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AIRBREATHING NUCLEAR PROPULSION-A NEW LOOK

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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)* (see Ref. 1) program 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 one million pounds are not only feasible but practical, desirable, and profitable.

Aircraft with gross weights of at least one million pounds are necessary to make nuclear aircraft practical. A practical nuclear aircraft would have complete shielding so that neither the flight and ground crew, nor 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 operation of about 10,000 hours between refuelings; long-life high-temperature oxidation resistant heat exchangers that heat the air of the turbofan engine; 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 competitive with transport by truck, rail, and general cargo ships. Inland cities built around large airports could then become new world trade centers.

The increasing demand for air transportation will require larger and larger aircraft.

*Joint project of the Atomic Energy Commission and Air Force, 1946-1961.

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 an another requires a powerplant with four times as much power, but it will be only two times as heavy.

In 1964 NASA initiated a low level effort to reassess the feasibility of nuclear aircraft. This current new look (see Refs. 2, 3, 4) by NASA (the Air Force also has been involved) 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 formed from the fissioned uranium atoms continues to be produced even after the reactor is shutdown. It amounts to a few percent of the normal reactor power and reduces with time to about one 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 distribute themselves uniformly around and near the inside surface of the containment vessel. Work is underway to demonstrate that the afterheat can be removed without melting the containment vessel and without excessive weight penalties.

A limited effort is underway to experimentally demonstrate 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 air breathing engines.

It appears as if the weight of aircraft nuclear powerplants would be more than an order of magnitude less than conventional nuclear marine powerplants. This feature makes the aircraft type air breathing nuclear propulsion system look extremely attractive for propulsion of ocean going air cushion vehicles (see Refs. 5, 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 indedependent of range at the vehicles top speed. Because of this attractive feature 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 paper 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 air breathing propulsion systems for aircraft and air cushion vehicles.

DESCRIPTION OF NUCLEAR AIR BREATHING PROPULSION SYSTEM

Figure 1 shows a schematic drawing of a typical nuclear aircraft 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 forward 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 on either 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, organic solids or liquids, for example. The use of organic materials like plastic or chemical aircraft 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 material can be made of material that can absorb kinetic energy as it deforms during the impact. See Fig. 2 which 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 to prevent 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 below. Results are presented in the areas of shielding, long life reactor fuel, long life heat exchangers, high-speed impact, and reactor meltdown containment safety studies.

Shielding

Unit or 4π shielding should enclose the reactor to reduce the dose levels to allowable levels in all directions. The allowable dose level for general population is 0.25 millirem per hour. In our studies we design for this dose rate at 30 ft from the reactor centerline. 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 the movement within or outside the aircraft either when the aircraft is flying or is on the ground.

Shield weight that we have calculated for uranium-water shields are shown in Fig. 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 mw the shield weights vary from about 350,000 to 450,000 pounds for a reactor power density of 5 mw per cubic foot. These are typical of the powers power densities and shield weights for aircraft in the range of gross weights from one to two million pounds. 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 Refs. 8 and 9. Other codes and calculation of shields are given in Refs. 10, 11, 12, and 13.

Shielding weight appears to be acceptable as long as aircraft gross weights are greater than one million pounds. Of course, reducing shield weight 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 it is large enough.

Long Life Reactor Fuel

NASA has proposed the use of a fuel pin concept which can achieve 20 percent burnup or higher (Ref. 14). It is a relatively simple approach that accepts in a conservative way well-known facts about fuel behavior. Figure 7 shows a schematic drawing of this fuel pin concept. As described in Ref. 3, it does not use any new physical principles or ideas which have not previously been thought of. 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 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 strong clad 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 clad tube wall material. We are currently carrying out in-pile experiments in the Plum Brook Reactor to verify the concept for aircraft 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 pin experiments now in progress is shown in Table II. The data are compared with what is derived 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 pin surface temperature, the fuel pin power per unit pin volume, the fuel pin total energy release per unit volume, and the fuel pin energy equivalent in gallons of gasoline for a pin 0.55 inch in diameter and 48 inches long. The desired operating conditions for a 10,000 hour propulsion reactor are: fuel pin temperature, 1800° F, fuel pin power, 0.5 kw per cm^3, and a total energy release of 8300 kw-hr per cm^3 which is the equivalent of 50,000 gallons of kerosene per pin. Commercial reactors operate with pin surface temperatures of about 600° F, with about the same power density and with about 2/3 of the total energy release. The UO_2-TZM fuel pin test is composed of 3 pins much as shown in Fig. 4 that are now operating at 2100° F with a power density of about 5 times that required for the propulsion reactor. This is an accelerated test so that data can be obtained in about 1/5 the time. The pins have already obtained a total energy release of 4800 kw-hr per cm^3 which is equivalent to more than half (about 6000 hr) of desired propulsion reactor operation at a surface temperature 300° F in excess of that derived. The UN-TZM fuel pins (3) are also operating at 2100° F. They are operating at about 3 times the desired power density for propulsion reactors. The total energy release obtained to date is also more than half of the derived value. These pins as well as the UO_2-TZM pins 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 tube material made of high temperature oxidation resistant materials. We have tested many high temperature oxidation resistant materials. The most suitable available material we have found so far is N-155 alloy (see 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 in the order of 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 Fig. 5. This header and tube section was designed to operate for 1500 hours at a pressure of 1000 psi and temperature of 1550° 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 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 life times 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

With 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 air breathing 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, 3, and 4 discuss this work. During the early phases of this study impact systems employing energy absorbing frangible tubes were investigated (ref. 16). They were found to be limited to providing impact protection for impact speeds up to 300 to 400 feet per second. Recently another approach utilizing the energy absorption capability of plastically deforming shells has shown promise for impact protection up to 1000 feet per second. The first NASA studies of this technique are published in Refs. 17 to 19. Work has begun on the problem of loss-of-reactor-coolant 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 energy absorbing 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 reactor system.

Uranium dioxide in the form of a layer of granular particles is placed on the inside of the containment vessel and reactor vessel. The uranium dioxide acts as an insulating material that causes the reactor core material to meltdown in the event of a major accident which destroys all normal reactor cooling systems. 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. 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, is also a good gamma shield.

Two experimental programs aimed at demonstrating that these containment principles work are being carried out.

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 five inches in outside diameter. The reactor model contains molybdenum uranium dioxide fuel pins. Fission heating will cause the fuel to melt. The tests will be conducted in NASA's Plum Brook Reactor Facility. The containment vessel is designed to operate at a temperature of the order of 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 completed, and will be inserted in the Plum Brook reactor in May-June of 1971.

Impact tests. - A schematic drawing that describes the models that were used to demonstrate the newest impact energy absorption principles is shown in Fig. 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 pieces in the real reactor. In the test models, steel was used in place of uranium for economy reasons. These models have been impacted with a concrete block at speeds up to 600 feet per second. Figure 8 shows the test setup that is being used. The impact model shown is 2 feet in diameter. It is mounted on a styrofoam block between the rails of a rocket sled facility. The rockets accelerate the 4.5 foot cube concrete block that weights $7\frac{1}{2}$ tons to the desired impact speed. Surplus 5 inch HVAR rockets are used to accelerate the concrete block. The case 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 Lewis Research Center. Figure 9 is a sequence of frames from this motion picture illustrating the impact of a model at 413 feet per second. The large amount of deflection that the containment vessel undergoes is readily visible. Figure 10 taken after the 5 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 Ref. 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 along side the track was 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 260 feet per second flattened one side slightly.

Figure 11 shows the effect on the concrete block and rocket sled of impacting the containment system model at 580 ft/sec. The containment system model weighed about 1200 pounds and was 38 inches 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 1000 feet per second. It is anticipated therefore that it will be able to design impact systems that will contain fission products up to speeds of 1000 feet per second (600 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.

Figure 12 gives the preliminary results of the operating cost study for 10 000 ton air cushion vehicles (ACV). The total operating cost in dollars per ton mile is shown as a function of speed in knots. Chemical ACV's are shown by the solid lines for ranges of 2000, 4000, and 6000 miles. 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 in the range of 2 cents per ton mile. Chemical systems operate in the range of 4 cents per ton miles for transoceanic (4000 nm or greater) ranges.

The ACV increases the cargo transportation speed from the 15-30 knots of the best of today's ships to 100 knot. It may be possible to attain rates of about 2 cents per ton mile operating cost if nuclear power is used.

It theoretically would take a fleet of about 3000 5000-ton ACV's (see fig. 13) to handle 10 percent of the world trade in 1980. Ten percent is assumed to be the function of world trade that could be shipped if shipping costs were about 2 cents per ton-mile. 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 1000 tons. Chemical aircraft performance is indicated by solid lines for ranges of 2000, 4000, and 6000 nautical miles. Nuclear aircraft performance is also shown. The nuclear airplane can carry cargo for a cost of 4 to 5 cents per ton mile at speeds of 400 to 450 knots. For ranges 5000 nautical miles 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 4000 tons. A very noticeable reduction in operating cost is noted. This reduction is due to lower unit costs of airframe of larger sizes and for nuclear aircraft the lower fraction of gross weight required for shielding. The 4000 ton nuclear airplane is competitive with chemical airplanes for ranges of less than 3000 miles. The operating cost is of the order of 2 cents a ton mile at speeds up to 500 knots. As previously stated, rates such as these are typical of rail and truck transportation. The transoceanic commerce that theoretically could be attracted by such a transportation system if it were developed would require a fleet of about 500 4000-ton aircraft in 1980 and 1000 by the year 2000. In addition, the attraction of speeds ten 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 supersonic nuclear aircraft cannot be made to fly successfully providing the aircraft is large enough. This is so because the weight of shielding increases with reactor power or aircraft gross weight at a rate about or somewhat less than the square root. Hence the larger the aircraft the smaller is the fraction of its weight that is required for shielding, and hence the larger will be the payload fraction. Shielding that gives dose levels in the aircraft less than 10 percent of normal background radiation from cosmic radiation requires that the aircraft be at least one million pounds 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 3/4 of a million pounds in gross weight. Reactor, heat transfer, materials, 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 duting 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 up to 584 feet per second with no post-impact leaks in the containment vessel. Analysis of the experimental data indicate a potential of impacts at speeds of 1000 feet per second without vessel rupture. 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 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 surface effect 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.

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TABLE I. - FOSSIL AND NUCLEAR FUEL COST

	Unit cost	$/10^6 btu
Marine fuel	$2.50/bbl	0.39
Aviation fuel	8¢/gal	.62
Nuclear fuel	12 $/gm	.16

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

	Required for 10 000 hr propulsion reactor	Commercial power factor practice	UO_2-TZM fuel pin test	UN-TZM fuel pin test
Fuel pin temperature, ^{o}F	1800	600	2100	2100
Fuel pin power, kW/cm^3	0.3	0.5	2.3	1.7
Total energy release, $kW\text{-}hr/cm^3$	8300	5000	4800[a]	4300[a]
Equivalent gallons of kerosene per pin[b]	50 000	30 000	29 000	26 000

[a]Test in progress; data as of 3/16/71
[b]Fuel pins 0.55 in. diam × 48 in. long; 4000 required for 300 MW reactor.

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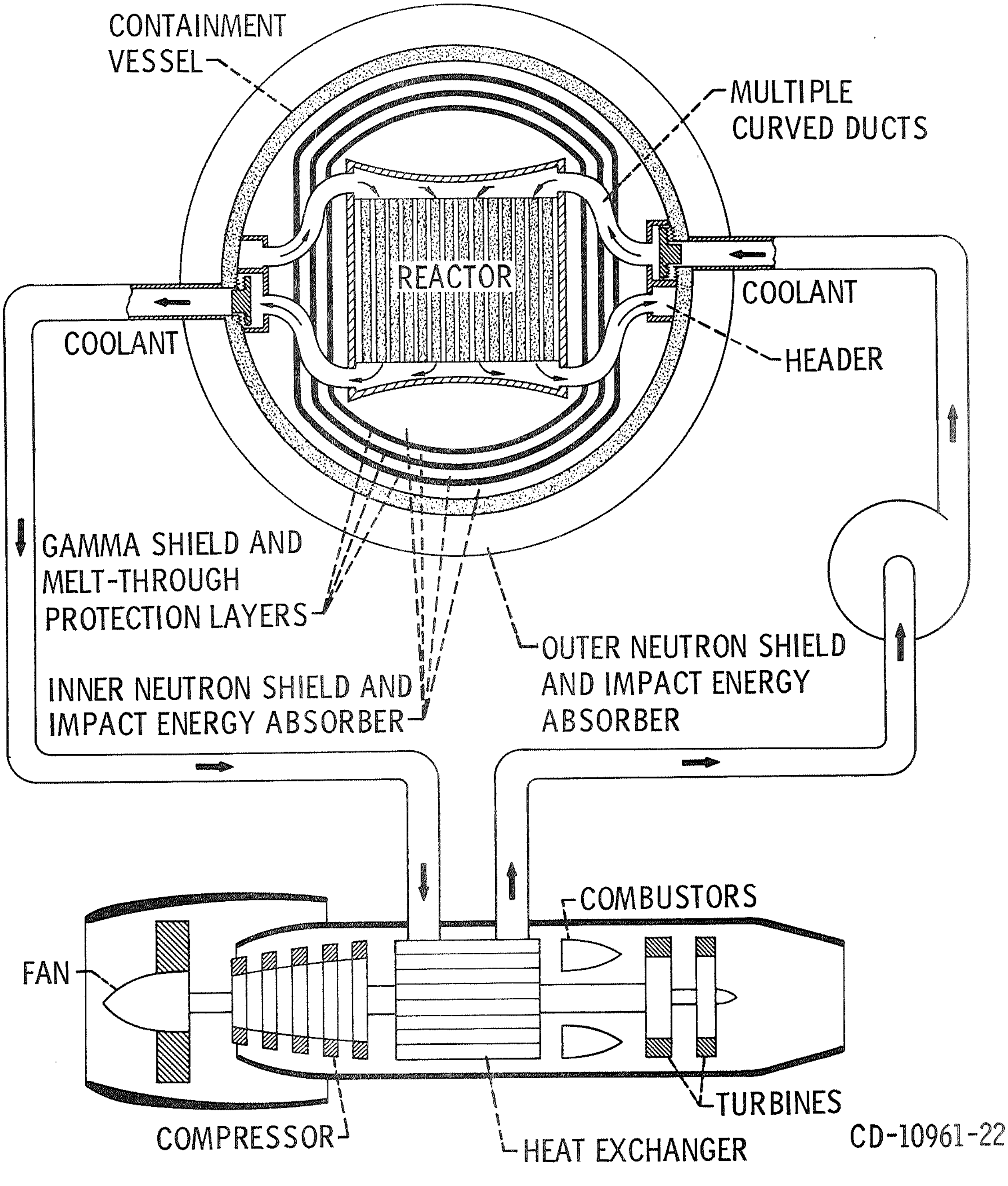

Figure 1. - Nuclear aircraft powerplant.

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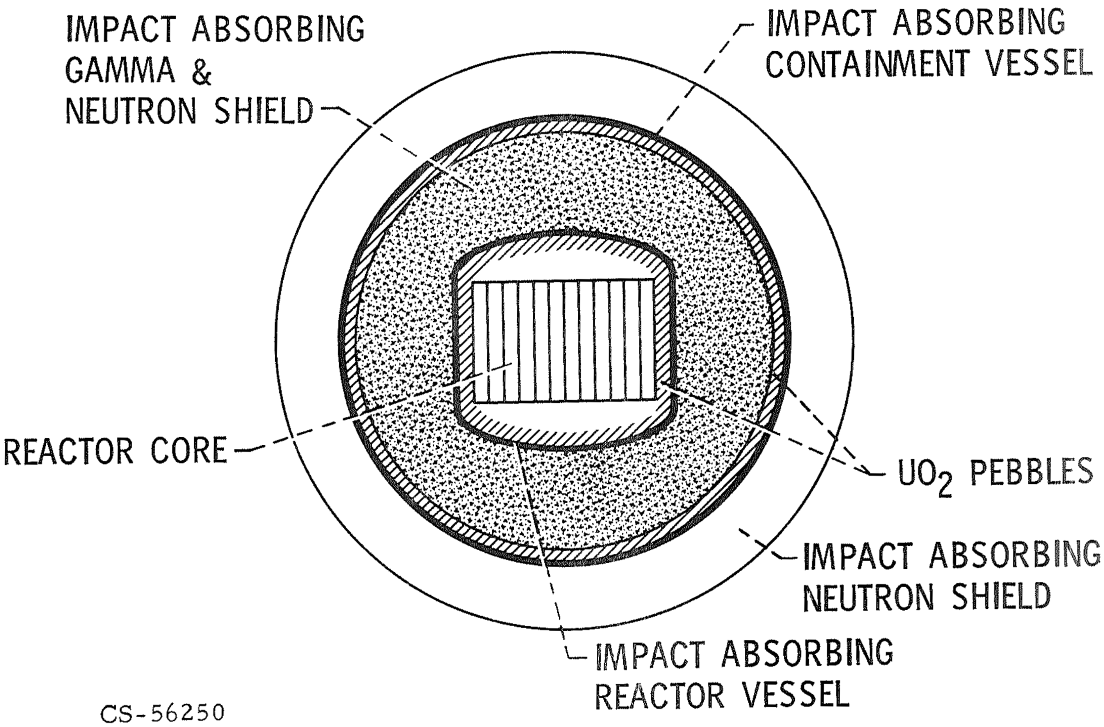

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Figure 2. - Principles of mobile reactor containment system.

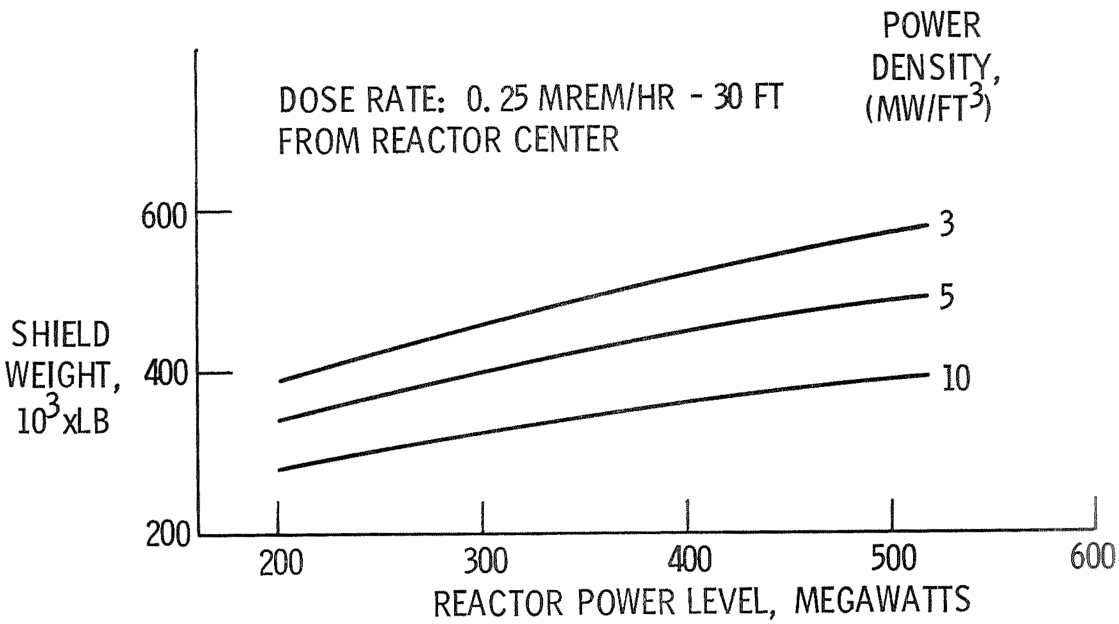

Figure 3. - Depleted uranium-water shield weights.

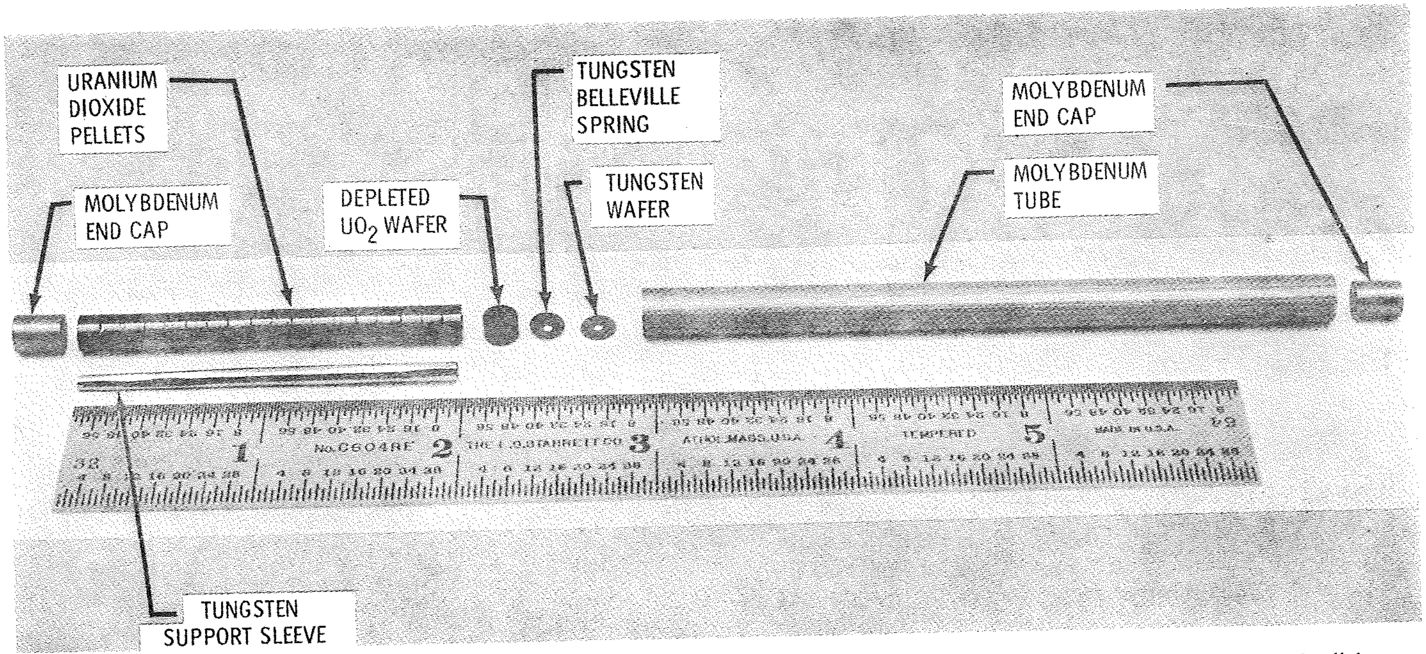

Figure 4. - Components for high temperature fuel pins containing UO_2 pellets. The tungsten support sleeves were used with cored pellets.

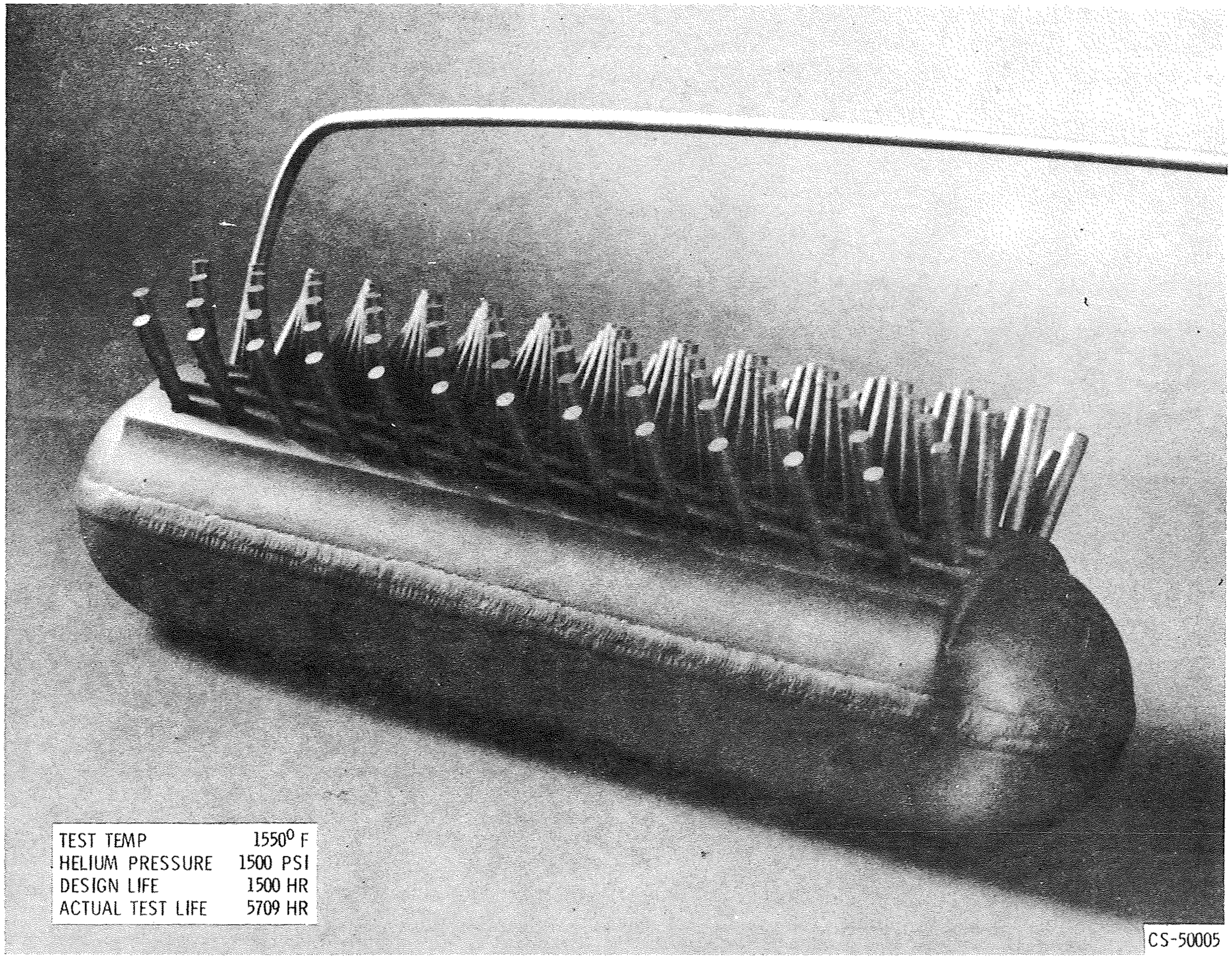

Figure 5. - Test of high pressure helium-to-air heat exchanger header.

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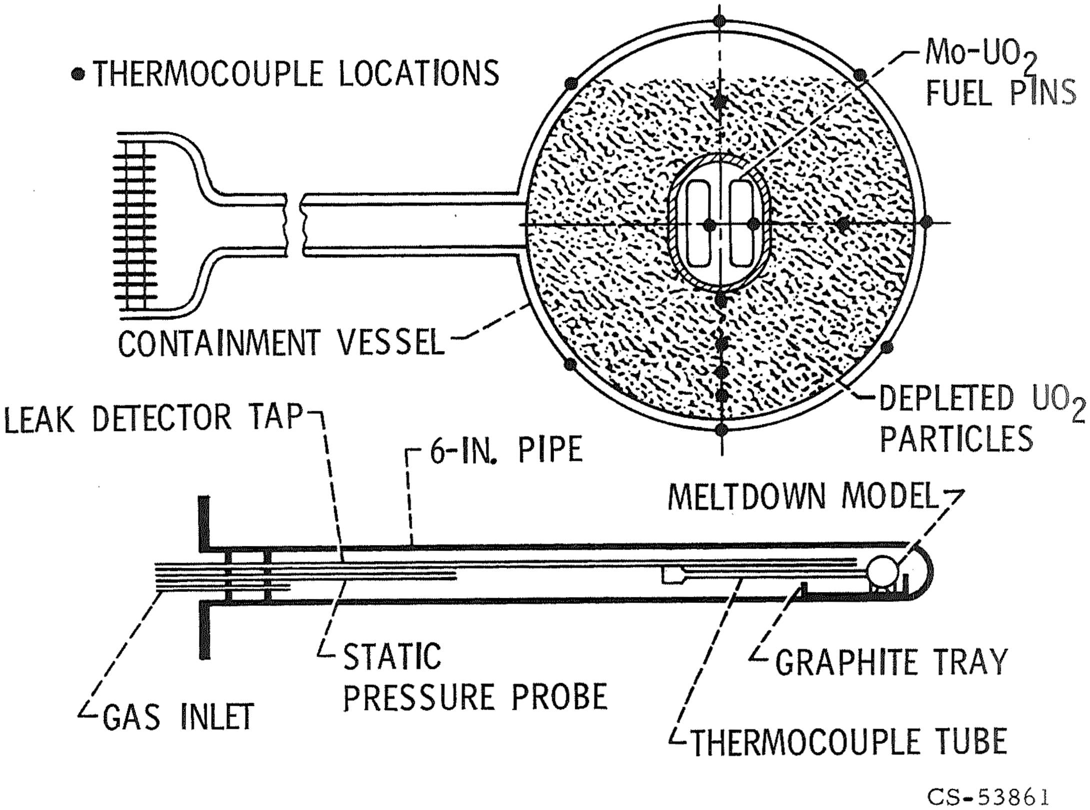

Figure 6. - Reactor meltdown containment experiment.

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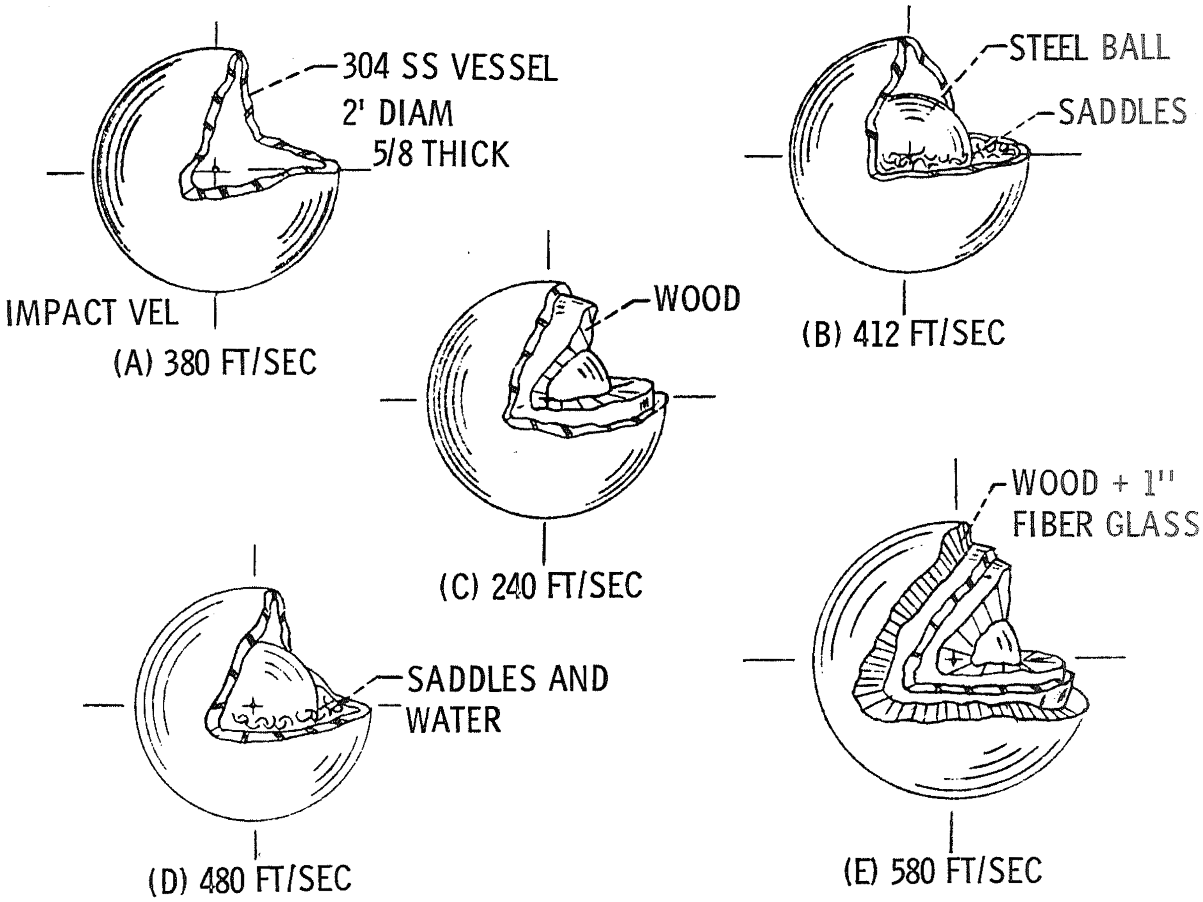

Figure 7. - Sketches of containment system models before impact at speeds indicated.

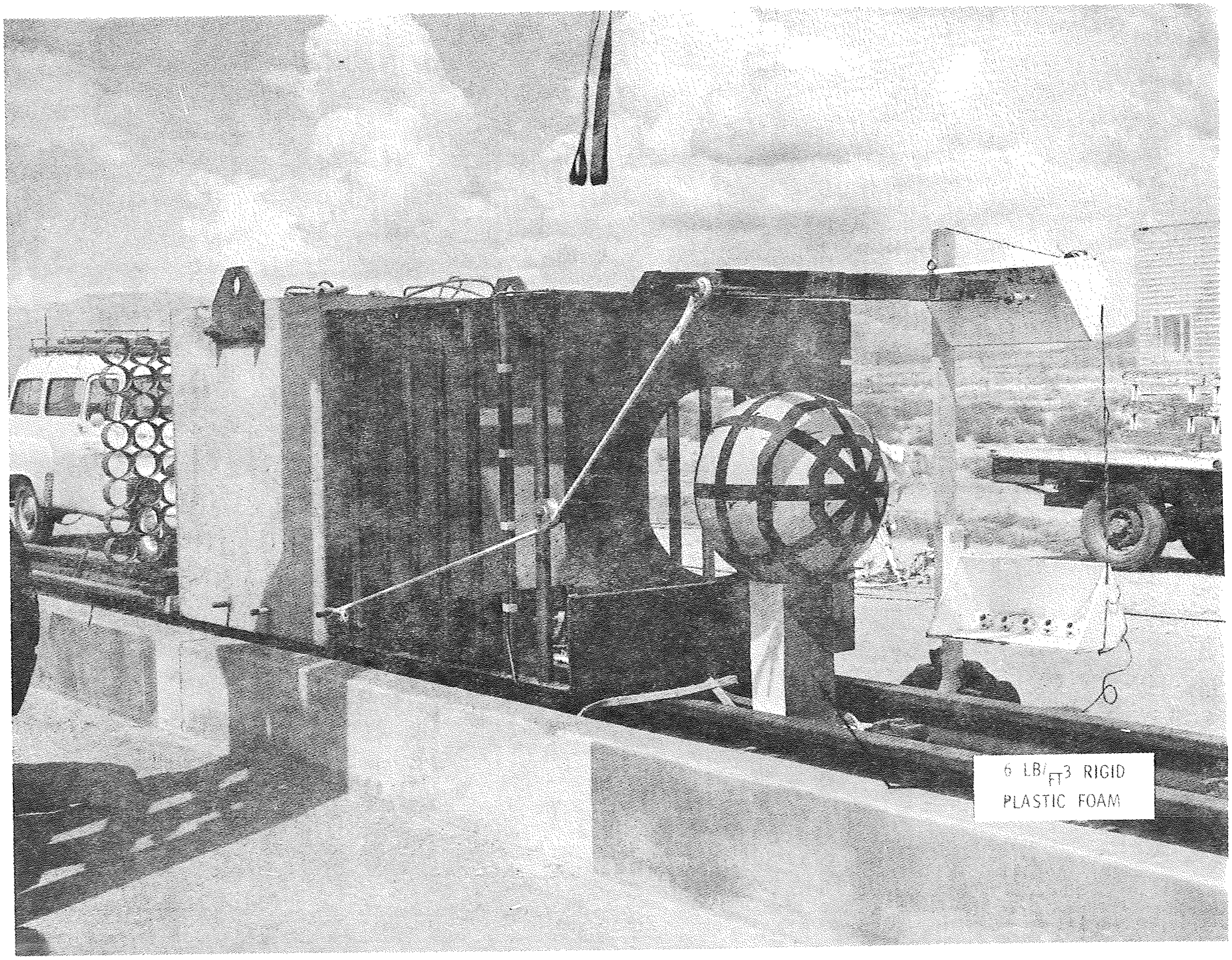

Figure 8. - Rocket sled and containment system model test.

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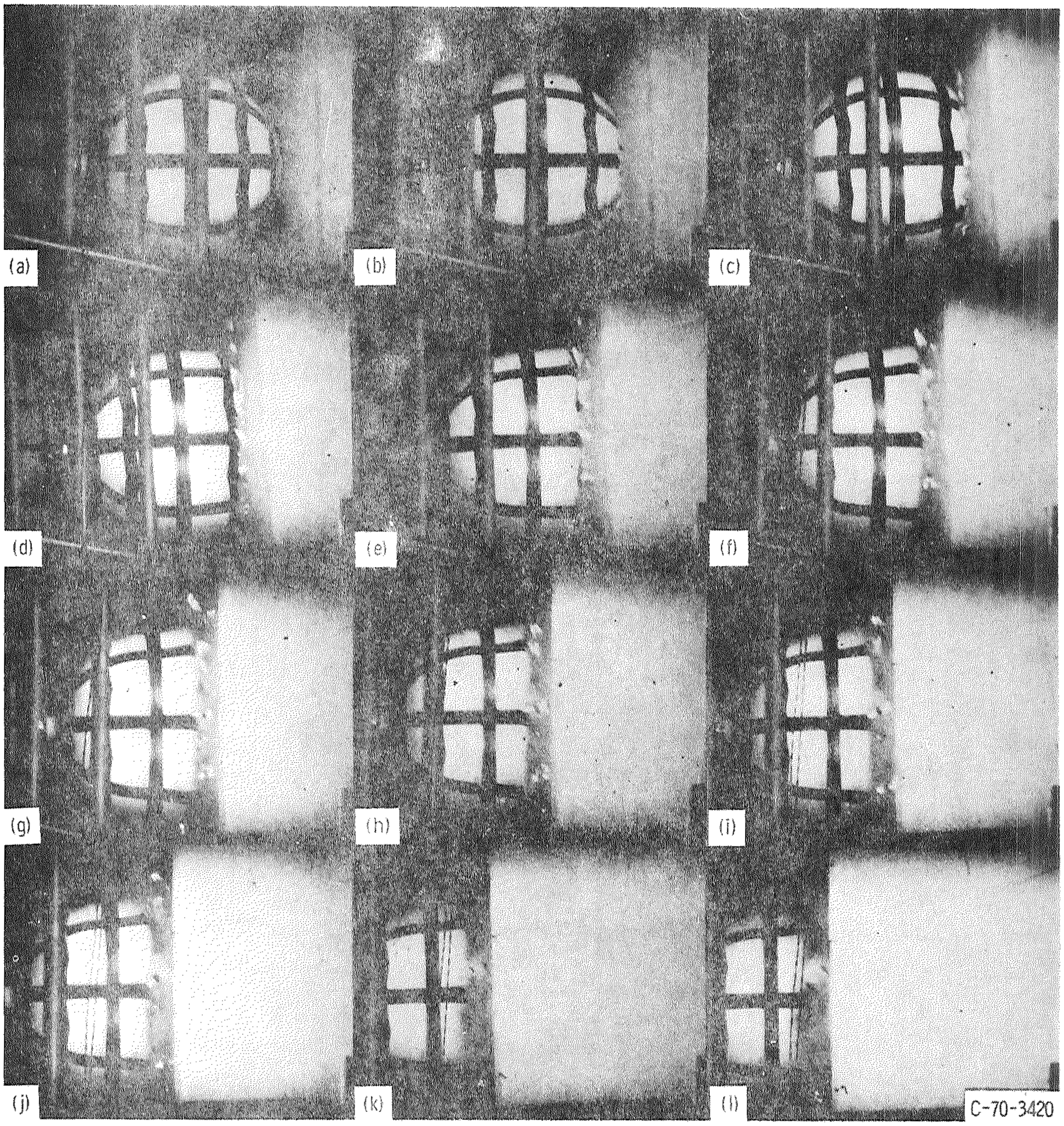

Figure 9. - Scenes from impact of two foot containment vessel at 413 ft/sec.

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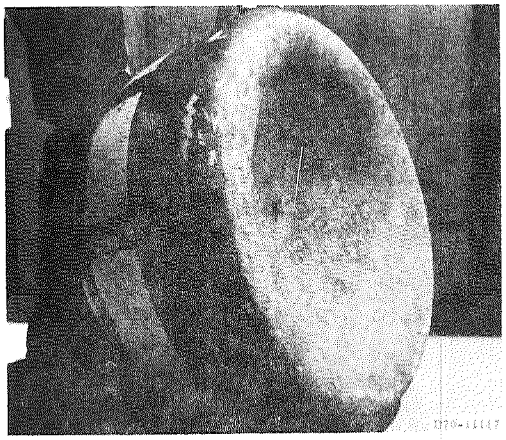
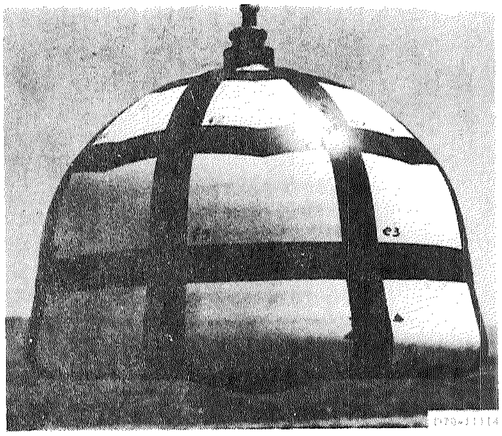
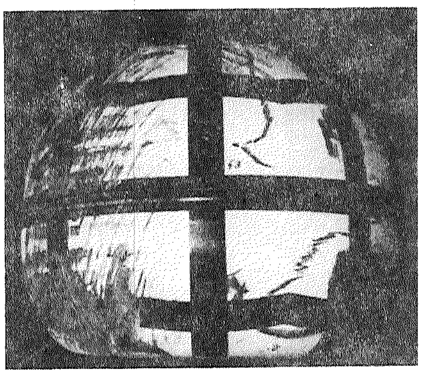


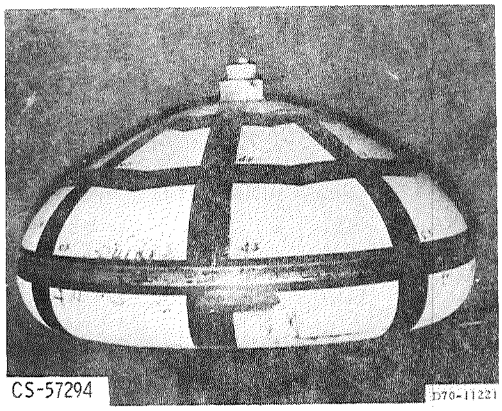
(a) 380 ft/sec.



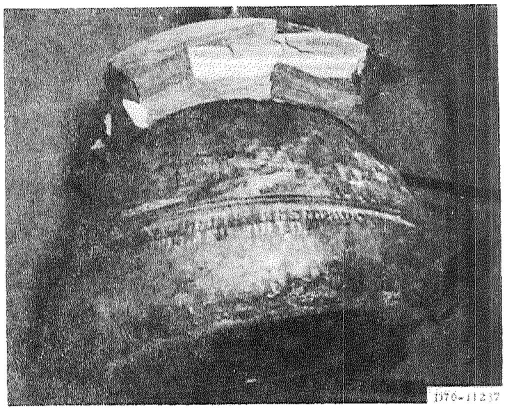
(b) 412 ft/sec.



(c) 240 ft/sec.



(d) 480 ft/sec.



(e) 580 ft/sec.

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

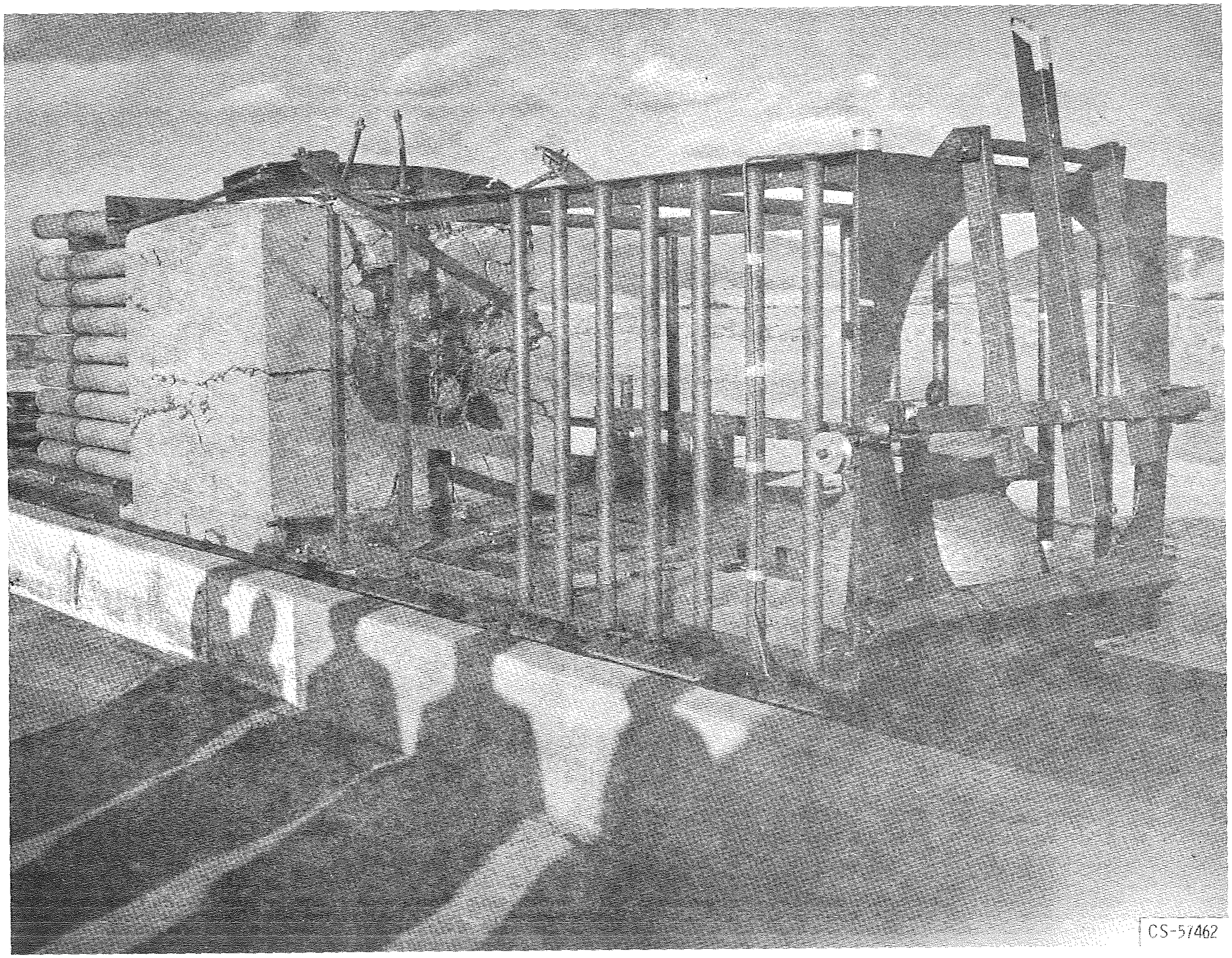


Figure 11. - Rocket sled and concrete block after impact of containment system model at 500 ft/sec.

E-6316

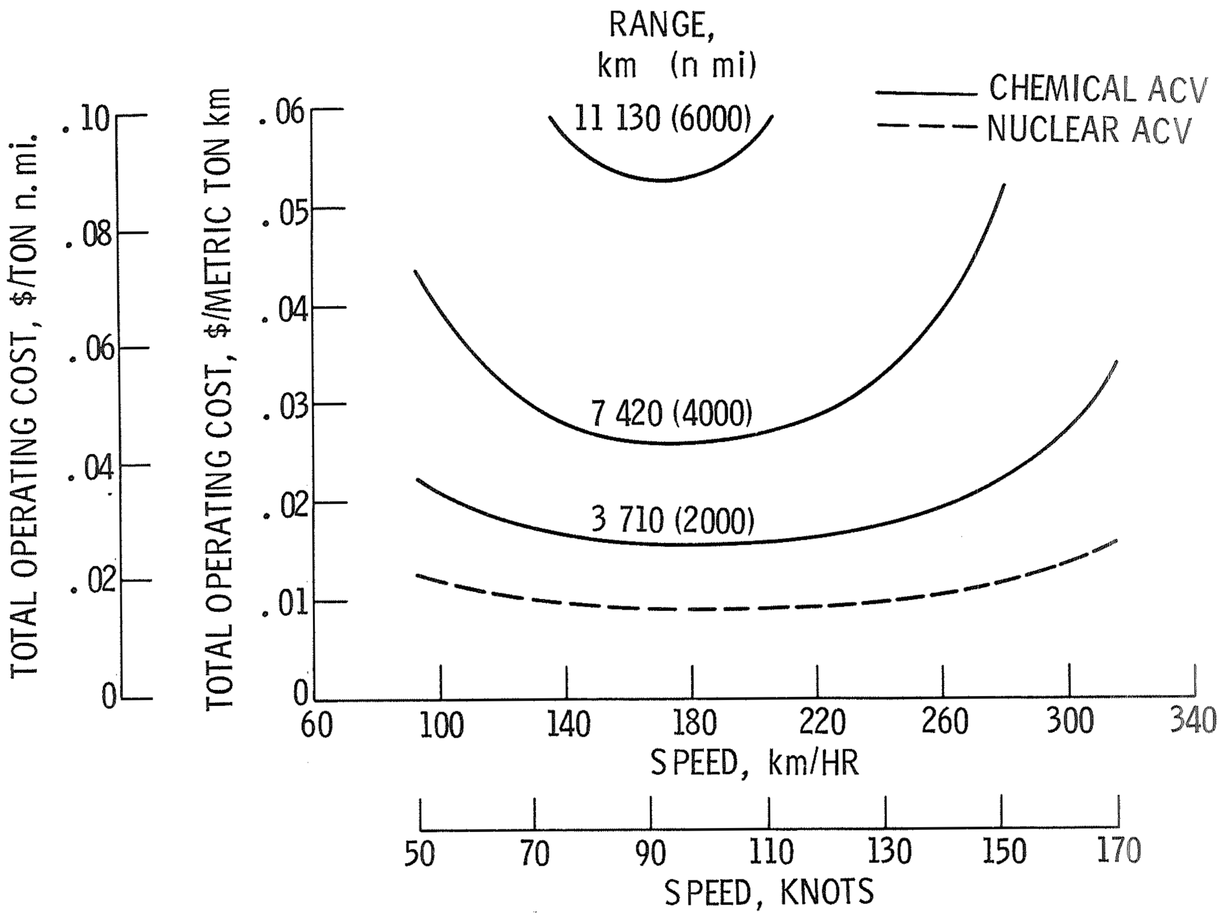


Figure 12. - Total operating cost as a function of speed for chemical and nuclear surface effect vehicles. Gross weight, 9050 metric tons (10 000 tons); structure weight fraction, 0.25; structure cost, $11/kg ($5/lb); load factor, 0.6; utilization, 0.5.

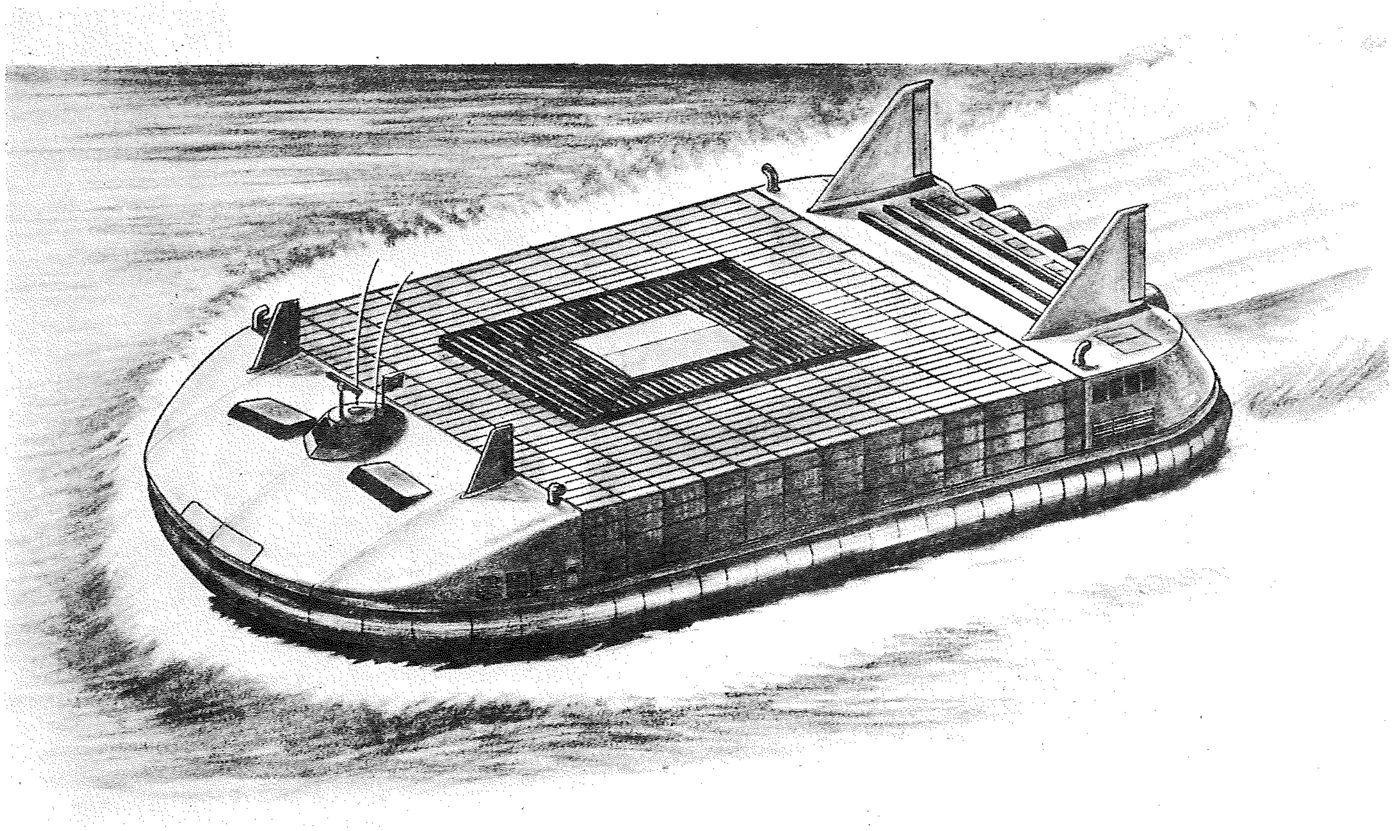


Figure 13. - 5000 Ton nuclear ACV freighter.

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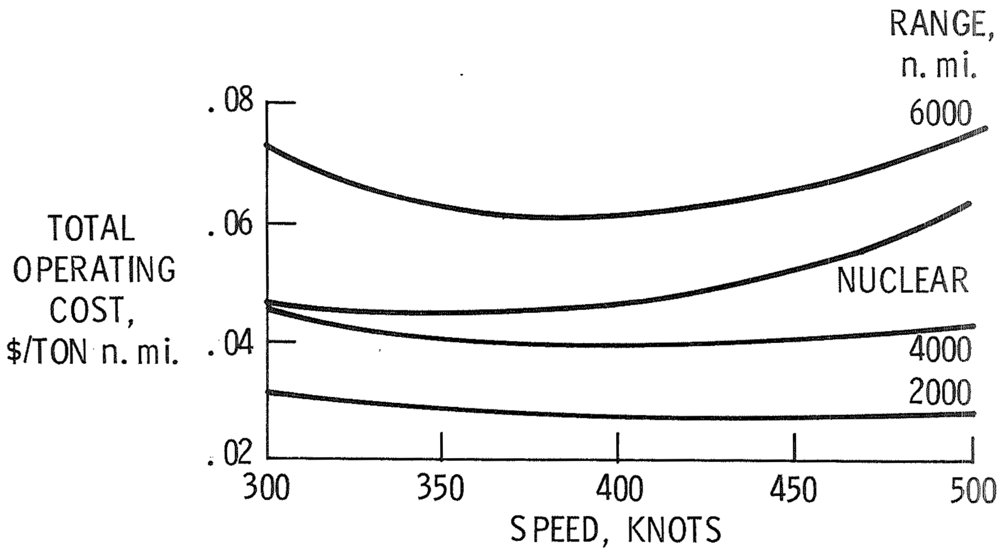

Figure 14. - Total operating cost as a function of speed for chemical and nuclear powered aircraft. Gross weight, 1000 tons; structure weight fraction, 0.30; structure cost, $50/lb; load factor, 0.6; utilization, 0.5.

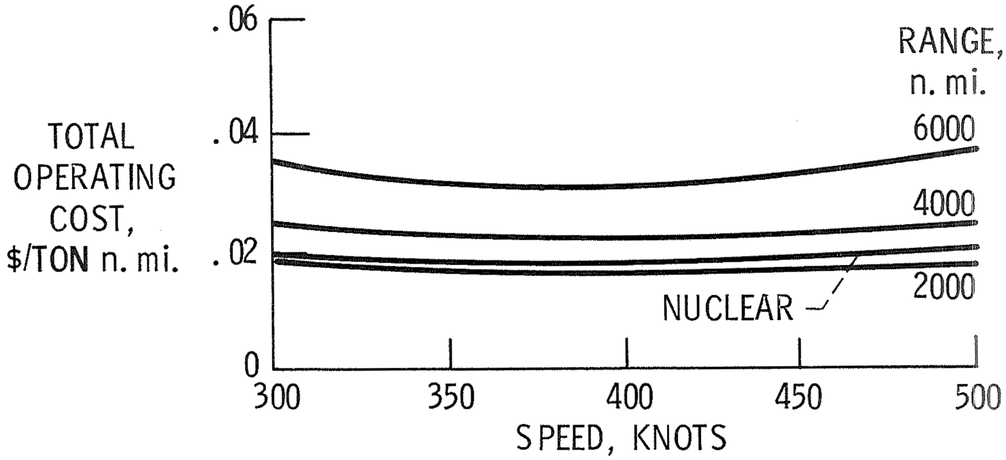

Figure 15. - Total operating cost as a function of speed for chemical and nuclear powered aircraft. Gross weight, 4000 tons; structure weight fraction, 0.30; structure cost, $25/lb; load factor, 0.6; utilization, 0.5.