHTWEIGHT MOBILE NUCLEAR POWER SYSTEMS

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ABSTRACT

After nearly two decades of study, analysis, and experiments relating to lightweight mobile nuclear power systems (LMNPS), it seems fitting to report the status and to assess some options for the future of this technology. This summary: (1) reviews the technical feasibility studies of LMNPS and airborne vehicles; (2) identifies what remains to be done to demonstrate technical feasibility of LMNPS; (3) reviews mission studies and identifies particular missions that could justify renewed support for such technology; and (4) identifies some of the non-technical conditions that will be required for the development and eventual use of LMNPS.

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SUMMARY

After nearly two decades of study, analysis, and experiments relating to lightweight mobile nuclear power systems (LMNPS), it seems fitting to report the status and to assess some options for the future of this technology. This report: (1) reviews the technical feasibility studies of LMNPS and airborne vehicles; (2) identifies what remains to be done to demonstrate technical feasibility of LMNPS; (3) reviews missions studies and identifies particular missions that could justify renewed support for such technology; and (4) identifies some of the non-technical conditions that will be required for the development and eventual use of LMNPS:

To develop and eventually implement a nuclear-powered airborne vehicle will likely require: an application of sufficient need, a sustained technology commitment (20 years), a good prospect of capital and operating costs low enough for the applications; compliance with stringent environmental and safety regulations; and favorable social and political climate.

INTRODUCTION

For more than two decades lightweight mobile nuclear power systems (LMNPS) for airborne vehicles have been investigated. Although potential applications for LMNPS other than aircraft have been identified, the technical demands for its use in aircraft have continued to guide the technical work.

The early work began in 1951 with the Aircraft Nuclear Propulsion (ANP) program, which was a joint project between the Atomic Energy Commission and the Air Force to develop a nuclear-powered bomber. However, the ANP program was cancelled in 1961. From about 1964

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until 1973 the sustaining work on LMNPS (conducted at and supported by NASA Lewis Research Center) was technology experiments on the nuclear reactor supplemented by analytical studies of power conversion systems and missions for air cushion vehicles (ACVs) (refs. 1-23, 43-44).

During this same period cooperative work on LMNPS was carried out between the U.S. Air Force and NASA Lewis. The objective of this work was to: determine the feasibility of a practical, safe, economical nuclear powerplant for ACVs and aircraft; define the key problems requiring research and development; and demonstrate or develop key technology required for the feasibility assessment. However, a policy decision has now ended NASA work on nuclear power and propulsion for aerospace use.

Therefore, it seems an appropriate time to assess the status and prospects for LMNPS. That is the purpose of this report, which (1) summarizes the technology studies of LMNPS; (2) identifies what remains to be done to demonstrate technical feasibility of LMNPS; (3) reviews mission studies and identifies particular missions that could justify renewed research and development support for LMNPS; and (4) identifies some of the non-technical conditions that must be met for the revitatization of R & D and the eventual use of LMNPS.

STATUS OF LIGHTWEIGHT MOBILE NUCLEAR POWER SYSTEMS

Two decades of work on LMNPS have not yet demonstrated technical feasibility. But the work (analysis and idealized experiments) has produced potential solutions to the technical problems. The first major section of this report is a summary of the analytical and experimental studies and potential technical solutions.

DESCRIPTION OF CONCEPTUAL POWERPLANT

As a focus for the technology and mission studies, a conceptual reactor and power conversion system was designed. A high-temperature, gas-cooled, water-moderated thermal reactor was chosen as the reference concept (Figure 1).

A thermal rather than fast reactor was chosen for several reasons: (1) The reactor could be more easily made subcritical (by removing water moderator) before an impending impact; (2) There is no penalty in weight or amount of fuel needed, relative to a fast reactor; (3) Accidental criticality from core compaction on impact would be less likely; (4) Immersion in water as a result of an accident would not add reactivity over its normal operating condition; and (5) A broader, more advanced technology base would be available for its development.

The primary reactor coolant would probably be helium; the secondary coolant either steam or air; the moderator would be water.

A long reactor life is desirable because of the complexity of the refueling operation and the fact that frequent refuelings would offset the energy autonomy of nuclear-powered vehicles. The reactor is designed for 10 000 hours of operation between refuelings. To eliminate the possiblity of critical masses forming in melted pools fuel after an impact, the total uranium investment (core loading) should be kept under 500 kilograms. References 21-22 list the power requirements at 200-3000 MWt for aircraft and 200-2500 MWt for ACVs, depending on the vehicles size and speed.

The reactor is surrounded by various layers of material constituting shielding, containment vessel, impact-energy-absorber, and melt-through protection material (fig. 1). The shield is a combination of borated water and tungsten or depleted uranium metal. The studies described in references 1-23 have indicated that for power levels needed by larger airborne vehicles (up to 3000 MWt) the reactor and shield could be contained within a spherical containment vessel less than 9 meters in diameter. At any point just outside the shield, the radiation level would be reduced to the maximum allowable dose for the general population, 0.25 millirem per hour. 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.

In figure 2 this conceptual shielded reactor is compared to a representative advanced marine reactor. Each of these mobile reactor concepts (marine and airborne) would produce 300 MWt. The Consolidated Nuclear Steam Generator (CNSG IV) reactor system (ref. 24) (actually designed to produce 314 MWt) has a volume of about 1800 cubic meters and a weight of 500 tons, excluding the biological shield. With the concrete aggregate shield the CNSG reactor system weighs more than 2000 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 300 MWt airborne reactor the dose rate would be about 4.5 millirem per hour just outside the shield (radius 2.9m) and about 0.25 millirem per hour at 9.15 meters from its spherical center. However, it must be pointed out that the CNSG marine reactor is being built while the "much-lighter-weight" airborne reactors are still in the early conceptual stages.

Another interesting comparison is of the dimensions of 1000 MWt conceptual airborne reactor to an equivalent power, conventional land-based reactor (fig. 3). In each case the shield reduces the dose rate to that permissible for the general population (0.25 mrem/hr).

Diagrams of the conceptual airborne reactor are shown in figure 1. Because of its familiarity and state-of-the-art, a steam turbine conversion system to provide vehicle electric power and drive fans of propellers was chosen for the air cushion vehicle (fig. 4).

A range of operating conditions for the reactor and steam conversion system is shown in table I. A range is specified because a precise set of conditions for minimum powerplant weight and maximum payload has not yet been defined.

Furthermore, the gas-cooled thermal reactor and steam turbine system should only be considered typical of the reactor cycle systems available. Other reactors may be the fast, liquid-metal cooled or the molten-uranium salt fueled and cooled. Other cycles may be the open-air Brayton, the closed Brayton, or the low-vapor-pressure (potassium) Rankine.

The air-Brayton system is shown in figure 5. Some sources of technology for lightweight reactors and power conversion systems are given in references 21-23, 25-27. Further study of all these systems is needed to determine which would give the lightest powerplant or the most payload or, more generally, which would result in the most economic, reliable, and safe vehicle.

TECHNICAL FEASIBILITY OF THE REACTOR

A high-temperature, helium-cooled thermal reactor (300 MWt) for airborne use might have peak fuel temperature of about 1000° C, a reactor coolant outlet temperature of about 750° C and a helium pressure of about 1070 newtons per square centimeter (1500 psi) (see table I). 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 HTGR's (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) (ref. 28); each reactor will have a thermal output of 3000 MW.

Hence, the land-based HTGR's should continue to provide a developing technology base of the same reactor type chosen for the conceptual design.

One purpose of the studies at NASA Lewis Research Center was to develop key technologies needed for a feasibility assessment of an LMNPS - long-life components, impact and meltdown survivability, and low weight.

Because about 100 kilograms of uranium will be consumed during 10 000 hours of operation of a 450 metric ton aircraft and because the initial loading is limited to about 450 kiligrams for safety reasons, the average fuel burnup must be 20 percent, with peak burnups of about 30 percent (ref. 11). The fuel pin power density must be about 0.5 kW/cc; the core power density would be about 0.125 kW/cc (3.5 MW/ft^3).

The fuel pin concept proposed to achieve this burnup is shown schematically in figure 6; the experimental components are shown in figure 7; The design of the fuel pin is described in references 9 and 45. The pin consists of a tube that is designed as a pressure vessel. Fuel is contained within the pin in a thin layer relative to the thickness of the tubular pressure vessel. The objective is to assure that the fuel material is weak compared to the clad strength so that when the fuel expands due to the buildup of fission products within it, the fuel will flow plastically into the central voidwithout introducing significant strains in the strong clad material. The void also provides room for the gaseous fission products to expand. Test results of pins based on this principle are shown in table II. One pin achieved 21 percent burnup of the heavy atoms without failing. For comparison in commercial power reactors only 3 percent burnup of the heavy atoms is achieved. A more meaningful comparison is energy density, which is 8300 kw hr/cc for a high-temperature strong clad pin compared to 6000 kw hr/cc for commercial fuel pins.

For jet thrust engines the helium-to-air heat exchanger material will limit the turbine inlet temperature and hence the performance of a nuclear-powered engine. Tests have been conducted to determine creep properties of high temperature oxidation resistant materials for heat exchangers. A suitable alloy was N-155 (ref. 12). This material is ductile and can be welded, worked, and machined readily; it can operate at temperatures up to 800° C. Both tube and header tests were conducted. The high pressure helium header (fig. 8) for the test was designed to operate for 2500 hours at a pressure of 1500 psi andtemperature of 840° C; it ran more than 5000 hours before it failed. This limited amount of heat-exchanger work has been adequate to determine design stresses and to verify header design techniques.

The reactor shield is the heaviest part of the nuclear powerplant and hence, directly affects its feasibility. Furthermore, nuclear powerplants for vehicles should use unit or 4π shields to reduce the radiation dose to allowable levels in all directions.

In the shield weight optimization studies described in references 2 to 4, the dose level at 9 meters from the reactor center is reduced to that allowable for the general population (0.25 millirem per hour). Using Monte Carlo analysis and optimizing techniques the shield materials, layer thicknesses, and layer order were varied to minimize the shield weight. Results of these calculations for depleted uranium - water shields are shown in figure 9 note that the shield weight increases slowly with reactor power. Consequently the ratio of shield weight to total gross weight decreases as vehicle gross weight increases.

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 neutron-poison addition or moderator removal. Radar sensing of impending impact situations would automatically activate the reactor shutdown, switch to chemical power, and close the valves thus sealing the penetrations in 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 a material configuration that is highly energy-absorbing, such as balsa wood, frangible tubes, or metal or plastic honeycomb (fig. 10). This passive technique appears reasonable for impact velocities up to about 100 meters per second (180 knots) (ref. 11) and hence would be adequate for air cushion vehicles. For aircraft at much higher speeds another technique will be necessary.

The other energy-absorbing technique examined has been simply the deformation of the containment vessel and its contents. 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 from 73 to 332 meters per second (240 to 1090 ft/sec) without rupturing (refs. 5 to 7) (figs. 11 and 12). There have also been impact tests involving ground burial (ref. 8).

After an impact the second stage of the accident safety problem would occur - potential meltdown. 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. Preliminary studies indicate that either of two approaches is feasible in principle. One approach is to provide enough impact energy absorber around the RSCV to ensure that the shutdown cooling system will function after an impact. This approach could probably work only up to some limiting velocity which is as yet undetermined. But could be equal to the ACV cruise velocity.

Another approach is to design an RSCV which will permit the core to melt, but not melt through the containment vessel (CV). An additional requirement is that this design must work regardless of the direction of impact of the RSCV (or vehicle) or the orientation of the RSCV after impact. This approach to meltdown has been discussed in references 10 and 11.

Conceptually, the heat redistribution process in such an RSCV would be as follows: By design, uranium dioxide (UO_2) would reside as a spherical shell of granular particles on the inside of the containment and the reactor vessels (see fig. 1). After an impact the high-density, high-melting-point UO_2 would act as an insulating material between the CV and pool(s) of melted core material floating on the UO_2. Some of the UO_2 will melt but because it has a higher denisty than the molten core, it will stay in place and act as a liquid insulator (ref. 29). The decaying fission product heat sources in the molten core would be boiled off and carried by vapor transport to materials above the pool or to the inside wall of the CV where they would condense and be deposited. This vapor transport should thus more uniformly distribute these heat sources in the CV causing the pool to solidfy. The heat flux to the outside of the CV above the pool would be fairly uniform so that the CV can be cooled by convection and radiation to the medium in which it is immersed; any pumped cooling system is assumed to be inoperable because of the impact.

A schematic of an experimental apparatus to test this meltdown concept is shown in figure 13. A photograph of the apparatus, which is essentially a model of a reactor and containment vessel, is shown in figure 14. In this photograph one-half of the model spherical containment vessel (CV), the cylindrical reactor-vessel, and 7 fuel pins in a hexagonal array are shown. The "CV" has a 13.4 cm outside diameter, the "reactor vessel" has a length and an outside diameter of 4.4 cm, and each fuel pin is about 3.9 cm long and 1.3 cm in diameter. For the experiment the assembled spherical "CV" was filled with UO_2 granules and the apparatus was positioned in the Plum Brook Reactor with the "reactor vessel" on its side.

Analysis of the temperature and pressure behavior of the apparatus monitored during the experiment indicated that the expected meltdown and heat redistribution process did occur.

A power increased in the apparatus indicated an outward progression of UO_2 toward the "CV" had occurred. From the measured "CV" surface temperature of about 830° C a back-calculation of the fuel pin temperature, assuming no melting, showed that a temperature considerably above the fuel pin melting point would have occurred.

Figure 15 is a neutron radiograph (2 views) of the apparatus midway during the exposure in the Plum Brook Reactor. The top radiograph shows that the horizontally positioned fuel pins twisted about a vertical axis during the test. This was probably due to nonuniform softening and melting of the materials (which is, turn, due to the spatial variation of neutron flux within the reactor). The bottom radiograph shows that the top fuel pins did indeed melt and flow down among the bottom pins which appear to be still intact (sharp edges at the bottom of the fuel mass). The stainless steel "reactor vessel" had begun to melt and flow into the surrounding UO_2 granules. The power was later doubled without significant changes in the model CV temperature distribution. Neutron radiographs have not yet been made at the higher power.

This meltdown concept and proof-of-principle experiment may have much broader implications than for just lightweight mobile nuclear power plants. It may be the basis for a solution to the loss-of-coolant accident, a matter of considerable current importance for commercial nuclear powerplants.

POWER CONVERSION SYSTEM

Another important part of a power system, of course, is the subsystem that converts the reactor heat to a more useable form, for example electricity or shaft rotation.

The technology of steam turbine systems is quite advanced. However, additional restrictions related to use with nuclear powerplants and airborne vehicles may require some development work.

Two prime requirements of space power systems, compactness and light-weight, may make that space technology useful for mobile nonspace applications. The status of several systems worked on at NASA Lewis is given in references 26-27.

The Brayton power conversion system seems particularly attractive because of its versatility and its technical status as described in reference 27. 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 (ref. 27).

One application being presently considered for larger Brayton systems is use with a land-based HTGR at about 830° C. Brayton systems are particularly attractive because they can be used with either fossil or nuclear-fueled powerplants and hence should adapt readily to nuclear/chemical switching capability needed for airborne vehicles.

PROSPECTS FOR LIGHTWEIGHT MOBILE NUCLEAR POWER SYSTEMS

To revitalize research and development on LMNPS will require the identification of at least one mission in which LMNPS can play an essential or major role. This second major section of the report identifies the factors that will likely underlie a revived interest in and an eventual implementation of the LMNPS.

However, as a prelude to this, it is useful to ask what characteristics of an LMNPS have already sustained two decades of interest in the formidable problems of developing a nuclear reactor that is compact and light enought to be mobile yet safe enought to withstand potential impacts? A quick answer is 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 in turn provides: (1) nearly unlimited vehicle range without refueling, (2) a larger "revenue-cargo" volume (which would have been taken up by chemical fuel) as the vehicle energy requirements get larger, (3) surface and weather-independence for undersea applications, and (4) energy independence and reserve endurance in remote areas such as the Arctic. A number of studies (refs. 1, 17-23) indicate LMNPS could offer distinct advantages in performance, convenience, and cost.

APPLICATIONS

LMNPS may be useful in (1) international or coastal cargo transportation, (2) resource development, and (3) remote power supply (ref. 22). Applications shown in table III and IV include: vehicles such as ships, submarines, aircushion vehicles (ACVs), 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 megawatt for small work submersibles and small habitats to several megawatts for research submarines, tunneling machines, and large habitats to hundreds of megawatts for ships, submarines, large aircraft, ACVs, and deep underwater shaft mining to thousands of megawatts for very large aircraft and ACVs.

Thus LMNPS could be put to a variety of uses if they were a available. But perhaps the key question is whether there will be sufficient need for any one nuclear-powered device to justify the R & D costs. This seems an especially important question when one considers the technical problems to be overcome, the full LMNPS and vehicle development costs, the uncertainties of capital and operating costs, and the social and political implications of mobile nuclear reactors.

Potential missions that now appear important enough to justify renewed federal support of research and development on LMNPS are: (1) military use for 100-knot naval surface effect ships (hybrid ACVs) after 1985; (2) military or civilian use for ACVs in and across the Arctic after 1990; and (3) holding open and more clearly defining options for military aircraft after 2000. The remainder of this section will discuss the applications of these two vehicles-the ACV and the airplane.

Although the technical demands for LMNPS use in aircraft have guided the technical work from the beginning, more recently the large ACV has helped sustain interest in LMNPS because: the impact safety problem is much simpler than for aircraft (the ACV would move about one-sixth as fast); the LMNPS could thus be available sooner for ACVs than for aircraft; nuclear ACV missions (both civilian and open-literature military) may be more clearly defined and needed sooner than nuclear aircraft missions; and the ACV could serve as a test bed to demonstrate the reliability of LMNPS that would be needed for aircraft. In general, because of the development time needed for the LMNPS and the time period when vehicles of such size and capability may be needed, a nuclear ACV could likely come only after 1985 and a nuclear airplane after 2000.

Air Cushion Vehicles

Small ACVs up to about 150 metric tons have been used all over the world in commercial, military, and exploratory roles. Much of the operating experience of the larger ACVs has come from the SRN4 (fig. 16) (ref. 30) which has provided English Channel ferry service since 1968. The SRN4 weighs 150 metric tons, cruises at 65 knots, and can carry 250 passengers and 30 cars.

Hybrid ACVs, called surface effect ships, of 2000 metric tons are being designed for the U. S. Navy, which has publicly stated its desire for a 100-knot Navy. At this size and speed, ACVs begin to be large enough to effectively use a LMNPS. ACV freighters of about 4000 metric tons are being designed in Britain and France.

Conceptual designs of large multi-thousand ton nuclear ACVs are described in references 15-20, and 23. An artists rendering of a conceptual nuclear powered ACV freighter (4500 metric tons gross weight) is shown in figure 17.

Civilian missions and implications of large ACVs have been discussed in references 17-23. Two particular applications of ACV freighters are described below because they seem sufficiently important and far-reaching to stimulate both the development of large ACVs and the demand for a LMNPS:

Oceanic ACV freighters. - As discussed in references 17 and 20, a 100-knot nuclear-powered ACV freighter in the 4 000-10 000 metric ton class might carry cargo at a cost under two cents per ton-nautical mile. The combination of speed, relatively low cost, and flatbed design of an ACV freighter would make it well-suited to carry the containerized and roll on/roll off portions of dry cargo trade that are now handled by ships, the containerized cargo now carried by aircraft, and also wholly new types and configurations of cargo (ref. 18).

Studies by the aircraft industry have identified categories of cargo (containerizable) that are "air-eligible" (table V) (ref. 31) but presently go by sea freight. These categories should be eligible for an ACV with its intermediate speed and cost. Furthermore, the industry studies have also identified categories of cargo that would become "air-eligible" if the total air cargo cost were reduced by 25-35 percent. An ACV freighter could reduce the freight cost by 75 percent (ref. 20) and thus much of the "air-eligible" cargo would be "ACV-eligible" on a cost basis. And on a time basis, at 100 knots and ACV would provide about 80 percent of the time savings that aircraft would provide over ships. Hence, an ACV freighter should compete for much of the containerized cargo that will be eligible to be carried by aircraft. Because of its speed several categories of "perishables", including monthly newsprint, fresh and prepared foods, cut floweres, competitive products, and short-lived chemical compounds, might be carried by ACV.

In a roll on/roll off mode (fig. 18) an ACV freighter could carry cars, tractors, road construction machinery, recreation vehicles, mobile homes, and trailer trucks, and carry them to and from new ports (ref. 18) that cannot be reached by ships. It could transport containerized cargo or large preloaded pallets of machinery or appliances fast enough to allow expensive inventories of goods to be reduced. ACV's could carry modular, prefabricated and preoutfitted building units. A building unit might be a factory, equipment service center, educational center, hospital, barracks, field kitchen, or temporary office. An ACV could also serve as a mobile base (fig. 19).

However, super-tankers and bulk/ore carriers will continue to transport inexpensive bulk cargos such as oil, liquified natural gas, grain and ores between present sources and markets much more cheaply than a nuclear ACV could. Very high value cargo or highly perishable cargo should remain the exclusive domain of air freighters. Examples of this type of cargo are: jewelry, cosmetics, daily newsprint, and small-lot highly competitive products for initial disclosure or demonstration (such as fashion clothing, electronic or optical instruments).

The large nuclear-powered ACV freighter could offer a trans-oceanic cargo transportation option with speed and cost intermediate between the low-speed, low-cost ships and the high-speed, high-cost aircraft. It could offer high-speed coastal freight and passenger transportation, to serve the increasing population density of the coasts. The ACV freighter could open shallow and reef-bound coastland for economic development and habitation; (fig. 20). New ports could be located inland, leaving the coastal area and its ecology relatively undisturbed. A new docking area could be created on land with little or no surface preparation. To link with the present transportation modes, existing dock facilities could be used with little modification.

Arctic ACVs. - The Arctic is now being recognized as an abundant source of many raw materials. Near Mary River, a town in the northern part of Baffin Island, lies the largest and richest iron ore deposit in North America (ref. 32). Natural gas, oil, iron, nickel, lead, zinc, silver, copper, and uranium have been discovered in the Canadian Arctic. The U.S.S.R. has enormous oil, gas, and mineral reserves in Siberia.

While the U.S. need for new domestic mineral resources is not presently as urgent as our need for fossil fuels, the U.S. does import (wholly or partially) 69 of 72 vital raw materials (ref. 33).

Large oil reserves have been discovered on the Alaskan North Slope and at the MacKenzie River Delta and Ellesmere Island in Canada. The North Slope and adjacent offshore areas of the Arctic may have a petroleum potential per cubic mile of sediment that matches that of the Middle East (ref. 34). Also recent photographs from the earth resources satellite, ERTS-A, have provided geologic indications that the oil and gas fields of the Alaskan North Slope are much larger than previously reported. Furthermore, the Canadian Arctic Islands have been estimated to overlie a greater oil deposit than the Middle East (ref. 35).

An increasing variety of small ACVs (up to tens of tons gross weight) is being evaluated experimentally in the Arctic by the Canadian government and industry (ref. 36) and by the U.S. military. There is U.S. work underway to define the characteristics needed for an operational Arctic ACV of several hundred tons gross weight. A 3200-metric-ton payload low-speed towed transporter (air cushion barge) for the Arctic oil fields has been designed and is under development by a Canadian company (ref. 37).

ACVs would offer versatility and year-round mobility virtually independent of Arctic terrain. ACV missions related to the exploitation of Arctic energy and mineral resources include exploration for resources, short-range resource hauling (such as crude oil from the North Slope to displacement tankers waiting in ice-free waters), equipment movement in oil fields (already in use) and workhorse transportation for people, supplies, equipment and habitats.

The possibility of using 10 000 ton 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 (ref. 19). Large ACVs 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 or transfer stations where the cargo could be transshipped to conventional displacement tankers, bulk carriers or pipelines.

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 (ref. 20, fig. 21). As described in reference 20, a nuclear-powered ACV freighter could provide (1) a shorter trade route between most of the major industrial and population centers of the world, (2) competitive cost with conventional displacement ships for containerized and roll on/roll off cargo, (3) independence from the Panama and Suez Canals, and (4) all-season Arctic-wide mobility.

Military missions for multi-hundred ton vehicles include patrol boats (SESs), amphibious assault landing craft (ACVs), and Arctic ACVs. Military missions for multi-thousand ton surface effect ships that have been discussed in the open literature (refs. 36, 38) are for naval use and include destroyers for anti-submarine duty, cargo and troop ships, and aircraft carriers to provide sea control.

Aircraft

Probably the main reason for failure of the ANP program was the ambitious goal to have a nuclear-powered aircraft with a chemically powered supersonic dash capability and a gross weight limited to 225 metric tons. Since that goal was set, however, larger aircraft have made their debut. Both the Boeing 747 (322 metric tons) and the Lockheed C-5A (361 metric tons) have a much larger gross weight. Growth versions of these aircraft will approach 500 metric tons. And aircraft with gross weights of 500-1600 metric tons (for example, the Boeing resource transport aircraft (ref. 39)) are in the preliminary design stages. Chemical fuel was condidered for the Boeing resource transport aircraft but the conditions of large size, high power needs, and high utilization make a nuclear powerplant (with its long time between refuelings) an attractive alternative.

The coming aircraft will thus be large enough to accommodate a nuclear powerplant based on the LMNPS concept. In fact, in its present size, the C-5A could accommodate a high-power density (13.5 MW/ft^3) reactor (ref. 40). Conceptual studies of a nuclear-powered airplane have been described in references 2, 10, 11, 40, and 41.

Nuclear aircraft potentially offer in a civilian capacity almost unlimited endurance for inflight experiments and scientific observations, nonstop flights between any two airports on earth, and very low cost for fast cargo transport (ref. 22). 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.

Because of their size and endurance nuclear aircraft would fulfill several military functions: global-range, large-payload logistic support; a missile platform ("flying Polaris"); missions requiring large energy expenditure such as low-altitude, high-speed penetrations of enemy territory; and a command and control post (see ref. 41).

TECHNOLOGY

Technology work on the RSCV materials and configuration is of course required.

Additional technology work is needed in several other areas to convincingly demonstrate technical feasibility and to form the technology base from which the subsequent design and development of a LMNPS for a particular application could proceed. These areas include: high pressure helium to air heat exchangers, pumping systems for high pressure inert gases, seals for these systems, valves, piping required to duct high-pressure, high-temperature gases from the reactor to and from the engines, auxiliary systems such as for afterheat cooling. Problems such as thermal cycling, vibration and thermal expansion of individual and coupled components must be addressed.

The airbreathing portion of the aircraft system requires studies of the problems involved in extending the shaft lengths of the turbofan engines so that the heat exchanger can be incorporated. An experimental program is needed to determine the feasibility of fast acting valves that are necessary to seal off coolant lines and other designed penetrations into the containment vessel during a major accident. Detailed overall powerplant conceptual designs are needed to arrive at realistic weight estimates of the entire system.

These designs would also provide base points for realistic parametric and optimization studies that are required for mission analyses. The designs and missions analyses would require that specific values for design and performance parameters be chosen. Each set of values constitutes one set of specifications or one definition of the state-of-the-art needed for a feasible vehicle and LMNPS. Hence, they represent interim technical and economic goals for further research and development work.

OTHER INFLUENCES

There are a number of non-technical factors that will influence the revitalization of research and development of LMNPS, the development of an airborne vehicle requiring an LMNPS, and the eventual implementation of the vehicle.

Economics

There are two major questions of commercial feasibility. First, are the long-term benefits of an airborne nuclear-powered vehicle clear and credible enough to justify the large R & D investment that will be required. Earlier sections have discussed the possible missions that could justify additional R & D on LMNPS. But further cost/benefit studies are needed to answer this question.

Second, will the capital and operating costs be low enough to be acceptable for military use or be competitive for civilian use? Comparison of costs for nuclear versus chemically fueled aircraft and ACVs may be found in references 1, 17, and 42. Further, detailed ACV cost estimates also constitute a major part of two ACV systems studies relating to the Arctic (refs. 19 and 20). These results are summarized in table VI. They show a 9000-metric ton nuclear ACV hauling cost of 1.7 cents per ton-nautical mile, which is: about 1/3 the cost of a chemical ACV on non-stop trans-oceanic routes; slightly more than nuclear containership costs; about 1/5 the cost of a large, chemically-powered aircraft, and about 1/4 the cost of a minimum size (~ 900 metric tons) nuclear aircraft. Figure 22 shows a comparison of payload for chemical and nuclear ACVs which gives a direct indication of hauling costs.

Operations

Although the trend has been toward increasingly larger aircraft, cargo ships, and oil tankers, there are limits to size other than technical feasibility. Even if giant vehicles can operate efficiently and safely, their size will make them unwieldly for physical handling in port and for cargo marshalling and scheduling which will affect their operating cost. When the vehicle size reaches a certain point the port and dock handling capability must be expanded. Can the new transport capability offered justify this modification? As a current example, how much should airports expand or modify to accommodate the new, large aircraft. Furthermore, other problems are magnified because of large vehicle size. For example, the recent air traffic slump and lower than expected reliability have particularly affected the profitability of the large aircraft.

A large nuclear-powered aircraft will have to carry cargo at high load factor to keep the cost low. The net result will be fewer vehicles in operation, which may present a scheduling inconvenience to the user. The greater the carrying capacity beyond a certain level, the more unwieldy it is to fit the vehicle into the existing transportation system.

Social Feasibility

There are also socially-related conditions which affect the future of LMNPS. They deal primarily with safety and political factors.

Safety

The present controversies regarding the safety of large, land-based nuclear electric powerplants and the disposal of radioactive waste suggest caution in discussing the prospects for mobile nuclear powerplants. However, for military ACVs or SESs the use of LMNPS would not be so controversial. The main reason is that most of the time military ACV reactors would be away from any civilian population (as they are now on submarines). Also the safety record has been good; and the amount of nuclear waste generated should be small compared to the amount generated by commercial nuclear electric powerplants.

Civilian ACVs, of course, will spend much more time near population centers. However, the social acceptance of civilian nuclear ACVs may be expected from the precedents set by: nuclear-powered submarines and naval surface vehicles and the beginnings of a nuclear-powered multi-nation fleet of merchant ships.

But a nuclear airplane is another matter. The safety technology would be different and more complex because of its speed. Also the civilian airplane would likely fly near and could fly over populated areas. In the past few years considerable opposition developed to several large technological and civil works porjects (SST, airports, freeways, dams) that threatened the quality of life of people the environment. In many cases this opposition has stopped the project. In view of this experience and the safety aspect of a nuclear airplane, substantially more opposition could be expected.

Political

To get and maintain political support for major R & D on LMNPS will require a clear need for the powerplant and vehicle to use it. In retrospect, an underlying cause of the legislative termination of the supersonic transport program was that the need for it was never convincingly demonstrated. It appears there must be a recognized and credible need with a readily identifiable public benefit for a high-cost technological undertaking, such as an LMNPS or the vehicle that will require it. Again, this echoes the requirement for a mission of sufficient need to justify major R & D support for LMNPS.

However, political support for minor R & D could arise in a rather traditional way - anticipating and reducing response time to a political or military challenge. From a political and military viewpoint, if one nation announced a nuclear airborne capability, that nation might have some important strategic and tactical advantage for a considerable time because of the development time needed for such a complex technology. It would take the nation that lacked this capability from 10 to 20 years to develop and implement a comparable technology to counter the advantage. However, if the technological state-of-the-art had already been advanced (but not applied to a particular vehicle) then less than 10 years would be required to respond to the challenge.

CONCLUDING REMARKS

Analysis and idealized experiments have given a preliminary indication that lightweight mobile nuclear power systems (LMNPS) are technically and economically feasible. But socio-political feasibility is another matter. Revitalization of major research and development on LMNPS will require identification of and perhaps commitment to missions of sufficient need. The best prospects for this seem to be naval surface effect ships (hybrid air cushion vehicle-ACVs) and civilian Arctic ACVs. Eventual implementation of LMNPS will require a clear demonstration of safety. The impact safety problem would be much less severe for ACVs than for aircraft. In fact, a different and simpler safety technology may be used for ACVs. To develop and eventually implement a nuclear-powered airborne vehicle will likely require: a sustained technology commitment (20 years), a good prospect of capital and operating costs low enough for the applications; compliance with stringent environmental and safety regulations; and favorable social and political climate.

REFERENCES

1. F.E. Rom and C.C. Masser, "Nuclear-Powered Air-Cushion Vehicles for Transoceanic Commerce," NASA-TM-X-2293, National Aeronautics and Space Administration (1971).
2. F.E. Rom and P.M. Finnegan, "Will the Nuclear-Powered Aircraft be Safe?, "Astronautics & Aeronautics, 6, 3, 32 (1968).
3. T.M. Jordan and M.L. Wohl, "Shield Weight Optimization Using Monte Carlo Transport Calculations," NASA-TM-X-52973, National Aeronautics and Space Administration (1971).
4. M.L. Wohl, J. Celnik and R.D. Schamberger, "Optimized 4π Spherical-Shell Depleted Uranium-Water Shield Weights for 200- to 550-Megawatt Reactors," NASA-TM-X-2503, National Aeronautics and Space Administration (1972).
5. R.L. Puthoff, "High Speed Impact Tests of a Model Nuclear Reactor Containment System," NASA-TM-X-67856, National Aeronautics and Space Administration (1971).
6. R.L. Puthoff, "A 1055 Ft/Sec Impact Test of a Two Foot Diameter Model Nuclear Reactor Containment System Without Fracture," NASA-TM-X-68103, National Aeronautics and Space Administration (1972).
7. R.L. Puthoff, W.G. Parker and L.E. Van Bibber, "Post Impact Behavior of Mobile Reactor Core Containment Systems," NASA-TM-X-68176, National Aeronautics and Space Administration (1972).
8. R.L. Puthoff, "A 810 Ft/Sec Soil Impact Test of a 2-Foot Diameter Model Nuclear Reactor Containment System," NASA-TM-X-68180, National Aeronautics and Space Administration (1972).
9. F.E. Rom, P.M. Finnegan and G.E. McDonald, "Very-High-Burnup Vapor-Transport Fuel-Pin Concept for Long-Life Nuclear Reactors," NASA-TN-D-4860, National Aeronautics and Space Administration (1968).

10. F.E. Rom, "Airbreathing Nuclear Propulsion - A New Look," NASA-TM-X-67837, National Aeronautics and Space Administration (1971).

11. F.E. Rom, "Nuclear-Powered Airplane," Technol. Review, 72, 2, 48 (1969).

12. R.E. Morris, "Creep-Rupture Data for Welded N-155 Tubes," NASA-TN-D-5195, National Aeronautics and Space Administration (1969).

13. R.E. Morris, "Permanent Impact Deformation of Spherical Shells," NASA-TM-X-2067, National Aeronautics and Space Administration (1970).

14. R.E. Morris, "Empirical Correlation of Small Hollow Sphere Impact Failure Data Using Dimensional Analysis," NASA-TM-X-52874, National Aeronautics and Space Administration (1970).

15. F.E. Rom and A.F. Kascak "The Potential of Nuclear Power for High-Speed Ocean-Going Air-Cushion Vehicles," NASA-TM-X-1871, National Aeronautics and Space Administration (1969).

16. A.F. Kascak, "Parametric Study of Large Nuclear Surface Effect Machines," NASA-TM-X-1888, National Aeronautics and Space Administration (1969).

17. J.L. Anderson, "A Nuclear Powered Air Cushion Freighter for the 1980's," NASA-TM-X-67876, National Aeronautics and Space Administration (1971).

18. J.L. Anderson and P.M. Finnegan, "Creating New Cities Through the Large Air-Cushion Vehicle," Astronautics & Aeronautics, 10, 1, 46 (1972).

19. J.L. Anderson, "Air-Cushion Tankers for Alaskan North Slope Oil," NASA-TM-X-2683, National Aeronautics and Space Administration (1973).

20. J.L. Anderson, "Northwest Passage - Trade Route for Large Air-Cushion Vehicles," NASA-TM-X-2684, National Aeronautics and Space Administration (1973).

21. J.L. Anderson, "Nuclear Powerplants for Mobile Applications," NASA-TM-X-68154, National Aeronautics and Space Administration (1972).

22. J.L. Anderson, "Emerging Needs for Mobile Nuclear Powerplants," NASA-TM-X-68164, National Aeronautics and Space Administration (1972).

23. J.L. Anderson, "Nuclear Air Cushion Vehicles," NASA-TM-X-68231, National Aeronautics and Space Administration (1973).

24. Anon., "Marine Nuclear Steam Propulsion Executive Briefing," U.S. Maritime Administration, (1971).

25. M.H. Krasner, H.W. Davison and A.J. Diaguila, "Conceptual Design of a Compact Fast Reactor for Space Power," NASA-TM-X-67859, National Aeronautics and Space Administration (1971).

26. R.E. English, "Technology for Nuclear Dynamic Space Power Systems," NASA-TM-X-52771, National Aeronautics and Space Administration (1970).

27. R.E. English, "Technology of Nuclear-Brayton Space Power Systems," NASA-TM-X-67957, National Aeronautics and Space Administration (1971).

28. Anon., "Persistence Rewarded," Nucl. Eng. Int., 16, 185, 874 (1971). (1971).

29. S.M. Zivi, "A Passive Safety Device Against a Melt-Through Accident," Nucl. Appl., 5, 53 (1968).

30. R.L. Wheeler, "The Development Phase of the Mountbatten Class (SR N4) Hovercraft," AIAA Paper No. 69-410, American Institute of Aeronautics and Astronautics (1969).

31. A.E. Smick, "Cargo Handling: Needed - A Marketing Systems Approach," Astronautics & Aeronautics, 8, 1, 68 (1970).

32. W.D. Smith, Northwest Passage, American Heritage Press, New York (1970).

33. J.L. Warner, "The Navy's New Challenge," Aviation Week and Space Technol., 97, 22, 7 (1972).

34. Anon., "Slope's NPR-4 May Hold Vast Reserves, Oil Gas J., 71, 38, 38 (1973).

35. R.J. Boyle, "Arctic Passages of North America," U.S. Naval Inst. Proc., 95, 1, 48 (1969).

36. R.J. Summers, Rendezvous, Bell Aerospace Corp., vol. 12, Sept. 1973.

37. E. Anders and L. Nichols, "Arctic offshore Rig Features Air Cushion and Ice-Melt System," Oil Gas J. 71, 7, 61 (1973).

38. R.P. Hudock, "Toward the 100-Knot Navy," Astronautics & Aeronautics, 11, 9, 6 (1973).

39. M.D. Taylor, "A Canadian Arctic Resource Air Transport System," Proc. 23rd Annual Petroleum Society Technical Meeting, Calgary, Alberta (May 1972).

40. K.L. Mills III and J.L. Meem, "Nuclear Power for the C-5 Transport Aircraft," Trans. Am. Nucl. Soc. 1972 Annual Meeting June 18-22, 1972, CONF-720607; also Trans. Am. Nucl. Sol., 15, 1, 5 (1972).

41. J.M. Wild, "Nuclear Propulsion for Aircraft," Astronautics & Aeronautics, 6, 3, 24 (1968).

42. F.E. Rom and C.C. Masser, "Large Nuclear-Powered Subsonic Aircraft for Transoceanic Commerce," NASA-TM-X-2386, National Aeronautics and Space Administration (1971).

43. C.J. Lennon and R.E. Hyland, "Criticality Study of Meltdown Configurations for Nuclear Aircraft Reactors," NASA-TM-X-2068, National Aeronautics and Space Administration (1970).

44. Anon., "Study of Thermal Gas-Cooled Reactor Technology," AN-1517 Aerojet-General Nucleonics, (1966); also, NASA-CR-72048.

45. D. L. Wilmer and R. F. Hyland "Redtop (Reactor Design from Thermal-Hydraulic Operating Parameters) a Fortran IV Code for Calculating Reactor Dimensions and Mass from Thermal-Hydraulic Considerations," NASA-TM-X-68236, National Aeronautics and Space Administration (1973).

TABLE I. - RANGE OF OPERATING CONDITIONS FOR GAS-COOLED THERMAL REACTOR-STEAM TURBINE SYSTEM

Steam turbine inlet temperature	315° to 600° C (600°-1100° F)
Steam turbine inlet pressure	6.9 to 13.8×10^{6} N/m^{2} (1000-2000 lb/in.^{2})
Steam condenser pressure	6.9 to 69×10^{4} N/m^{2} (10-100 lb/in.^{2})
Steam condenser temperature	95° to 150° C (200°-300° F)
Reactor coolant outlet temperature	480° to 760° C (900°-1400° F)
Fuel element clad temperature	650° to 980° C (1200°-1800° F)
Reactor core average power density	70 to 280 W/cm^{3} (2-8 MW/ft^{3})

TABLE II. - LONG-LIFE FUEL PIN TESTS

(PLUMBROOK REACTOR FACILITY)

	Required for 10,000-hour propulsion reactor	Commercial power reactor	UO_2-TZM test	UN-TZM test
Fuel pin surface temperature, °F	1800	600	2100	2100
Fuel pin power[a] kW/cm^3	0.5	0.5	2.3	1.7
Total energy release $kW\text{-}hr/cm^3$ of pin	8300[b]	6050[b]	8300[c]	4900[d]
Burnup,[e] percent	21	3	21	7

[a] The volume in the kW/cm^3 is the total volume of the pin, i.e., the sum of the of the center void, the fuel, and the clad volume.

[b] End-of-core life.

[c] Blower-motor failure.

[d] Fuel pin rupture; failure believed to be understood and correctable.

[e] Burnup given is the percentage of heavy metal; burnup percentage of uranium-235 would be greater for commercial reactors than the other because of the low enrichment fuel used.

TABLE III. - 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	research 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

[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 IV. - SYSTEMS AND THEIR POWER NEEDS

Instrument	Reactor power level (megawatts thermal)
Submersible	0.05 - 10
Habitat(s)	0.10 - 30
Energy depot	0.5 - 400
Mining machines	0.5 - 400
Tunneling machines	3 - 50
Airship	20 - 40
Existing ship	36 - 80
Future merchant ship	80 - 300
Cargo submarine	70 - 600
Air cushion vehicle	200 - 2500
Aircraft	200 - 3000

TABLE V. - CARGO CATEGORIES

(FROM SMICK, REF. 31)

	Product value per pound	
	$0.65 - $1.00	>$1.00 (Air eligible - substantial percentages now move long distances by air)
Product families	Refrigerators	Electronic data processing machinery
	Automobiles	Finished apparel
	Air conditioners	Optical equipment
	Stoves	Hi-fi equipment
	Clothes washers	Transistor radios
	Dishwashers	

TABLE VI. - OCEAN-GOING VEHICLE HAULING COSTS

	Gross weight, ton	Range, n. mi	Speed, knots	Cost (cents/ton-n. mi)		Load factor	Reference
				DOC[a]	TOC[b]		
Nuclear ACV	10 000	-----	100	1.3	1.7	1.0	20
Nuclear ACV	10 000	-----	100	1.5	---	.6	1
Nuclear ACV	4 000	-----	100	1.8	---	.6	1
Nuclear SES	4 000	-----	85	2.5	---	1.0	(c)
Chemical ACV	10 000	1500	60	---	1.2	.75	19
Chemical ACV	10 000	2000	100	2.5	---	.6	1
Chemical ACV	10 000	4000	100	4.4	---	.6	1
Chemical SES	4 000	2000	85	1.6	---	1.0	(c)
Chemical SES	4 000	4000	85	3.3	---	1.0	(c)
Containership (oil fired or nuclear)	(d, e)	-----	33	---	1.4	1.0	20
Aircraft (chemical CSA or 747)	(f)	3500	450	3.5	9.4	.85	20
Aircraft (nuclear)	1 000	-----	500	6.3	---	1.0	
Aircraft (nuclear)	4 000	-----	500	2.0	---	.6	42
Super tanker (oil-fired)	(g)	-----	16	---	.034	1.0	20

[a] DOC = Direct operating cost.

[b] TOC = Total operating cost.

[c] James L. Decker: Economic Comparison of Large Aircraft and Surface Effect Ships for Ocean Commerce. JSESPO. Jan. 1968.

[d, e, f, g] Payload tonnage: 20 000 (oil-fired); 30 000 (nuclear); 120; 200 000.

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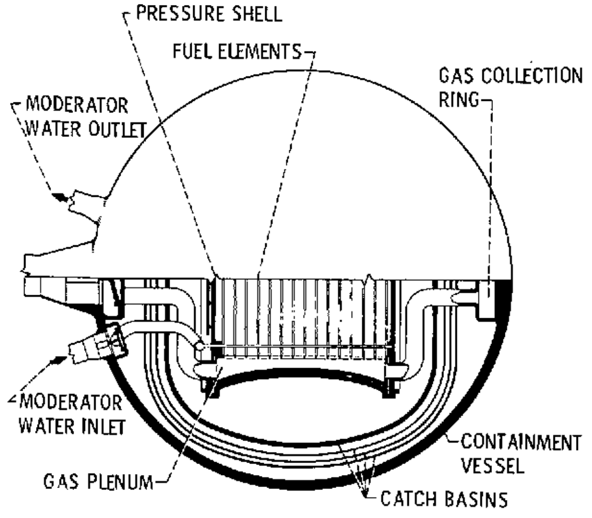
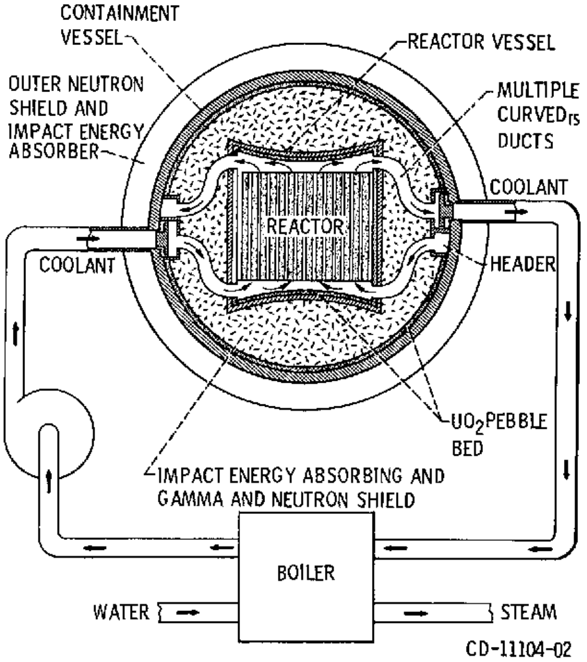


(a) SCHEMATIC DRAWING EMPHASIZING FLUID SYSTEMS.



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(b) DRAWING EMPHASIZING SAFETY SYSTEMS.

Figure 1. - Light weight mobile nuclear reactor concept.

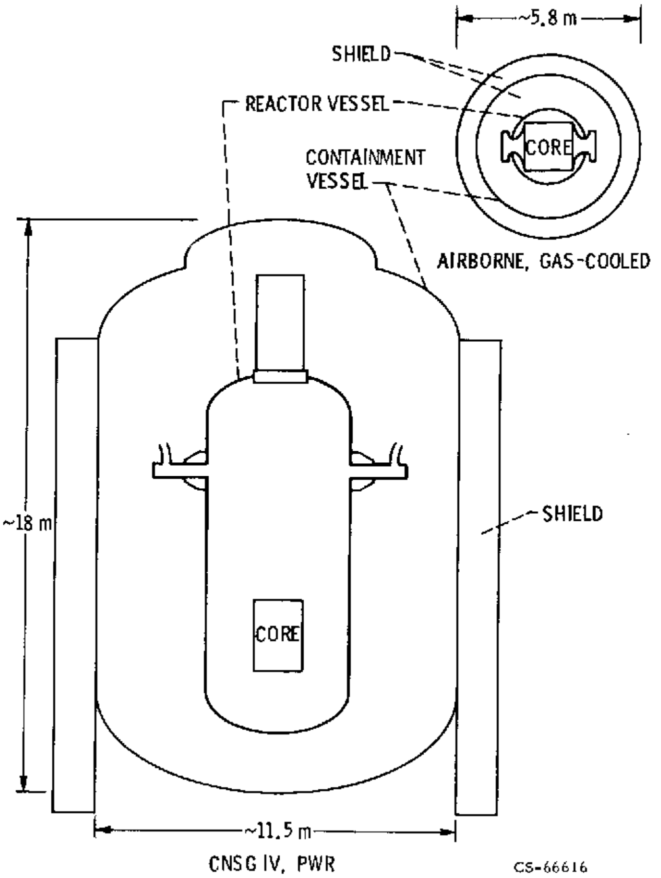

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Figure 2. - Comparison of mobile reactor concepts at ~300 MWt.

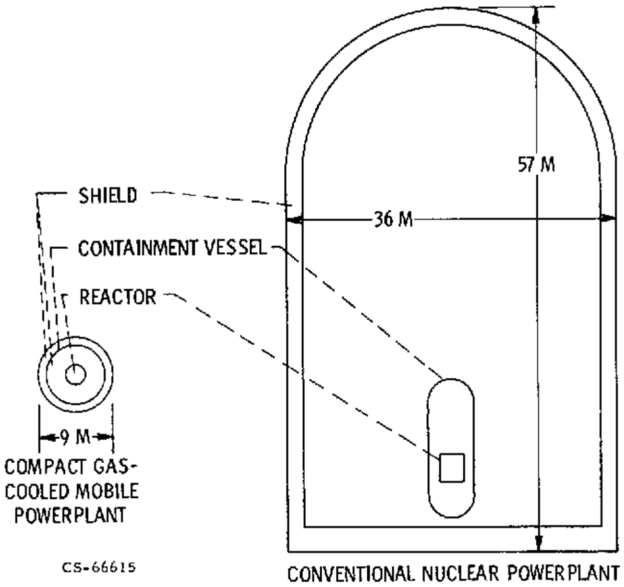


Figure 3. - Contrast of reactor sizes at 1000 MWt (shielded for 0.25 MR/hr at the outer shield surface.

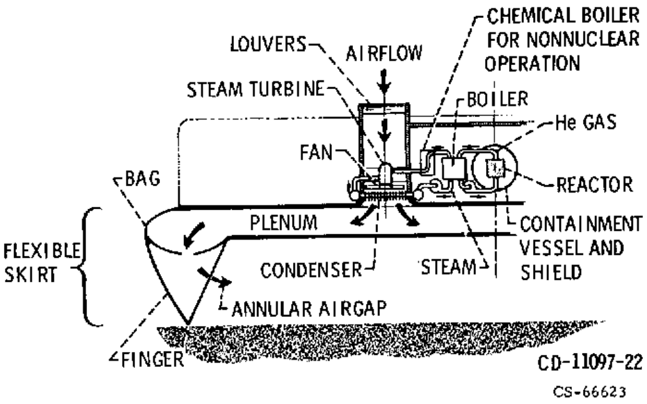


Figure 4. - Schematic drawing of steam turbine drive for lift fan.

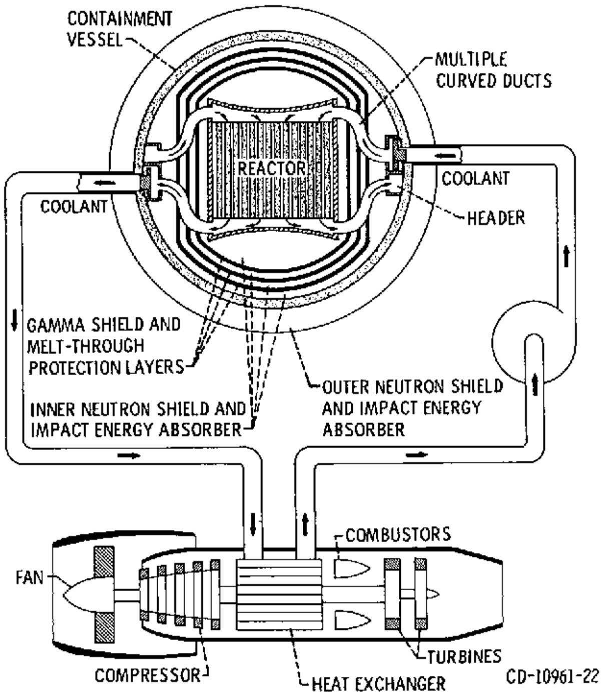


Figure 5. - Nuclear aircraft powerplant.

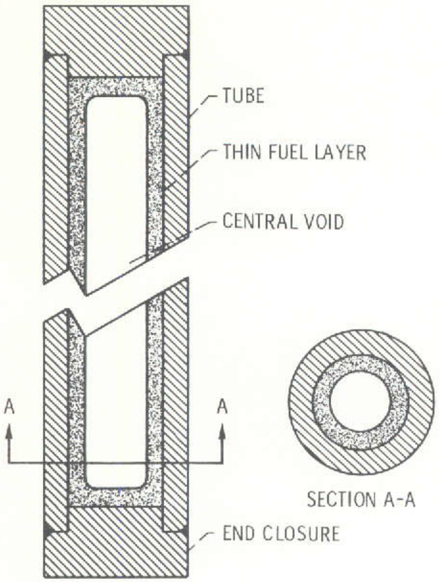


Figure 6. - Schematic drawing of very-high-burnup vapor-transport fuel-pin concept.

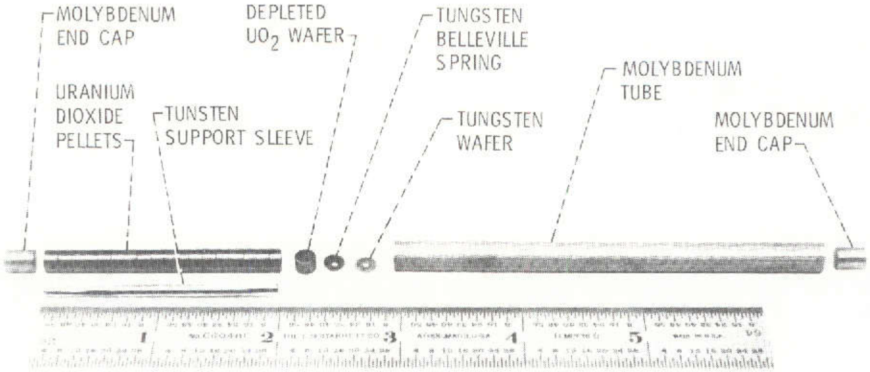
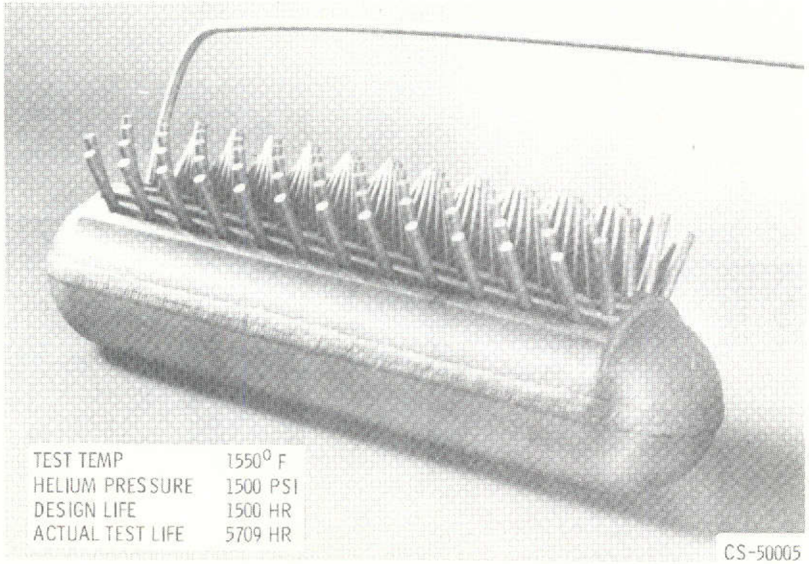


Figure 7. - Components for high temperature fuel pins containing UO_2 pellets. The tungsten support sleeves were used with cored pellets.



TEST TEMP	1550° F
HELIUM PRESSURE	1500 PSI
DESIGN LIFE	1500 HR
ACTUAL TEST LIFE	5709 HR

Figure 8. - Test of high pressure helium-to-air heat exchanger header.

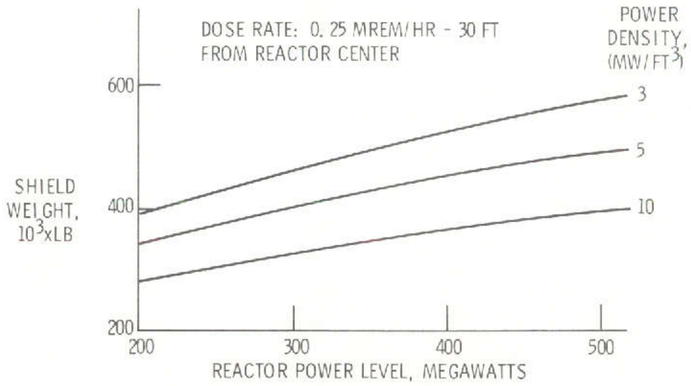


Figure 9. - Depleted uranium-water shield weights.

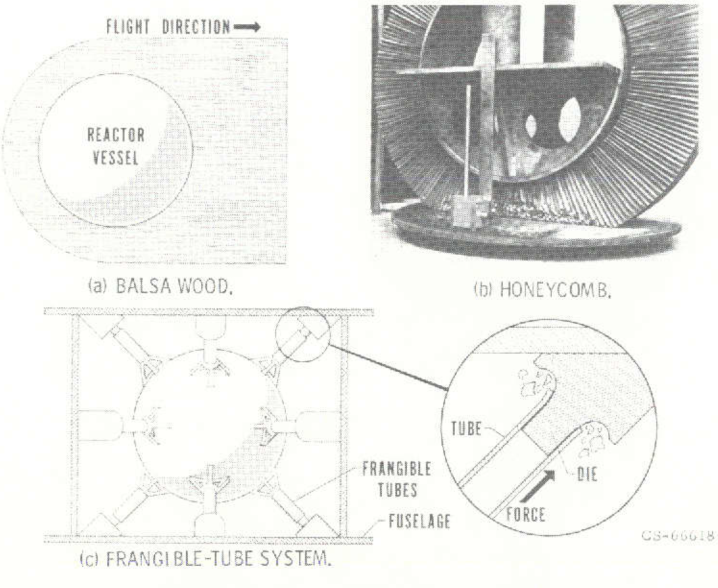
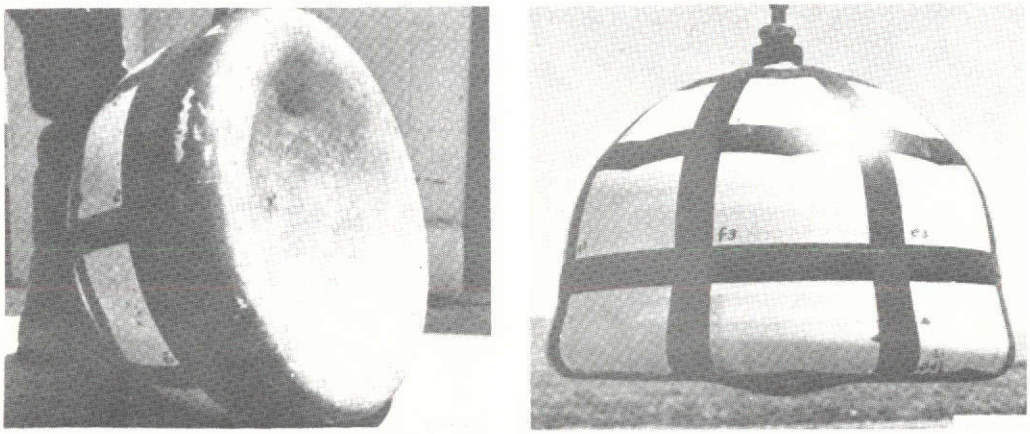
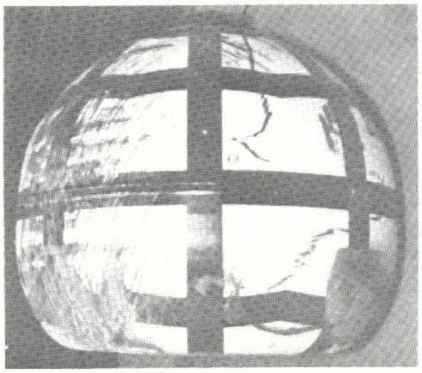


Figure 10. - Passive impact-energy absorbers.

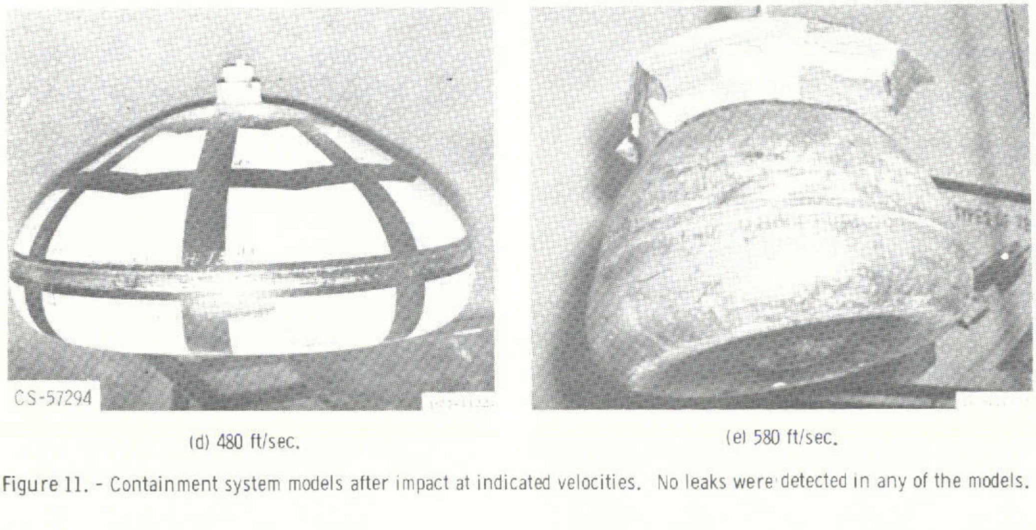


(a) 380 ft/sec.

(b) 412 ft/sec.



(c) 240 ft/sec.



(d) 480 ft/sec.

(e) 580 ft/sec.

Figure 11. - Containment system models after impact at indicated velocities. No leaks were detected in any of the models.

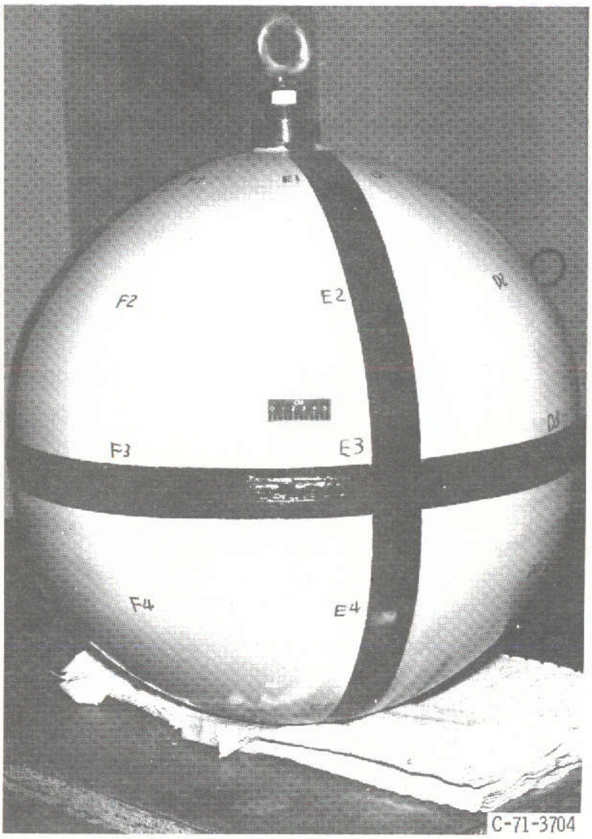


Figure 12(a). - Nuclear containment system - before impact.

Figure 12(b). - Nuclear containment system - after impact at 1055 ft/sec.

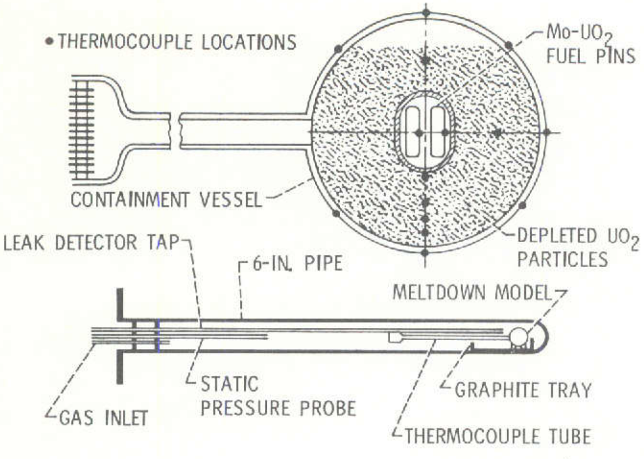


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Figure 13. - Reactor meltdown containment experiment.

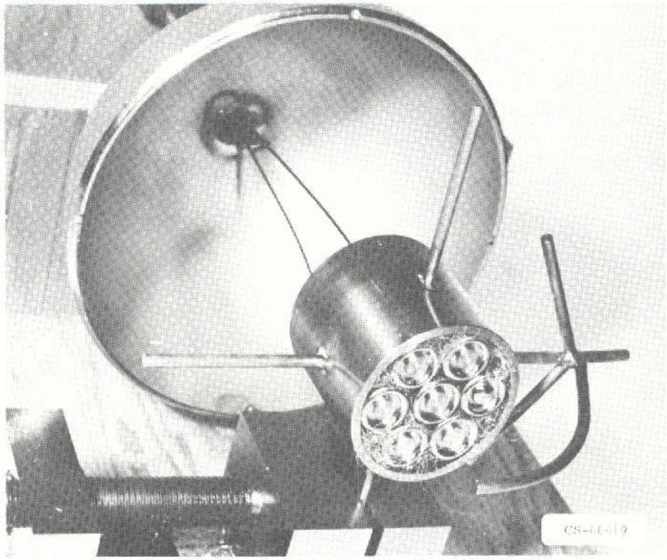

Figure 14. - Reactor meltdown containment apparatus.

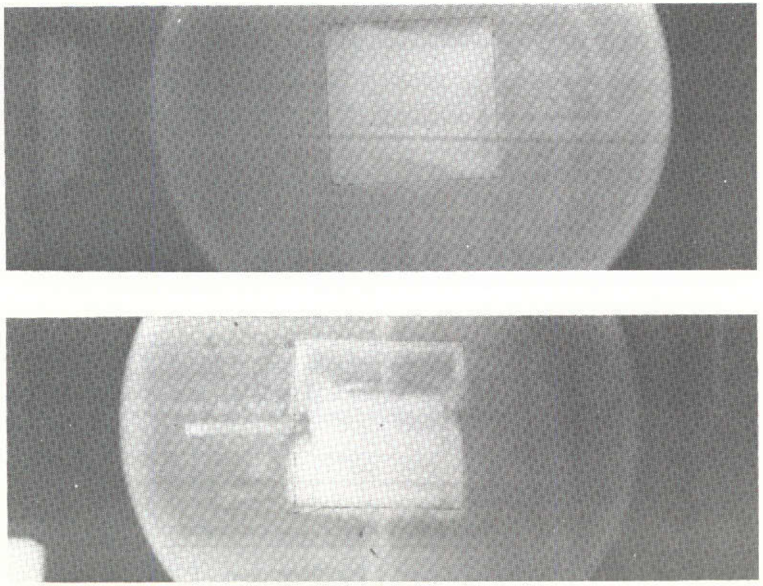

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Figure 15. - Neutron radiograph of meltdown containment apparatus after experiment.

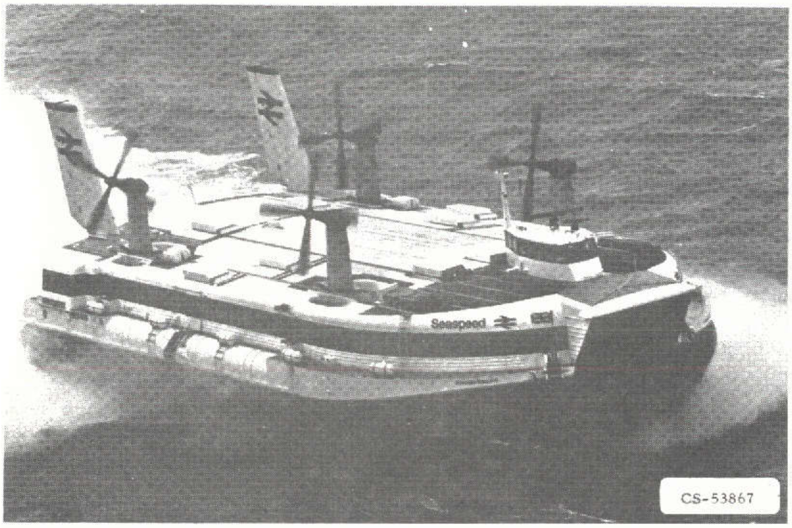

Figure 16. - British Hovercraft LTD. SRN-4 air cushion vehicle.

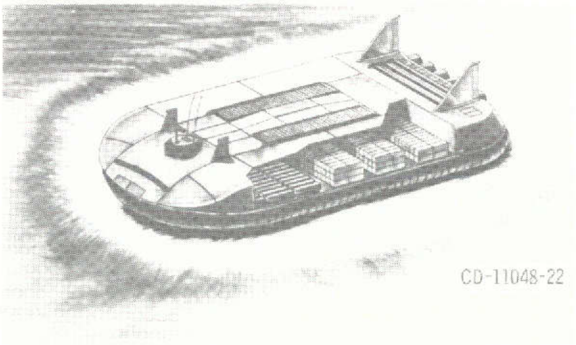

Figure 17. - 4500 Metric ton nuclear ACV freighter.

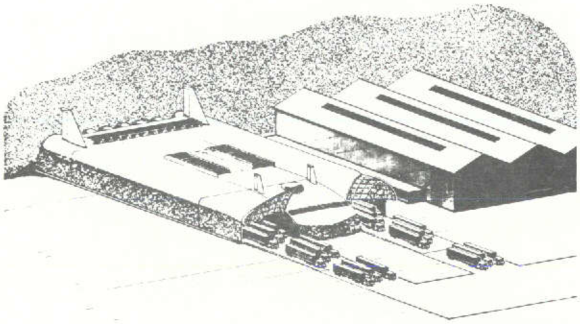

Figure 18. - ACV freighter in roll off cargo transfer mode.

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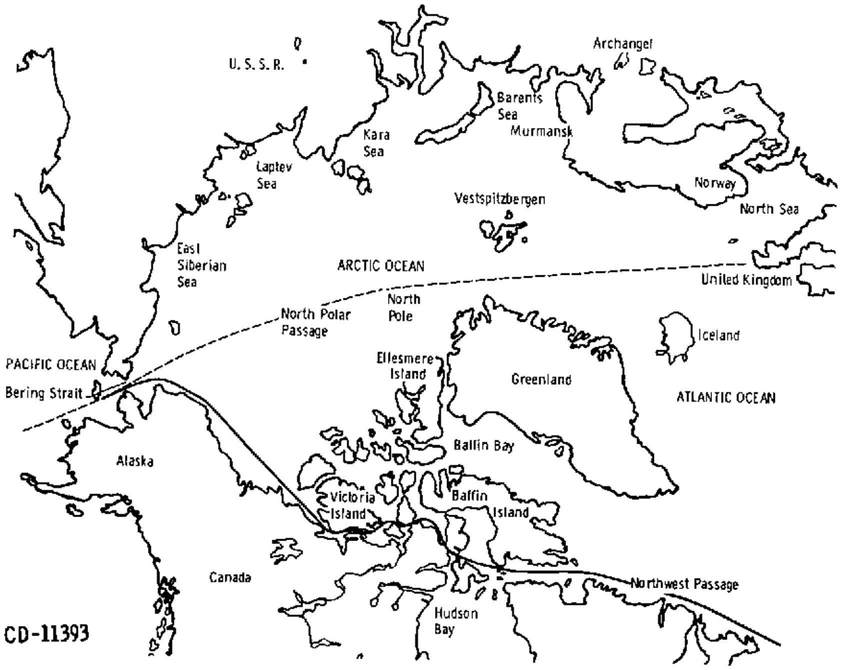

Figure 21. - Air-cushion-vehicle Arctic routes.

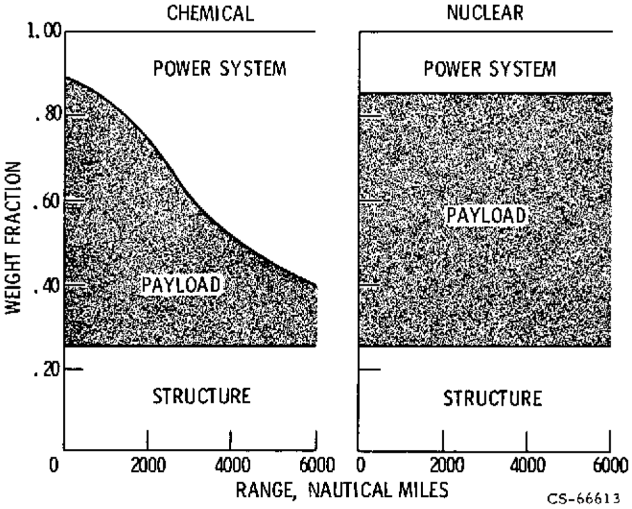

Figure 22. - Payload for 10 000 ton ACV.