NASA TECHNICAL MEMORANDUM

NASA TM X-2425

NASA TM X-2425

AIRBREATHING NUCLEAR PROPULSION — A NEW LOOK

by Frank E. Rom

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1971

1. Report No. NASA TM X-2425	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle AIRBREATHING NUCLEAR PROPULSION - A NEW LOOK		5. Report Date December 1971
		6. Performing Organization Code
7. Author(s) Frank E. Rom		8. Performing Organization Report No. E-6316
		10. Work Unit No. 126-15
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Nuclear-powered air-cushion vehicles using lightweight aircraft-type nuclear powerplants show promise of carrying transoceanic cargo at cost-per-metric-ton-kilometer (cost-per-ton-n mi) rates comparable to railroad rates. These rates are independent of the distance traveled. Cargo rates for nonstop distances of 7420 kilometers (4000 n mi) are expected to be less than one-half those for similar fossil-fueled air-cushion vehicles. For 11 130-kilometer (6000-n mi) nonstop distances, the rates are expected to be less than one-sixth as much. There are no fundamental technical reasons why subsonic nuclear aircraft cannot be made to fly successfully if the gross weight is over 0.45 million kilograms (1 million lb). Public safety of airborne nuclear powerplants is receiving the greatest attention in NASA Lewis Research Center low-level experimental and analytical investigations. Idealized model containment vessels which have been impacted on reinforced concrete showed no leaks after impact at velocities to 640 kilometers per hour (400 mph). The experiments indicate feasibility of impacting at speeds over 960 kilometers per hour (600 mph) with no leaks.

17. Key Words (Suggested by Author(s)) Nuclear propulsion Nuclear airplane Transportation Airbreathing nuclear propulsion Air-cushion vehicle		18. Distribution Statement Unclassified - unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 26	22. Price* $3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

AIRBREATHING NUCLEAR PROPULSION - A NEW LOOK

by Frank E. Rom

Lewis Research Center

SUMMARY

Nuclear-powered air-cushion vehicles using lightweight nuclear powerplants such as those being investigated for nuclear aircraft may be able to achieve transoceanic cargo cost rates per metric ton-kilometer (ton-n mi) comparable to rail transport rates independent of the distance traveled. Cargo rates for 7420 kilometers (4000 n mi) (typical of transatlantic routes) are expected to be less than one-half those for similar fossil-fueled air-cushion vehicles. For 11 130-kilometer (6000-n mi) nonstop distances, the rates are expected to be less than one-sixth as much.

The technical problems associated with providing containment of fission products in the worst conceivable accidents are much easier to solve for nuclear air-cushion vehicles than for nuclear aircraft. This is because (1) the operating speed is much lower, (2) the operation is at zero altitude, and (3) the operation is over water.

There are no fundamental technical reasons why subsonic nuclear aircraft cannot be made to fly successfully providing the aircraft is large enough. The weight of a completely shielded nuclear aircraft reactor varies about as the square root of the reactor power. Hence, the larger the aircraft the less is the weight fraction of the nuclear power system. Aircraft of 0.45 million kilograms (1 million lb) or greater are required to make the payload fraction greater than 15 percent of the gross weight.

The NASA Lewis Research Center is conducting experimental and analytical investigations of the key problems of aircraft nuclear propulsion. The key problems are safety or public acceptance, long life, low weight, and low cost. Most emphasis in this low-level effort is placed on safety. Idealized containment vessel models have successfully survived impacts on reinforced concrete at speeds up to 640 kilometers per hour (400 mph). All five models tested thus far were helium leak tested after impact and found to be leak free. Examination of the containment vessel materials indicates a potential survival impact velocity of 960 kilometers per hour (600 mph).

INTRODUCTION

Nuclear energy offers the possibility of an aircraft that could fly anywhere on the surface of the earth or remain aloft for weeks at a time without refueling. The major obstacle to this accomplishment has been that aircraft have not been large enough to carry the heavy nuclear powerplant required. This, and the fact that it was desired to have supersonic dash capability, was the basic reason that the nation's aircraft nuclear propulsion (ANP) program, a joint project of the Atomic Energy Commission and the Air Force from 1946 to 1961 (ref. 1), was abandoned a decade ago. Since then, the development and introduction into military and commercial service of the Lockheed C-5 and the Boeing 747 aircraft have shown that very large subsonic aircraft weighing almost 0.45 million kilograms (1 million lb) are not only feasible but practical, desirable, and profitable.

Aircraft with gross weights of at least 0.45 million kilograms (1 million lb) are necessary to make nuclear aircraft practical. A practical nuclear aircraft would have complete shielding so that neither the flight and ground crew nor the passengers receive radiation doses significantly greater than that normally received from natural sources. It also would have safety provisions that are designed to prevent the release of radioactive material in the worst aircraft accidents.

Other features are required to make a nuclear aircraft practical. Among these are reactors which will permit long operation (of the order of 10 000 hr) between refuelings, long-life high-temperature oxidation-resistant heat exchangers that heat the air of the turbofan engine, and reliable lightweight long-life pumps and valves that can handle high-temperature heat-transfer mediums which are used to transfer heat to the propulsion engines.

In addition to virtually unlimited range and flight duration, nuclear aircraft may also have an economic attraction. Because energy from nuclear fuel costs only a fraction of that for fossil fuel (see table I), nuclear-powered aircraft could significantly reduce the cost of air transportation. This factor, in addition to the potential economy of construction and operation of very large aircraft, could make air transportation more competitive with transport by truck, rail, and general cargo ships. Inland cites built around large airports could then become new world trade centers. This in turn, should cause a shift in population distribution and urban areas.

The increasing demand for air transportation will require larger and larger aircraft. Aircraft weighing several thousand tons will probably be required to handle the traffic. The larger the aircraft, the more attractive nuclear power becomes. The weight of nuclear powerplants increases approximately as the square root of the power. An aircraft of four times the weight of another requires a powerplant with four times as much power, but the powerplant will be only two times as heavy.

In 1964 a low-level effort to reassess the feasibility of nuclear aircraft was initiated. This current new look (refs. 2 to 4) by NASA and the Air Force was prompted by the fact that aircraft no longer seemed limited to sizes that rule out nuclear powerplants. The goal is to determine whether it may be possible to provide practical and safe nuclear aircraft powerplants that have complete shielding and that will not release fission products in the worst possible aircraft accidents.

Prime attention has been focused on the safety problems. Major aircraft accidents involve impact at high speeds. Such impacts are highly destructive unless special design provisions are made to protect parts such as the reactor containment vessel. Its rupture would allow the escape of radioactive fission products. Means of absorbing kinetic energy during crashes to prevent reactor containment vessel rupture are being investigated.

Another problem is the potential melt-through of the containment vessel after an accident. The heat generated by the decay of the radioactive fission products that are formed from the fissioned uranium atoms continues to be produced even after the reactor is shut down. It amounts to a few percent of the normal reactor power and reduces with time to about 1 percent after a day. In an accident which destroys all normal reactor cooling systems, this afterheat will cause the reactor to increase in temperature and melt. The volatile reactor materials and fission products will form vapors. The vapors will condense in lower temperature regions and, therefore, tend to move toward the relatively cool containment vessel. In so doing, they will, fortunately, distribute themselves uniformly around and near the inside surface of the containment vessel. Work is underway to demonstrate that due to this redistribution of heat sources the afterheat can be removed without melting the containment vessel and without excessive weight penalties.

A limited effort is underway to demonstrate experimentally the feasibility of reactor fuel that can achieve 10 000-hour reactor operation. Experiments are also being carried out to demonstrate the feasibility of long-life oxidation-resistant heat exchangers that are required to heat the air of airbreathing engines.

Recent studies (refs. 2 to 4) suggest that the weight of aircraft nuclear powerplants would be more than an order of magnitude less than that of conventional nuclear marine powerplants. This comes about because nuclear aircraft powerplant designs including reactor, shielding, crash protection, and propulsion machinery are based on a "fight for every pound" philosophy that is used in the aerospace industry. This is to be contrasted to marine powerplant design approach that tends to use existing land based components that are plumbed together with standard pipes and fittings with no regard for weight at all. This feature makes the aircraft-type airbreathing nuclear propulsion system look extremely attractive for propulsion of ocean-going air-cushion vehicles (refs. 5 and 6). For large air-cushion vehicles, the nuclear powerplant would become only a small fraction of the gross weight (less than 10 percent). This manifests itself as a large payload capacity that is independent of range at the vehicle's top speed. The problem of crash protection is greatly simplified when compared to those for aircraft because the vehicle speeds are low and the vehicle flies at zero altitude. Because of these attractive features, nuclear-powered air-cushion vehicles are currently receiving greater attention. A recent cost study (ref. 7) indicates the potential for transoceanic commerce at rates equivalent to railroad rates.

The purpose of this report is to present the most significant results of the investigations that are now underway to determine the potential feasibility of safe, practical, and economically desirable airbreathing propulsion systems for aircraft and air-cushion vehicles.

DESCRIPTION OF NUCLEAR AIRBREATHING PROPULSION SYSTEM

Figure 1 is a schematic drawing of a typical nuclear aircraft or air cushion vehicle powerplant that incorporates shielding and safety provisions. The fissioning uranium releases energy within the reactor. A heat-transfer medium such as high-pressure helium flows through passages in the hot reactor and picks up the fission-generated heat. The hot helium is then ducted to helium-to-air heat exchangers located upstream of the conventional combustors of ordinary turbofan engines. The air that is heated in flowing through the heat exchangers expands through turbines which drive the compressors and fans. Propulsive thrust is provided by the fan airflow. The turbofan engines can be operated either on nuclear power and/or by combustion of kerosene.

The reactor is surrounded by various layers of material constituting shielding, containment vessel, impact-energy-absorbing material, and melt-through protection material. The gamma shielding consists primarily of multiple layers of heavy material such as lead, uranium, or tungsten. The containment vessel acts as a portion of the gamma shield. The neutron shielding is composed of relatively light materials with high hydrogen-atom concentration: water, lithium hydride, and organic solids or liquids, for example. The use of organic materials like plastic or fossil fuel would be limited to the outer shield layers, where the radiation levels are sufficiently low to avoid radiation damage.

During an impact with the earth, the containment vessel and shield materials are designed to absorb the kinetic energy of the reactor and shield assembly without rupturing the containment vessel. For example, the outer shield can be made of material that can absorb kinetic energy as it deforms during the impact. Figure 2 shows the principles of a mobile reactor containment system. A portion of the gamma and neutron shield can be made of refractory materials such as uranium dioxide pebbles, which provide insulation that prevents molten materials from melting through the containment vessel. Shield materials thus serve not only as shielding, but also as melt-through protection, impact-energy absorbers, and containment vessel. Because materials are used to perform multiple functions, substantial weight savings are obtained.

IMPORTANT RESULTS OF NASA STUDIES

The most significant results that have been obtained in the NASA study of mobile airbreathing nuclear powerplants are summarized in this section. Results are presented in the areas of shielding, long-life reactor fuel, long-life heat exchangers, and high-speed-impact and reactor-meltdown-containment safety studies.

Shielding

Complete 4π steradian (unit or 4π) shielding should enclose the reactor to reduce the dose levels to allowable levels in all directions. In the Lewis studies the shields are designed for a dose rate of 0.25 millirem per hour at 9.15 meters (30 ft) from the reactor centerline. At this rate it would take an exposure of 2000 hours to receive the dose normally received on the earth's surface from natural sources. At further distances from the reactor, the dose rate is reduced approximately as the square of the distance. When the reactor is shut down, the dose levels will, of course, be very much lower. There is, therefore, no restriction to movement within or outside the aircraft either when the aircraft is flying or when it is on the ground.

Shield weights that we have calculated for uranium-water shields are shown in figure 3. The shield weight increases at a rate less than the square root of the reactor power. For reactors in the power range of 200 to 400 megwatts, the shield weights vary from about 159 000 to 204 000 kilograms (350 000 to 450 000 lb) for a reactor power density of 176.5 watts per cubic centimeter (5 MW/ft^3). These are typical of the powers, power densities and shield weights for aircraft in the range of gross weight from 0.45 to 0.91 million kilograms (1 to 2 million lb). Shield weights are thus of the order of 15 to 35 percent of the gross weight for this gross weight range. The Monte Carlo code which we are now using to determine weights of optimized shields is described in references 8 and 9. Other codes and calculation of shields are given in references 10 to 13.

Shielding weight appears to be acceptable as long as aircraft gross weights are greater than 0.45 million kilograms (1 million lb). Of course, reducing shield weight by further optimization of shield materials and their distribution will allow increases in payload weight, and is worth working for. But, a more important point is that the necessity for shielding does not prevent the nuclear aircraft from being feasible, as long as the aircraft is large enough.

Long-Life Reactor Fuel

NASA has proposed the use of a fuel-tube concept which can achieve 20 percent burnup or higher (ref. 14). High burnup fuel tubes are required for long life, minimum size reactors, and for safety considerations that are discussed in a later section. It is a relatively simple approach that accepts in a conservative way well-known facts about fuel behavior. Figure 4(a) is a schematic drawing of this fuel-tube concept. As described in reference 3, it does not use any physical principles or ideas which have not previously been though of. The fuel tube is designed as a pressure vessel. Fuel is contained within the tube 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 tube wall so that when the fuel swells or expands due to the buildup of fission products within it, the fuel will flow plastically into the central void without introducing a major stress in the tube material. The void also provides room for the gaseous fission products to expand. The void is designed large enough so that at the desired burnup level the fission gas pressure can be held by the strong tube wall material. We are currently conducting in-pile experiments in the Plum Brook Reactor to verify the concept for aircraft and air-cushion-vehicle use. The experiments are being conducted at the pressure levels, temperatures, power densities, heat fluxes, and neutron fluxes that would be characteristic of aircraft reactors.

A summary of recent results of long-life fuel-tube experiments now in progress is shown in table II. The data are compared with what is desired for a 10 000-hour aircraft reactor and with what is current practice in commercial electric-power-producing reactors. The quantities compared are the fuel-tube surface temperature, the fuel-tube power per unit tube volume, the fuel-tube total energy release per unit volume, and the fuel-tube energy equivalent in cubic meters (gal) of gasoline for a tube 1.40 centimeters (0.55 in.) in diameter and 1.22 meters (48 in.) long. The desired operating conditions for a 10 000-hour propulsion reactor are fuel-tube temperature, 1255 K (1800° F); fuel-tube power, 0.5 kilowatt per cubic centimeter; and total energy release, 8300 kilowatt-hours per cubic centimeter, which is the equivalent of 189.25 cubic meters (50 000 gal) of kerosene per tube. Commercial reactors operate with tube surface temperatures of about 590 K (600° F), with about the same power density as desired for aircraft and air-cushion reactor fuel tubes, but with about two-thirds of the total energy release. In the UO_2-TZM fuel-tube test three tubes much as shown in figure 4(b) are now operating at 1422 K (2100° F) with a power density of about five times that required for the propulsion reactor. This is an accelerated test so that data can be obtained in about one-fifth the time. The fuel tubes have already obtained a total energy release of 6000 kilowatt-hours per cubic centimeter, which is equivalent to more than 70 percent (about 7300 hr) of desired propulsion reactor operation at a surface temperature 167 K

(300 F°) in excess of that desired. Three UN-TZM fuel tubes are also operating at 1422 K (2100° F). They are operating at about three times the desired power density for propulsion reactors. The total energy release obtained to date is also more than one-half of the desired value. These tubes, as well as the UO_2-TZM tubes, are expected to operate for longer than the equivalent of 10 000 hours desired for the propulsion reactor.

Long-Life Heat Exchangers

In aircraft nuclear systems the heat from the reactor is transferred by means of a heat-transfer fluid to a heat exchanger which transfers the heat to the air of a jet engine. In the case of a high-pressure helium system, the high-pressure helium gas transfers heat to the air of the turbofan engine. The heat-exchanger material limits the turbine inlet temperature that can be achieved in a nuclear powerplant that operates on nuclear power alone. The heat-exchanger material must be an oxidation resistant and strong high-temperature material. In the case of liquid-metal systems, the heat-exchanger material must also be compatible with the liquid metal used.

We have carried out an experimental program aimed at determining the capability of helium-to-air heat-exchanger materials. We have been performing two kinds of tests. One kind of test involves determination of the creep properties of high-temperature oxidation-resistant materials for fuel tubes. We have tested many such materials. The most suitable available material we have found so far is N-155 alloy (ref. 15). It is a ductile material that can be welded, worked, and machined readily. It allows operation of high-pressure helium-to-air heat-exchanger tubes at temperatures of the order of 1089 to 1144 K (1500° to 1600° F).

We have also done experiments on header configurations. The high-pressure gas heat exchangers we envision would be composed of high-pressure helium headers which have closely spaced heat-exchanger tubes welded into them. A picture of one header design for which we made a representative section for tests is shown in figure 5. This header-and-tube section was designed to operate for 1500 hours at a pressure of 10.35×10^6 newtons per square meter (1500 psi) and a temperature of 1089 K (1500° F). It actually ran for more than 5000 hours before it failed. The limited amount of heat-exchanger work we have done has been adequate to determine design stresses and to verify header design techniques. It remains to be shown, however, that whole heat exchangers or representative sections of a heat exchanger will perform reliably for the lifetimes we predict when exposed to the complete environmental conditions that would exist in an airplane. This involves investigation of thermal cycling, vibration, and thermal expansion problems.

Other Long-Life Components

Because of the limited effort we have not been able to do much work in many areas that would require attention if nuclear airplanes were considered for development. These areas involve 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, and auxiliary systems such as for afterheat cooling. The airbreathing portion of the 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 required to determine the feasibility of fast-acting valves that are necessary to seal off coolant lines and other penetrations into the containment vessel during a major aircraft accident. Detailed overall powerplant conceptual designs are required to arrive at realistic weight estimates of the entire system. They would also provide base points for realistic parametric and optimization studies that are required for mission analyses.

Recent Safety Studies

For the past several years various concepts have been studied for safely impacting reactor systems at high speeds such as could occur in major aircraft accidents. References 2 to 4 discuss this work. During the early phases of the present study, impact systems employing energy-absorbing frangible tubes were investigated (ref. 16). They were found to be limited to providing impact protection for impact velocities to 91.5 to 122. meters per second (300 to 400 ft/sec). Recently another approach utilizing the energy absorption capability of plastically deforming shells has shown promise for impact protection 305 meters per second (1000 ft/sec). The first NASA studies of this technique are published in references 17 to 19. Work has begun on the problem of reactor coolant loss and afterheat removal in the event of a major aircraft accident.

Figure 2 shows the reactor containment concept that is being investigated at present. The reactor core is surrounded by shield material that is formed into geometrical shapes that act as energy-absorbing material. The gamma shielding, which is typically a heavy metal such as depleted uranium, would be made in the form of a honeycomb or some similar shape that would absorb energy on impact by deformation. Water is used as a neutron shield material. The water will also serve to absorb energy because the high hydraulic pressure generated during impact causes the containment vessel to stretch and thereby absorb energy. The containment vessel is made of a ductile high-strength material. It absorbs the energy as it is plastically deformed during impact. Surrounding the containment vessel is an energy-absorbing neutron shield. It can be envisioned as a plastic material formed so that on impact the deformation and plastic flow of this material will absorb some of the kinetic energy of the impacting reactor system.

Uranium dioxide in the form of a layer of granular particles is placed on the inside of the containment and reactor vessel. The uranium dioxide acts as an insulating material that causes the reactor core material to melt down in the event of a major accident in which all normal reactor cooling systems are destroyed. Core meltdown and the flow of heat to the containment vessel surface causes the decaying fission-product heat sources to be uniformly distributed throughout the inside of the containment vessel by vapor transport. Vapor transport from the molten material tends to cause vapors to condense in uniform concentric shells in the uranium dioxide insulation bed. This in turn tends to provide a relatively uniform heat flux to the outside of the containment vessel. The heat flux must be fairly uniform in order that the containment vessel can be cooled by convection and radiation to the atmosphere without hot spots. The containment vessel is made large enough so that its temperature will stay within the limits of the strength of the containment vessel material. The uranium dioxide granules, besides providing this insulation, are also a good gamma shield.

Two experimental programs aimed at demonstrating these containment principles work are being conducted.

Meltdown experiment. - The first is a reactor meltdown containment experiment (fig. 6). It is a test of a reactor model within a containment vessel containing uranium dioxide insulating material. The model is 12.7 centimeters (5 in.) in outside diameter. The reactor model contains molybdenum uranium dioxide fuel tubes. Fission heating causes the fuel to melt. The tests are conducted in NASA's Plum Brook Reactor Facility. The containment vessel is designed to operate at a temperature of the order of 973 to 1033 K (1300° to 1400° F). When the fuel material melts, it is predicted that the fuel and fission products will be redistributed in layers as they condense within the insulating uranium dioxide particles. Calculations indicate that the containment vessel will not melt through. The first two models are being tested in the Plum Brook reactor.

Impact tests. - A schematic drawing that describes the models that were used to demonstrate the newest impact-energy-absorption principles is shown in figure 7. The containment vessel is formed of a ductile, high-strength material so that, when deflection occurs, plastic flow absorbs kinetic energy. The containment vessel is surrounded by an energy-absorbing neutron shield material such as a plastic honeycomb. The reactor vessel model is located in the center. In the first tests, an iron ball was used to simulate the reactor. Between the reactor vessel and the containment vessel, there is an inner shield and energy absorber. This inner shield material would be fabricated of depleted uranium or other gamma shield material pieces in the real reactor. In the test models, carbon steel was used in place of shield material such as uranium for economy reasons. These models have been impacted with a concrete block at speeds up to about 183 meters per second (600 ft/sec). Figure 8 shows the test setup that is being used. The impact model shown is 0.61 meter (2 ft) in diameter. It is mounted on a styrofoam block between the rails of a rocket sled facility. The rockets accelerate the 1.37-meter (4.5-ft) cube concrete block that weighs 7.13 metric tons (7.5 tons) to the desired impact speed. Surplus 12.7-centimeter (5-in.) HVAR rockets are used to accelerate the concrete block. The cage in front of the block serves to catch the ball after impact. High-speed motion pictures are taken during the impact. A motion picture that summarizes the test results is available from Mr. Richard Puthoff of the Lewis Research Center. Figure 9 is a sequence of frames from this motion picture illustrating the impact of a model at 126 meters per second (413 ft/sec). The large amount of deflection that the containment vessel undergoes is readily visible. Figure 10, taken after the five impact tests that have been run to date, shows this more clearly. The vessels were leak tested after the tests. No leaks were found. In other words, no fission products could have escaped had there been fission products within these vessels. The results of two of these tests are reported in reference 19.

In the third test (fig. 10(c)) a misfire occurred that allowed the model to escape from the cage after impact with the concrete. The secondary impacts due to bounding along the countryside and destroying a utility stanchion alongside the track were shown to be of no consequence as far as damaging the containment vessel was concerned. The picture indicates that the secondary bounces merely scratched the surface. The primary impact at about 79.3 meters per second (260 ft/sec) flattened one side slightly.

Figure 11 shows the effect on the concrete block and rocket sled of impacting the containment system model at 177 meters per second (580 ft/sec) (~640 km/hr, ~400 mph). The containment system model weighed about 545 kilograms (1200 lb) and was 96.5 centimeters (38 in.) in diameter.

It appears from the preliminary measurements of the deformations that occurred that models of this type should be able to withstand impacts of 305 meters per second (1000 ft/sec). It is anticipated therefore that it will be possible to design impact systems that will contain fission products to speeds of 305 meters per second (1000 ft/sec) (1090 km/hr, 680 mph).

APPLICATION STUDIES

Preliminary cost studies have been and are being made of air-cushion vehicles and large subsonic aircraft powered with mobile nuclear airbreathing propulsion systems. The studies are aimed primarily at determining whether there is a possibility that such vehicles are commercially attractive. The development cost is not included in the study. It is assumed that a sufficiently large number of vehicles will be required so that the development cost charged per vehicle is not an important cost factor.

Figure 12 gives the preliminary results of the operating cost study for 9050 metric-ton (10 000-ton) air-cushion vehicles (ACV). The total operating cost in dollars per metric ton-kilometer (ton-n mi) is shown as a function of speed in kilometers per hour (knots). Chemical ACV's are shown by the solid lines for ranges of 3710, 7420, and 11 130 kilometers (2000, 4000, and 6000 n mi). The performance of the nuclear vehicle is independent of range. Air-cushion vehicles are well suited for transportation in the vicinity of 100 knots and perhaps higher. The nuclear ACV shows operating costs less than 1.2 cents per metric ton-kilometer (2 cents per ton-n mi). Chemical systems operate in the vicinity of 2.4 cents per metric ton-kilometer (4 cents per ton-n mi) for transoceanic ranges 7420 kilometers (4000 n mi) or greater.

The ACV increases the cargo transportation speed from the 27.7 to 55.5 kilometers per hour (15 to 30 knots) of today's ships to 185 kilometers per hour (100 knots). It may be possible to attain rates of about 1.2 cents per metric ton-kilometer (2 cents per ton-n mi) operating cost if nuclear power is used.

It theoretically would take a fleet of about three thousand 4520-metric-ton (5000-ton) ACV's (fig. 13) to handle 10 percent of the total predicted world trade in 1980. Ten percent is assumed to be the fraction of world trade that could be economically shipped if shipping costs were about 1.2 cents per metric ton-kilometer (2 cents per ton-n mi). These figures do not reflect the additional cargo traffic that might be attracted by the higher speed transportation system.

Figure 14 shows the total operating cost for chemical and nuclear aircraft with a gross weight of 905 metric tons (1000 tons). Chemical aircraft performance is indicated by solid lines for ranges of 3710, 7420, and 11 130 kilometers (2000, 4000, and 6000 n mi). Nuclear aircraft performance is also shown. The nuclear airplane can carry cargo for a cost of 2.4 to 3.0 cents per metric ton-kilometer (4 to 5 cents per ton-n mi) at speeds of 740 to 832 kilometers per hour (400 to 450 knots). For ranges 9250 kilometers (5000 n mi) or higher, the nuclear aircraft can haul cargo at a lower cost than the chemical aircraft for the particular assumptions used in the preparation of this figure.

Figure 15 shows the effect of increasing the aircraft gross weight to 3620 metric tons (4000 tons). A very noticeable reduction in operating cost is noted. This reduction is due to anticipated lower unit airframe costs of larger sizes, and for nuclear aircraft the lower fraction of gross weight required for shielding. The 3620-metric-ton (4000-ton) nuclear airplane is shown to be competitive with chemical airplanes for ranges greater than 5555 kilometers (3000 n mi). The operating cost is of the order of 1.2 cents per metric ton-kilometer (2 cents per ton-n mi) at speeds to 925 kilometers per hour (500 knots). As previously stated, rates such as these are typical of rail transportation. The transoceanic commerce that theoretically could be attracted by such a transportation system, if it were developed, would require a fleet of about five hundred 3620-metric-ton (4000-ton) aircraft in 1980 and one thousand by the year 2000. In addition, speeds 10 times that for ships may attract substantial additional demand that is not accounted for in the trade forecast.

CONCLUDING REMARKS

There are no fundamental technical reasons why subsonic nuclear aircraft cannot be made to fly successfully providing the aircraft is large enough. The weight of shielding increases with a rate somewhat less than the square root of the reactor power (or aircraft gross weight). Hence, the larger the aircraft, the smaller is the fraction of its weight that is required for shielding, and the larger will be the payload fraction. Shielding that gives dose levels in the aircraft less than normal background doses from cosmic radiation requires that the aircraft be at least 0.45 million kilograms (1 million lb) in gross weight to maintain about 15 percent of its weight as payload. Aircraft of this size are not a great extrapolation from the 747 and C-5 which are about 340 000 kilograms (750 000 lb) in gross weight. Reactor, heat-transfer, material, and propulsion technology is sufficiently well advanced so that adequate thrust to propel large subsonic aircraft can be developed with large turbofan engines through normal engineering development.

The major obstacle to overcome is the problem of public safety in major aircraft accidents. The successful achievement of practical, publicly acceptable, nuclear-powered aircraft requires the solution to the problem of containing radioactive fission products during a major high-speed aircraft accident. An experimental investigation of techniques for prevention of reactor containment vessel rupture during impact has shown very encouraging first results. Models have been successfully impacted at speeds to 640 kilometers per hour (400 mph) with no post-impact leaks in the containment vessel. Analysis of the experimental data indicates that impacts at velocities in excess of 960 kilometers per hour (600 mph) without vessel rupture may be possible. Of course, much work would have to be done to reduce the principles demonstrated to practice.

The safety problems of reactors for air-cushion vehicles are small compared to those for aircraft because of the lower speeds of travel and because they would travel on the surface of the earth and mainly over water. Nuclear-powered air-cushion vehicles are, therefore, potentially much closer to practical application. The experience gained in design, construction, and operation of large nuclear-powered air-cushion vehicles could pave the way for very large nuclear aircraft if they continue to appear economically sound and as the safety problems are solved.

The preliminary results of this simple and preliminary cost analysis indicate that nuclear air-cushion vehicles should be considered more carefully to verify the apparent good economical performance predicted by this simple study.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 3, 1971,
126-15.

REFERENCES

1. Comptroller General of the United States: Review of Manned Aircraft Nuclear Propulsion Program - Atomic Energy Commission and Department of Defense. Report to the Congress of the United States, GAO, Washington, D.C., Feb. 1963.
2. Rom, Frank E.: Status of the Nuclear Powered Airplane. J. Aircraft, vol. 8, no. 1, Jan. 1971, pp. 26-33.
3. Rom, Frank E.; and Finnegan, Patrick M.: Will the Nuclear-Powered Aircraft Be Safe? Aeronautics and Astronautics, vol. 6, no. 3, Mar. 1968, pp. 32-40.
4. Rom, F. E.: The Nuclear Powered Airplane. Tech. Rev., vol. 72, no. 2, Dec. 1969, pp. 48-56.
5. Rom, Frank E.; and Kascak, Albert F.: The Potential of Nuclear Power for High-Speed Ocean-Going Air-Cushion Vehicles. NASA TM X-1871, 1971.
6. Rom, Frank E.: Nuclear Power for Surface Effect Vehicles and Aircraft Propulsion. Paper 70-1221, AIAA, Oct. 1970.
7. Rom, Frank E.; and Masser, Charles C.: Nuclear-Powered Air-Cushioned Vehicles for Transoceanic Commerce. NASA TM X-2293, 1971.
8. Jordan, T. M.: FASTER-III, A Generalized-Geometry Monte Carlo Computer Program for the Transport of Neutrons and Gamma Rays. Rep. ART-45, vol. 1, ART Research Corp., Dec. 1970.
9. Jordan, T. M.: FASTER-III, A Generalized-Geometry Monte Carlo Computer Program for the Transport of Neutrons and Gamma Rays. Rep. ART-45, vol. 2, ART Research Corp., Dec. 1970.
10. Wohl, Millard L.; and Schamberger, Robert D.: Check of a Three-Dimensional Reactor Shielding Code by Comparison with ML-1 Reactor Experiment. NASA TM X-1956, 1970.

11. Wohl, Millard L.; and Jordan, Thomas M.: Fast Neutron Scattering in Helical Ducts. NASA TM X-52725, 1969.

12. Wohl, Millard L.; and Jordan, Thomas M.: Use of "FASTER" Code for Significantly Reducing Ducted Reactor Shield Computation Time. NASA TM X-1828, 1969.

13. Troubetzkoy, Eugene S.; and Wohl, Millard L.: UNAMIT: A One-Dimensional 4 pi Spherical Multilayer Reactor-Shield-Weight Optimization Code. NASA TM X-2048, 1970.

14. Rom, Frank E.; Finnegan, Patrick M.; and McDonald, Glen E.: Very-High-Burnup Vapor-Transport Fuel-Pin Concept for Long-Life Nuclear Reactors. NASA TN D-4860, 1968.

15. Morris, Richard E.: Creep-Rupture Data for Welded N-155 Tubes. NASA TN D-5195, 1969.

16. Puthoff, Richard L.; and Gumto, Klaus H.: Parametric Study of a Frangible-Tube Energy-Absorption System for Protection of a Nuclear Aircraft Reactor. NASA TN D-5730, 1970.

17. Morris, Richard E.: Permanent Impact Deformation of Spherical Shells. NASA TM X-2067, 1970.

18. Morris, Richard E.: Emperical Correlation of Small Hollow Sphere Impact Failure Data Using Dimensional Analysis. NASA TM X-52874, 1970.

19. Puthoff, R. L.; and Dallas, T.: Preliminary Results of 400 ft/sec Impact Tests of Two 2-Foot Diameter Containment Models for Mobile Nuclear Reactors. NASA TM X-52915, 1970.

TABLE I. - FOSSIL AND NUCLEAR FUEL COST

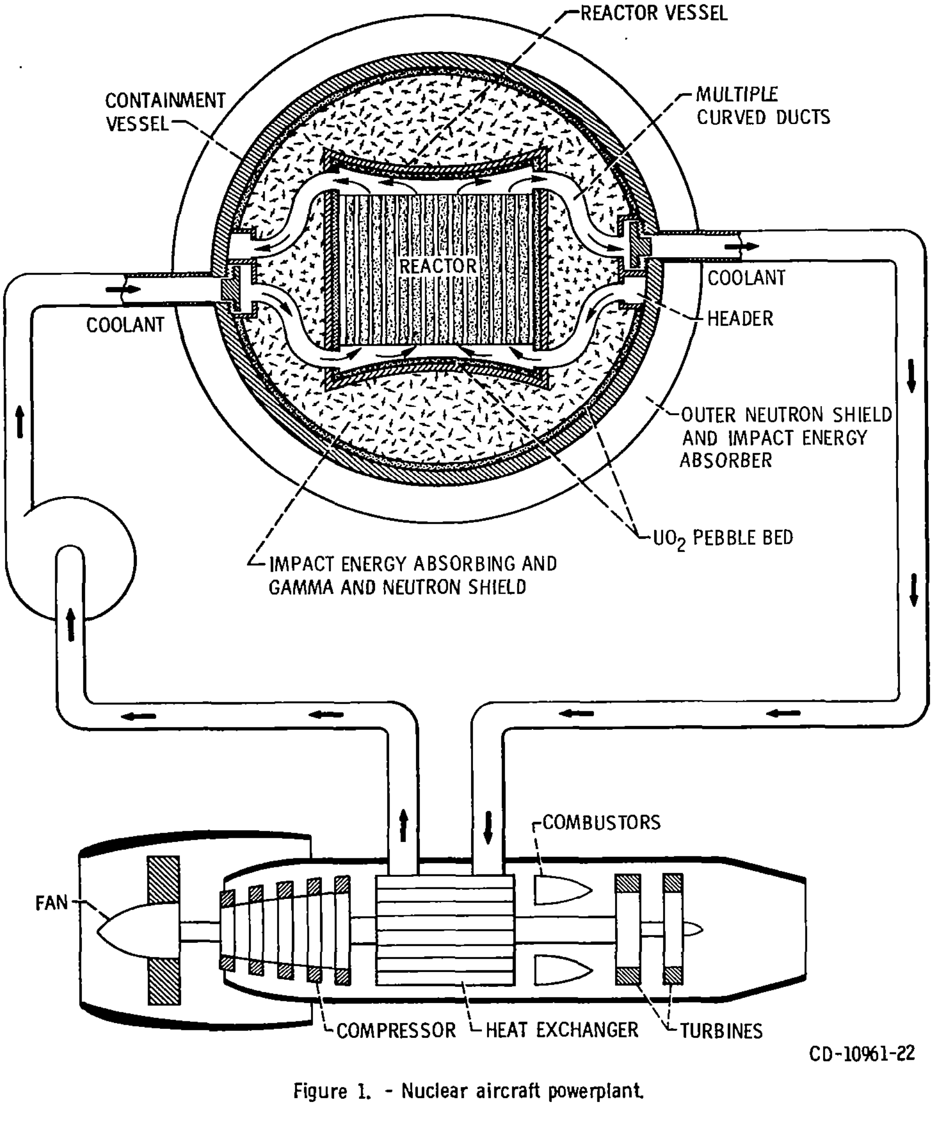
	Unit cost		Cost, dollars per 10^9 J	Cost, dollars per 10^6 Btu
	SI units	U.S. customary units		
Marine fuel	1.57¢/liter	$2.50/bbl	0.370	0.39
Aviation fuel	2.1¢/liter	8¢/gal	.588	.62
Nuclear fuel	$12/g	$34/oz.	.152	.16

TABLE II. - LONG-LIFE-FUEL-TUBE TESTS (PLUM BROOK REACTOR FACILITY)

	Required for 10 000-hr propulsion reactor	Commercial power reactor practice	UO_2-TZM fuel-tube test	UN-TZM fuel-tube test
Fuel-tube temperature, K (°F)	1256(1800)	589(600)	1422(2100)	1422(2100)
Fuel-tube power, kW/cm^3	0.3	0.5	2.3	1.7
Total energy release, $kW\text{-}hr/cm^3$	8300	5000	[a]6000	6700
Equivalent gallons of kerosene per tube[b]	50 000	30 000	36 000	40 000

[a] Test in progress; data as of 7/8/71.

[b] Fuel tubes 1.40 cm in diam by 1.22 m long (0.55 in. by 48 in.); 4000 required for 300-MW reactor.



CD-10961-22

Figure 1. - Nuclear aircraft powerplant.

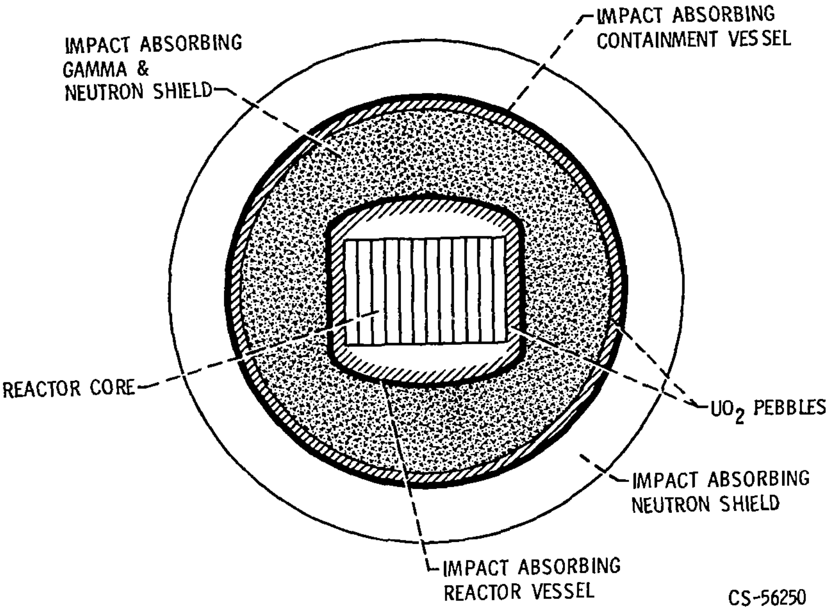


Figure 2. - Principles of mobile reactor containment system.

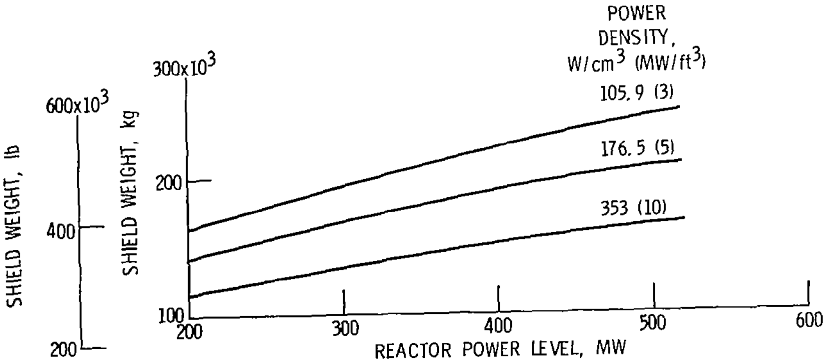
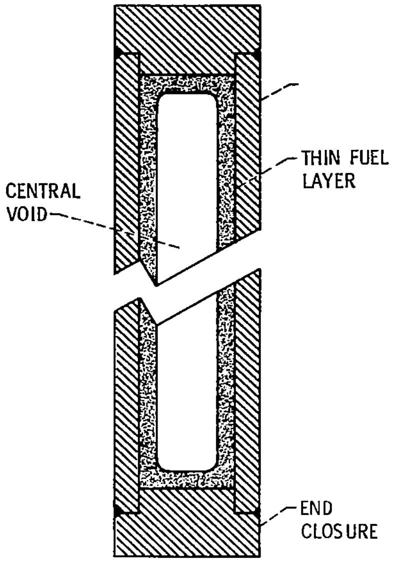
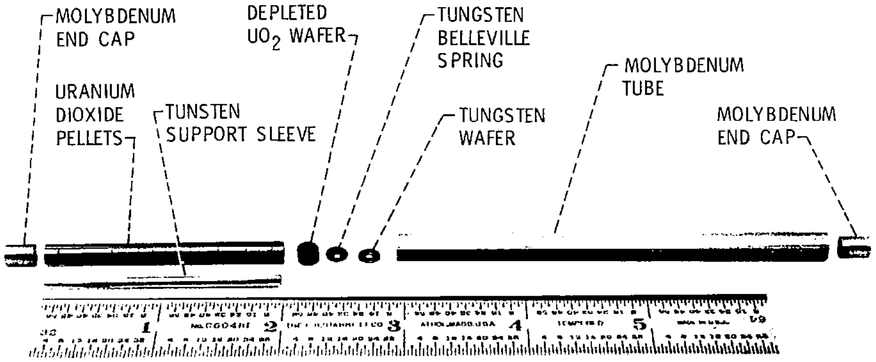


Figure 3. - Depleted uranium-water shield weights. Dose rate, 0.25 millirem per hour at 10 meters (30 ft) from reactor center.

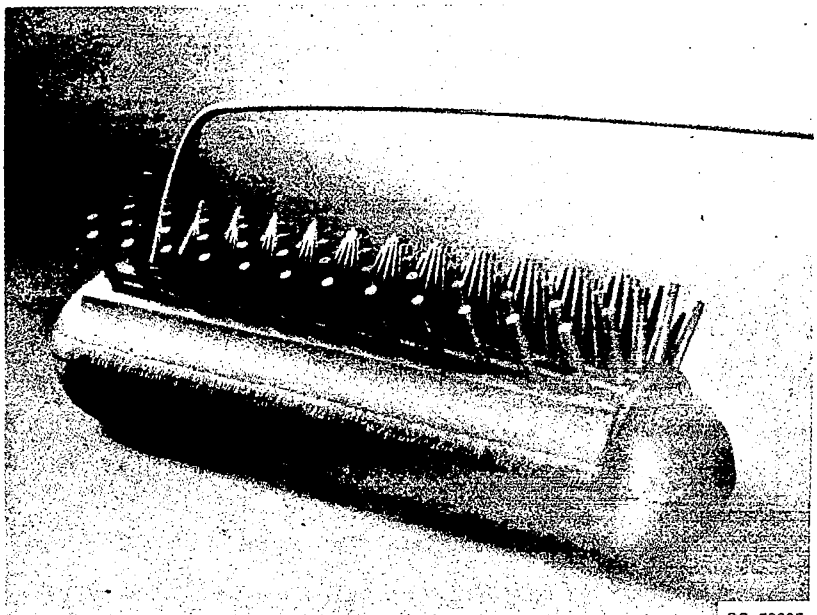


(a) Schematic of concept.



(b) Components for high-temperature fuel tubes containing UO_2 pellets.

Figure 4. - Long-life fuel tubes.



CS-50005

Figure 5. - Test of high-pressure helium-to-air heat-exchanger header. Test temperature, 1117 K (1550° F); helium pressure, 10.35×10^6 newtons per square meter (1500 psi); design life, 1500 hours; actual test life, 5709 hours.

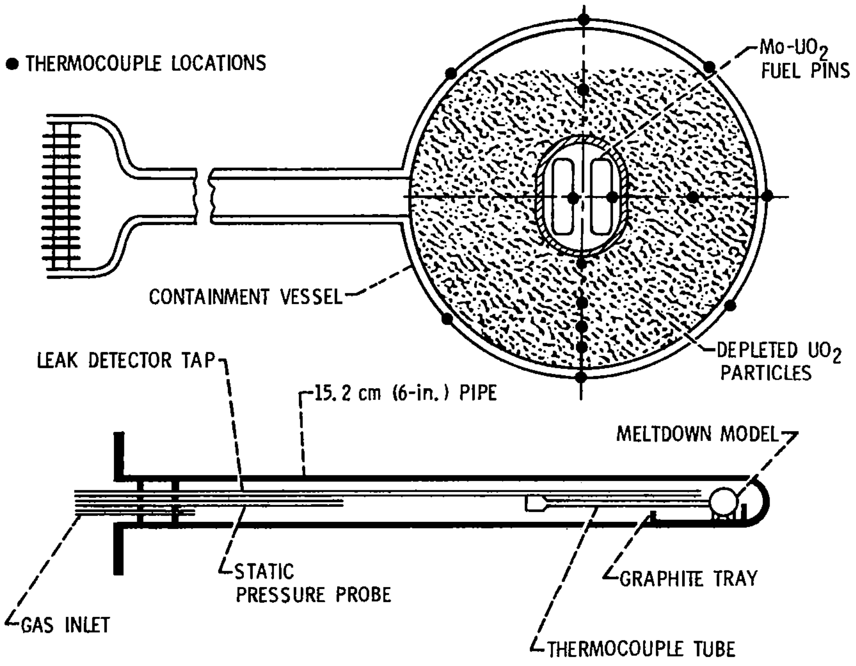
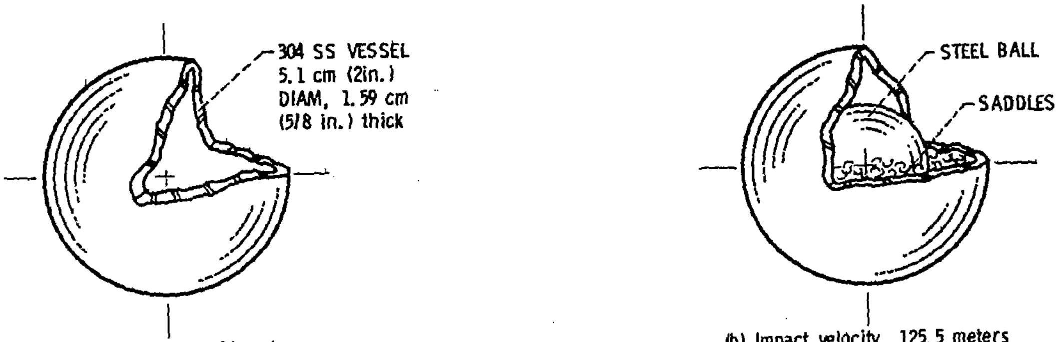


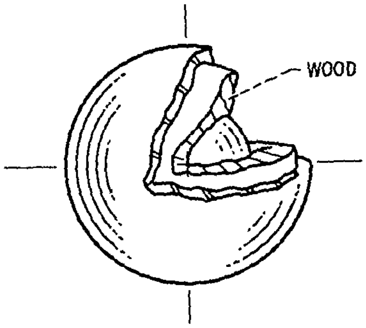
Figure 6. - Reactor meltdown containment experiment.

CS-53861

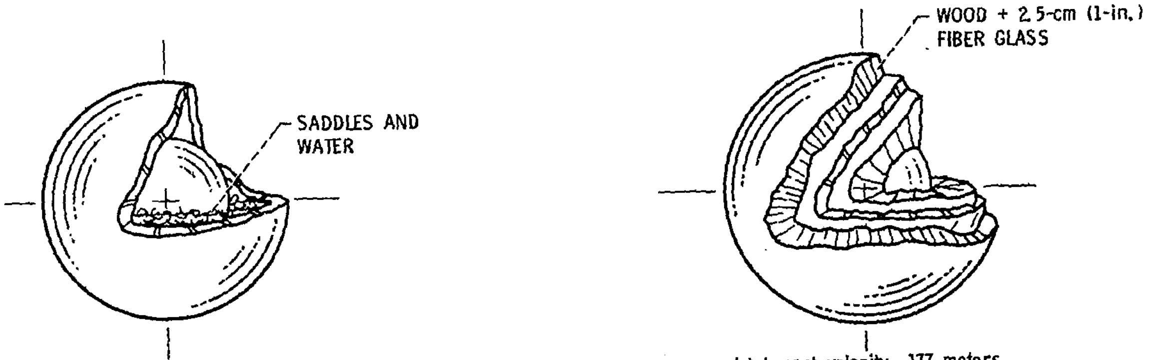


(a) Impact velocity, 116 meters per second (380 ft/sec).

(b) Impact velocity, 125.5 meters per second (412 ft/sec).



(c) Impact velocity, 73 meters per second (240 ft/ sec).



(d) Impact velocity, 146 meters per second (480 ft/sec).

(e) Impact velocity, 177 meters per second (580 ft/sec).

Figure 7. - Sketches of containment system models before impact at indicated velocities.

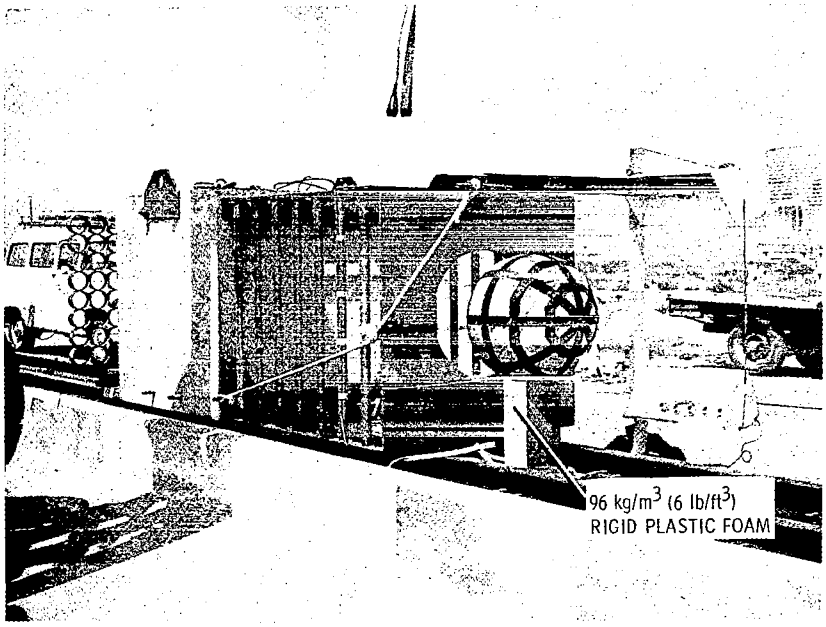


Figure 8. - Rocket sled and containment system model test.

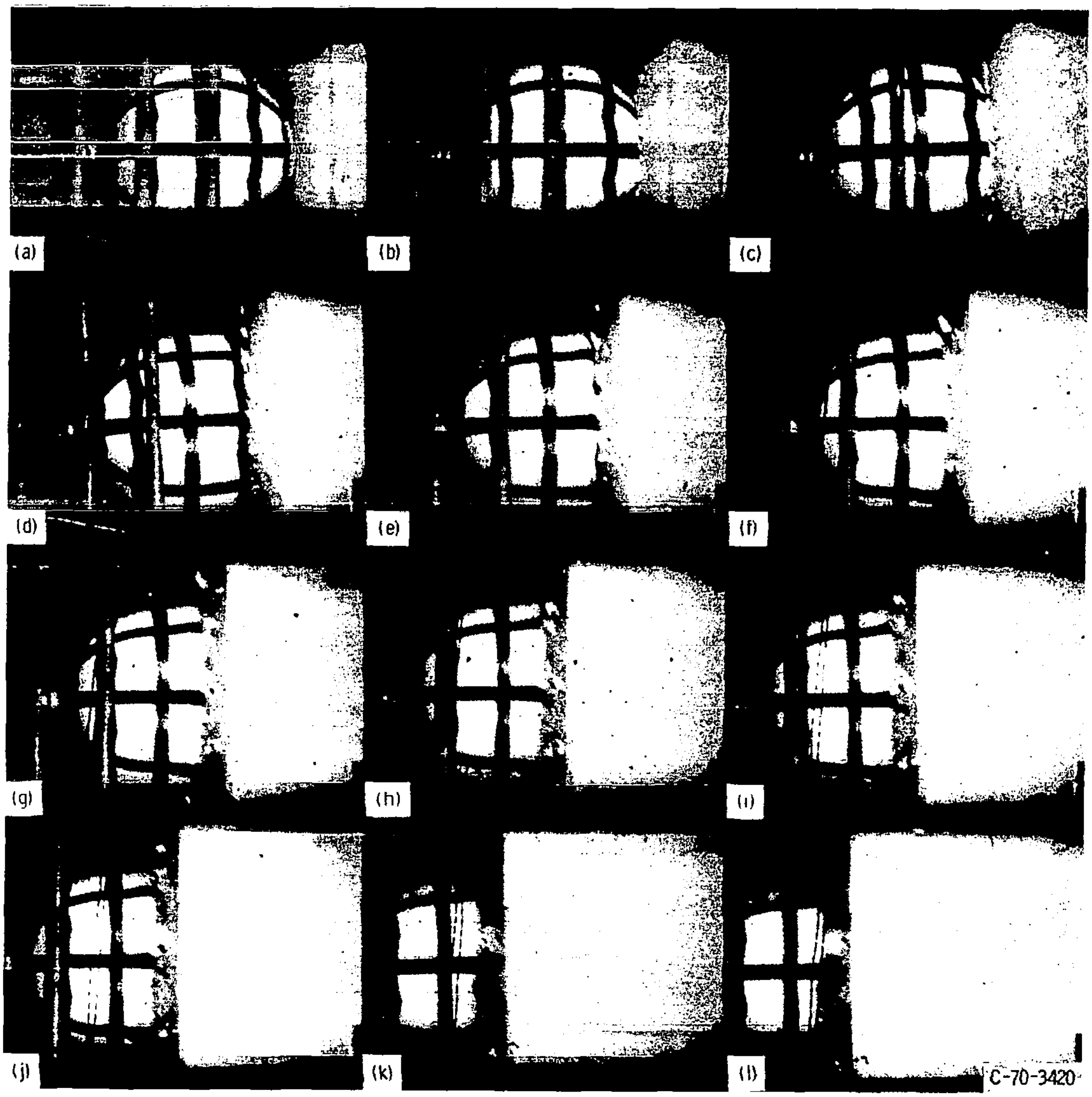
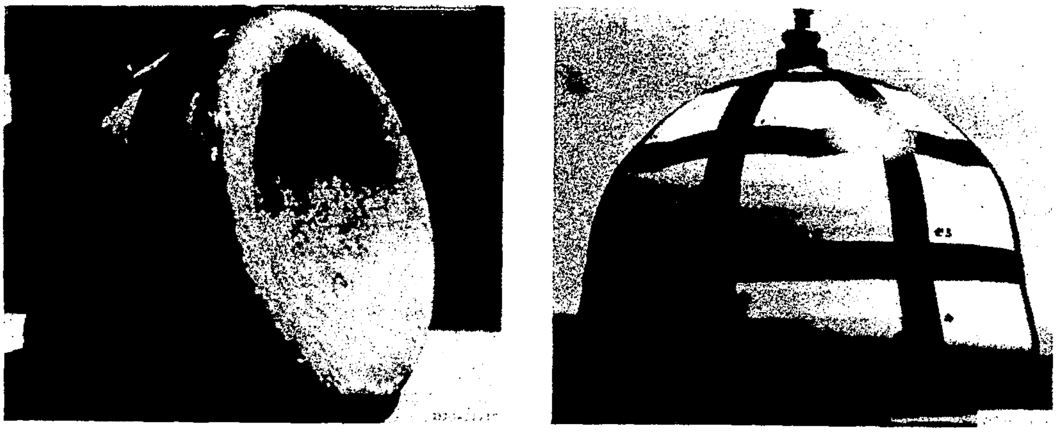
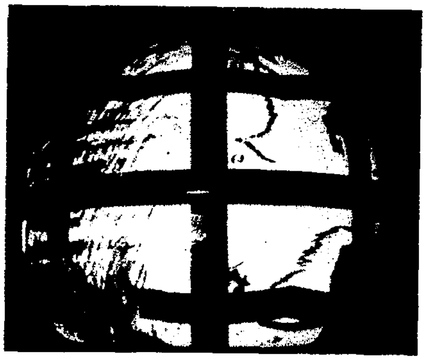


Figure 9. - Scenes from impact of 0.61-meter (2-ft) containment vessel at 126 meters per second (413 ft/sec).

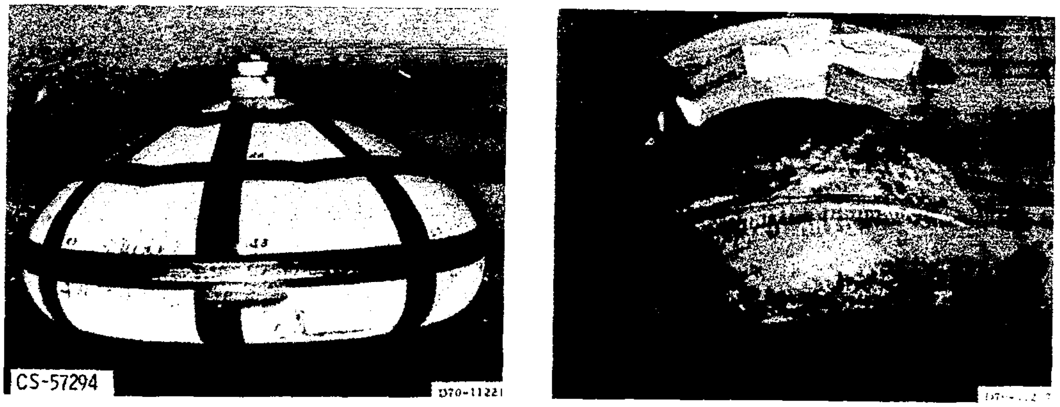


(a) Impact velocity, 116 meters per second (380 ft/sec).

(b) Impact velocity, 125.5 meters per second (412 ft/sec).



(c) Impact velocity, 73 meters per second (240 ft/sec).



(d) Impact velocity, 146 meters per second (480 ft/sec).

(e) Impact velocity, 177 meters per second (580 ft/sec).

Figure 10. - Containment system models after impact at indicated velocities. No leaks were detected in any of the models.

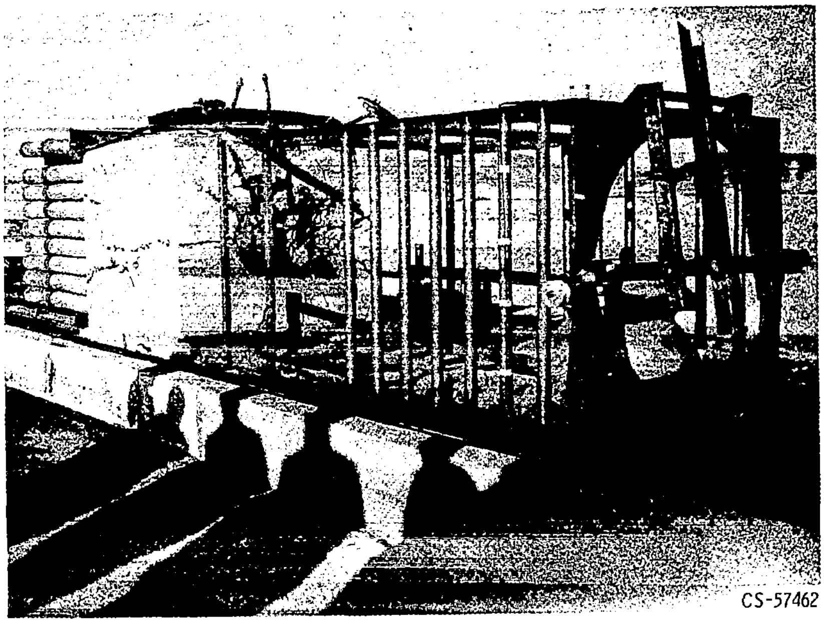


Figure 11. - Rocket sled and concrete block after impact of containment system model at 177 meters per second (580 ft/sec).

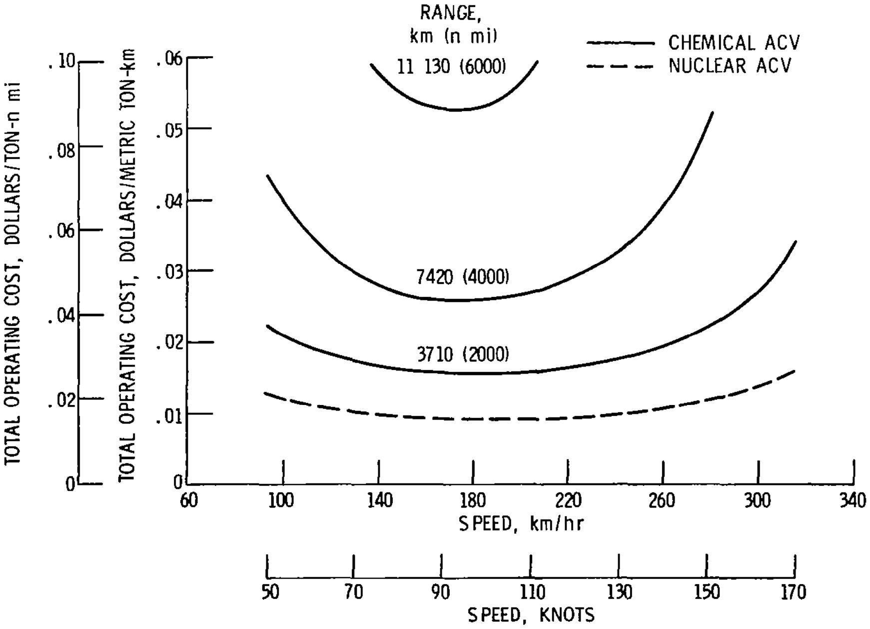
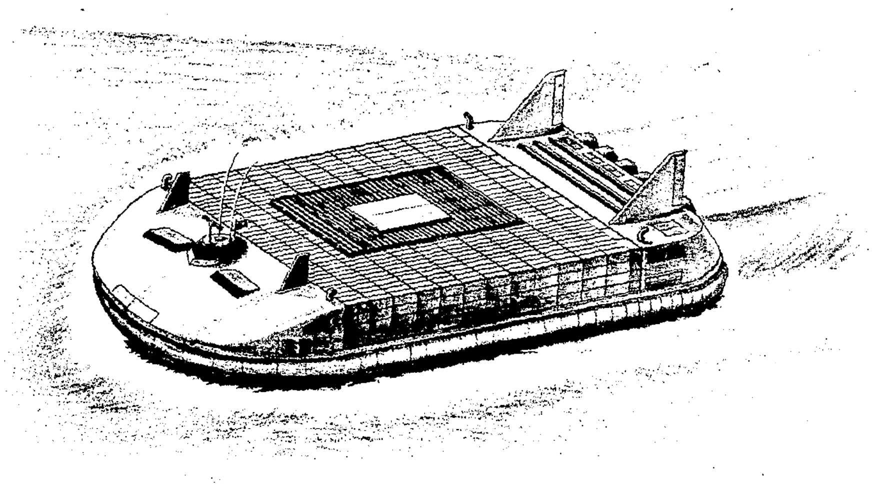


Figure 12. - Total operating cost as a function of speed for chemical and nuclear air-cushion vehicles. Gross weight, 9050 metric tons (10 000 tons); structure weight fraction, 0.25; structure cost, $11 per kilogram ($5/lb); load factor, 0.6; utilization, 0.5.



CD-10987-22

Figure 13. - 4525-Metric-ton (5000-ton) nuclear ACV freighter.

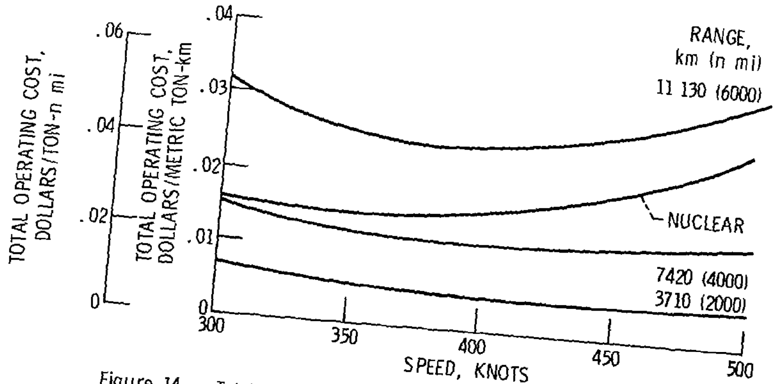


Figure 14. - Total operating cost as a function of speed for chemical- and nuclear-powered aircraft. Gross weight, 905 metric tons (1000 tons); structure weight fraction, 0.30; structure cost, $110 per kilogram ($50/lb); load factor, 0.6; utilization, 0.5.

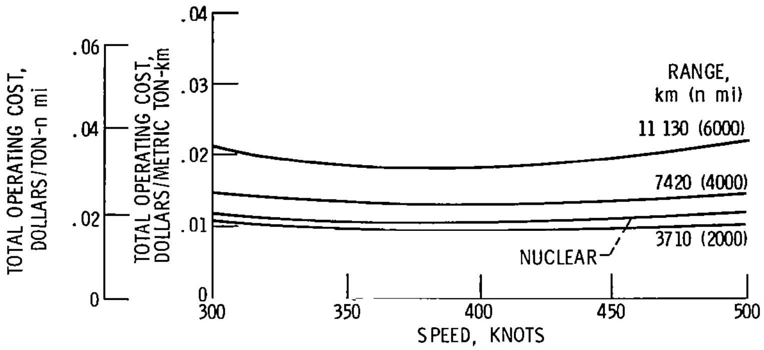


Figure 15. - Total operating cost as a function of speed for chemical- and nuclear-powered aircraft. Gross weight, 3620 metric tons (4000 tons); structure weight fraction, 0.30; structure cost, $55 per kilogram ($25/lb); load factor, 0.6; utilization, 0.5.

NATIONAL AERONAUTICS AND SPACE ADMISTRATION
WASHINGTON, D.C. 20546

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

U.S.MAIL

0218 01 C2 UL 22 711124 S00903DS 720401
DEPT OF THE AIR FORCE
AF WEAPONS LAB (AFSC)
TECH LIBRARY/WLOL/
ATTN: E LOU BOWMAN, CHIEF
KIRTLAND AFB NM 87117

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

---

> *"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*
>
> —NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546