N72-11844

NASA TECHNICAL MEMORANDUM

NASA TM X- 67963

NASA TM X- 67963

CASE FILE COPY

WHAT CAN NUCLEAR ENERGY DO FOR SOCIETY?

by Frank E. Rom
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Second Uranium Plasma Symposium sponsored by
the American Institute of Aeronautics and Astronautics
Atlanta, Georgia, November 15-17, 1971

E-6674

WHAT CAN NUCLEAR ENERGY DO FOR SOCIETY?

By

Frank E. Rom

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

INTRODUCTION

Why should we be interested in nuclear energy? What can nuclear fuel as an energy source do for us? First of all, we are interested in nuclear fuel because it is a compact source of energy. It produces one to two million times as much energy per pound as fossil fuel. Secondly, it is an abundant source of energy. There are large reserves of nuclear energy sources in the Earth's crust. There is 30,000 times as much energy available from fissionable atoms as from fossil sources. Thirdly, nuclear fuel basically costs less per unit of energy than fossil fuel. Table I shows that one million BTUs of marine fuel costs 0.39 dollars and aviation fuel costs 0.62 dollars. The basic cost of nuclear fuel is only 0.16 dollars for a million BTUs. It costs less than 1/2 as much as marine fuel and about 1/4 as much as aviation fuel.

There are disadvantages that tend to offset the advantages of nuclear fuel. The cost of capital equipment that is used to release nuclear energy is high. The high cost is in part a result of social and political pressures that demand extreme safety precautions far

beyond that required for any other means of producing energy. Another is the necessity for shielding. The latter has the greatest impact for mobile applications where the heavy shield must be carried by the vehicle.

COMMERCIAL ELECTRIC POWER AND SHIP APPLICATIONS

In the case of commercial electric power production and marine propulsion, the advantages have outweighed the disadvantages. Table II shows the number of operational stationary and shipboard nuclear powerplants in operation in the world today. The stationary powerplants are for electric power generating stations. The mobile powerplants are chiefly for submarines. There are 111 nuclear stationary powerplants and about 184 nuclear submarine propulsion systems in operation today. There are also a few nuclear surface ships in operation. Of the total of 301 reactors, more than half are used for submarines. In the 1976-1980 period the numbers will increase considerably. There will be about 256 stationary powerplants and more than 243 submarine and ship nuclear powerplants. Thus there will be more than 500 nuclear powerplants in operation by 1980. Thus, nuclear energy is playing an expanding role in commercial electric power and marine propulsion.

A comment about nuclear ships. The NS Savannah shown in figure 1 was the first commercial nuclear powered ship. It demonstrated without doubt the feasibility of nuclear power for ships. It travelled 1/2 million miles in eight years and it opened up 45 separate worldwide ports to commercial nuclear ships. Some question the economics

of nuclear shipping because the economic performance of the NS Savannah was inferior to fossil powered cargo ships. This should not be surprising. The Savannah was designed as a showpiece to demonstrate the peaceful use of the atom. It is a very beautiful ship, containing luxurious passenger staterooms and crew quarters. To demonstrate that it could also be used to haul cargo, cargo holds were built into the ship. But it is neither an efficient cargo ship nor a passenger carrier. In addition it is too small for nuclear power to be attractive. It was, therefore, not surprising that this ship was not economically competitive with fossil ships. It did, however, show that nuclear energy could be used to propel a ship and that it would be accepted in almost every major seaport.

What is the potential for nuclear ships? The Department of Transportation two years ago forecast worldwide trade through the year 2010 (ref. 1). The result is shown in figure 2. By 1990 worldwide ocean trade will be three times as much as today. The capacity of today's maritime fleet will be tripled to handle this increase. It would be foolish to assume that the world would merely duplicate the ships we have now to increase the fleet capacity. Obviously, new technology will be used by each of the world's nations to gain a better competitive position in supplying the necessary shipping capacity. Accordingly, the U.S. Maritime Administration is now executing a program which provides for the establishment of a large U.S. commercial fleet by upgrading our shipyards and standardizing our ships to reduce construction costs. Its aim is to reduce subsidies

required by the industry but still make it attractive enough so that 300 ships will be built in the next 10 years in U.S. shipyards. There is a definite intent that the U.S. capture a share of the benefits of the expanded world trade.

In 1990 it will take 2500 ships of 40,000 horsepower or greater (ref. 2) to service the volume of cargo forecast. The Maritime Administration also estimates that by 1980 nuclear ships of 40,000 horsepower or greater should be economically competitive or superior to fossil powered ships. This is to be compared to the current situation where horsepowers greater than 100,000 are needed to make nuclear ships attractive. Accordingly, nuclear propulsion can be expected to capture an increasingly larger share of the ship propulsion market. If nuclear propulsion penetrates the new ship market only to the extent of 10 percent, 250 nuclear ships will be constructed by 1990. This conclusion is strongly underlined by Japan's recently announced maritime building program which calls for 280 nuclear ships to be built by 1990.

In the area of nuclear submarines, there are applications other than military that may prove feasible. There have been proposals made by the industry for cargo submarines to haul oil from the Alaskan North Slope beneath the Arctic ice. Estimates have shown that this should be cheaper than transporting oil by pipe line. Before the rather disappointing experience with the icebreaking tanker, the Manhattan, it was thought that submarines would be competitive with the ice breaker. After the experience with the Manhattan, it now appears that the nuclear powered submarine could do the job better.

It is interesting to contemplate the use of nuclear submarines for carrying cargo. Submarines are more efficient than surface ships. Because they travel under the surface they do not produce the waves that surface ships do. The drag for submarines is therefore less than for a comparable size surface ship. It, therefore, takes less power to propel a submarine, or, for the same power, submarines would travel at higher speeds. Submarines, however, are more expensive to build. The increase in productivity would tend to offset the higher capital cost. This could result in lower freight rates at higher speeds (ref. 3). In addition, submarine operation would be unaffected by weather and sea states.

Air-Cushion Vehicle Application

Air-cushion vehicles, as exemplified by the SRN-4 English Channel ferry (fig. 3) are vehicles that float on a cushion of air trapped beneath them. Blowers maintain the air cushion by making up for the air that leaks from the periphery of the vehicle (see fig. 4). The cushion of air provides a relatively frictionless contact with the surface. Propulsion and directional control are provided by conventional aircraft thrustors like ducted fans, prop jets, or propellers. The air-cushion vehicle has been called the fourth basic technique for transportation that has been discovered since the beginning of civilization (ref. 4). The wheel for land movement and the boat for water movement are first and second; flight in the atmosphere is third.

Air-cushion vehicles have the flexibility of operation that no other vehicles have (ref. 4). They can travel over land, water, ice, marshes, rapids, mud, shallow water, fields and many other kinds of terrain which are difficult or impossible to navigate in any other way. They are at present less efficient than aircraft because it takes additional power to maintain the cushion of air beneath the vehicle. Typically the lift drag ratio is about 2/3 that of high speed subsonic aircraft. This means that they require more fuel to operate over a given distance.

For transoceanic ranges, the larger amount of fuel required for air-cushion vehicles tends to offset the advantages of the lower capital cost and higher payload fraction that is typical of air-cushion vehicles. In this case the cost of delivering payload may not be much less than achievable with future very large cargo aircraft (see ref. 3 and 5). Nuclear powerplants can change this picture, however. The nuclear powerplant has a virtually unlimited supply of energy and consequently can operate unrefueled for distances of the order of one or two million miles and the operating cost per ton mile is independent of range. The basic cost of nuclear energy is lower than the fossil fuel cost.

Figure 5 shows the results of an economic analysis of air-cushion vehicles (ref. 6). The figure of merit is total operating cost in cents per ton mile which is plotted as a function of range. Four to six thousand miles is typical of the range required for transoceanic

vehicles. The nuclear air-cushion vehicle is shown to be considerably lower in cost to operate than chemical vehicles. The operating cost is independent of range.

An artist's concept of a commercial cargo carrying air-cushion vehicle that is designed for transoceanic commerce is shown in figure 6. It is a 5000 ton freighter 450 feet long and about 250 feet wide. It utilizes flexible skirts to trap the air cushion beneath the vehicle. The flexible skirt minimizes the leakage of air from underneath as the vehicle traverses waves. The flexible skirts also serve to smooth the ride of the vehicle over the waves. The skirts are approximately 30 feet high so that waves of about this height can be navigated without contact with the hard structure. If it is desired to have a capability for traversing higher waves, the skirts could be made higher. This particular vehicle is designed to operate at 100 knots and carry a load of cargo which is more than half the gross weight of the vehicle. It can carry 125 roll-on roll-off type (trailer truck) cargo trailers. In the mixed cargo shown, the vehicle carries 50 trailers and about 200 or 300 low density containers.

The cushion is provided by fans located below the louvered inlets on the upper deck. This type of inlet and the fact that the fans are submerged within the vehicle makes the vehicle quiet in operation. The fan and the nuclear reactor are located in the center. The fans are driven by either gas turbines or steam turbines that obtain energy from the nuclear reactor. The fans provide the flow of air required

to maintain the cushion. The thrust for propulsion is provided by a very high bypass ratio engines (ratios of 25 or 30). Because this is a low speed vehicle (relative to aircraft) high bypass ratios are required for good propulsive efficiency. The inlets are louvered and the engines are buried in the vehicle to minimize any noise problem.

An important feature about this vehicle is that it has the potential for relieving urban congestion by causing a better population distribution through its use. This comes about as follows: The air-cushion vehicle has the capability of flying over sand bars, mud flats, surf, and shallow water. It does not require a natural deep water harbor. It, therefore, can make a port near coastal regions which are inaccessible by other modes of transoceanic transportation. Examples are the southern coast of the U.S. and the Gulf coast. Large land areas in these locations are wasteland because they are inaccessible and nonuseable. A vehicle like this can travel over the reefs, shallow water, marshes, lakes and rivers inland to an area of terrain that is firm enough to build a large parking lot type of facility as shown in figure 7. This ACV port is accessible to railroads and our interstate highway systems. The air-cushion vehicle could operate like a ferry boat between ports such as the one described. It would transport roll-on roll-off trailers from one port to another (see figure 8). They would be hauled off by tractors and driven away on our interstate highway system or on piggyback railroad cars. The ACV port would be a trade center that would allow rapid access and movement of cargo to any place in the world.

The real estate around these new ACV trade centers would be cheap. Industry would be attracted to the ACV terminal area. The cost of shipping would be reduced since the distance and delays in hauling cargo through congested urban areas which exist around today's ports would be avoided. Industry would attract people. People would attract supporting service industries such as food, clothing, housing, entertainment, recreational industries. A city will, therefore, develop around this ACV port just as they developed around the deep water ports of the world in the past. The possibility of developing attractive ideal cities opens up because they could be well planned from their birth. Thus, the unique capability of the air-cushion vehicle to travel over normally submarginal or impassable terrain can be used to provide new transportation centers to attract the future growth of population to areas that are now sparsely populated.

NUCLEAR AIRCRAFT

There is probably no potential transportation system that creates a greater general negative response than nuclear aircraft. The Atomic Energy Commission and the Air Force undertook the task of developing a nuclear powered bomber and after a ten year effort costing one billion dollars the ANP (Aircraft Nuclear Propulsion) project was cancelled in 1961 (see ref. 6). Probably the main reason for failure was the ambitiousness of the goals that were set out for the program. It was desired to have a nuclear powered aircraft with a chemically powered

supersonic dash capability, all in an aircraft with a gross weight limited to about 500,000 pounds. This limitation in gross weight did not allow sufficient shielding to reduce radiation dose levels to acceptable limits. Only in a very confined shielded crew compartment was the dose level tolerable. Even when the reactor was shut down, normal aircraft maintenance could not be accomplished easily because of the high radiation levels in and around the aircraft.

The low gross weight limit did not permit the incorporation of any means for preventing the release of radiation fission products in the event of a major aircraft accident. It also did not allow the design of reactors that had long life between refuelings. The reactor had to be so compact that it could contain only enough fissionable fuel for about 100 hours of full power operation. The refueling operation was found to be a relatively costly operation that requires large complex shielded facilities.

Some have also ascribed poor management and shifting goals as strong contributors to the failure to develop a successful nuclear aircraft (see ref. 6). The primary cause, however, was the limitations and problems brought about by the restriction of the gross weight to 500,000 pounds. Except for the containment of fission products in the event of a major aircraft accident (which could not receive serious attention in the ANP program because of the weight limit), there was no basic technical reason why a nuclear propulsion system could not be successful.

Since the end of the ANP program, practical large aircraft have made their debut. Both the Boeing 747 and Lockheed C-5A (fig. 9 and 10) have a gross weight of about 3/4 of a million pounds. Growth versions of these aircraft will approach one million pounds. Aircraft are now on the drawing boards with gross weights of one to two million pounds. Projections of the size aircraft required to economically handle the large air traffic growth we are undergoing indicates the need for larger and larger aircraft. This is especially true for the air cargo industry which is now just beginning to emerge from its earliest embryonic stages.

Assuming that the airborne nuclear reactor safety problems can be solved, such large aircraft make nuclear power extremely attractive. The reason for this is that the weight of a completely shielded nuclear aircraft powerplant increases only as the square root of its power level. For example, the weight of a nuclear powerplant for a 500,000 pound aircraft is about 1/2 of the aircraft gross weight; then for a 2,000,000 pound aircraft the powerplant weighs only 1/4 of the aircraft gross weight. In this case, assuming that the aircraft structure weight is about 1/4 of the gross weight, the payload weight would be 1/2 of the gross weight. Contrasted to a fossil fueled aircraft which must carry fuel in proportion to the distance travelled, the payload weight fraction would be independent of the distance travelled. The nuclear fuel consumed would be less than 1/2 pound for a 10 hour flight.

The major stumbling block to the acceptance of nuclear power for aircraft is the prevention of the escape of fission products in the event of a major aircraft accident. It goes without saying that if the safety questions were solved, and if nuclear aircraft can be shown to be cost effective in a total transportation system, nuclear aircraft would be developed and used. In the case of military applications, the ability to fly without need for fuel that is prepositioned at remote bases or supplied by airborne tankers is obviously a tremendous advantage that has no competition.

The safety question is receiving the most attention in the new look at aircraft nuclear propulsion that NASA and the Air Force undertook starting in about 1965 (ref. 7, 5, and 8). Also receiving attention is the potential for compact airborne nuclear reactors that can be operated for 10,000 hours between refuelings. In all these studies the struggle to achieve a light weight system that is low in cost, safe and practical is prominent. The goals are lofty and difficult to achieve, yet significant progress has been made in areas which were considered hopeless only five years ago.

The most spectacular achievement has been in the area of demonstrating the potential feasibility of containment of fission products during impacts of a reactor containment system on reinforced concrete at speeds up to about 700 mph. Models of proposed containment systems and reactors (see fig. 11) have been accelerated to high speeds on the Holloman Air Force Base rocket sled test facility (fig. 12). The

models were then impacted on a reinforced concrete block (see fig. 13). They are then checked for leaks after the test (fig. 14). Even though these tests are on idealized models, they have shown that it is not inconceivable that a crash proof system can be developed for containing fission products in a major full flight speed aircraft accident. The impact program is now continuing with the addition of more and more realism. The next impact, for example, will be on a surface with a boulder about 1/4 the size of the containment vessel.

Studies have shown that methods that have been conceived for preventing the release of fission products in the event of a reactor melt down are possible. The first actual melt down of a small reactor model with a containment system such as shown in figure 15, is now ready for test in NASA's Plum Brook Reactor Test Facility.

The feasibility of aircraft reactors fuel elements that can operate for 10,000 hours is in the process of being demonstrated. The first three fuel elements which have been tested in NASA's Plum Brook Reactor have achieved the equivalent of about 8000 hours of aircraft operation before a failure occurred. A second set of fuel elements have now achieved 8000 hours of equivalent aircraft operation and the test is still in progress. Based on analysis of previous tests, it is expected that the second set of pins will exceed the 10,000 hour goal before failure occurs.

The low level effort that is currently being carried out by NASA appears to justify the consideration of a more intensive technology

effort at this time. The goal of the more intensive technology effort should be to prove conclusively the feasibility of practical, safe, economical nuclear aircraft. Aircraft that will not allow the escape of fission products even in the worst conceivable accidents. This intensive technology program is a necessary requirement before the development of nuclear aircraft for military or commercial application can be undertaken, justified, or publicly accepted.

NUCLEAR ROCKETS

The use of nuclear energy for rockets has resulted in the attainment of specific impulses about twice that of the best chemical rockets. The NERVA reactor (see fig. 16) has demonstrated a specific impulse of 825 seconds for more than one hour of operation. The NERVA propulsion system that is now ready for final development if a go ahead is obtained should permit manned 450 day round trips to Mars with less than half the initial gross weight in Earth orbit compared to the best chemical systems.

The gas-core nuclear rocket engine, which has had a long history of research on the basic problems, has recently been shown to have a potential for producing specific impulses greater than 5000 seconds (see ref. 9). No reason has yet been found that says a gas-core reactor is not feasible. We are just now beginning to approach the problem of proving that it is feasible. If it does prove feasible, it will make it possible for astronauts to explore Mars and return safely to Earth in a total of 60 days (see ref. 10). The mission

profile would be very similar to the Apollo Moon exploration mission profile.

The gas-core reactor is a whole new reactor concept (see fig. 16). The fissioning fuel is in the form of a gaseous uranium plasma operating at many tens of thousands of degrees of temperature. Energy is removed from the plasma via gaseous thermal radiation. In the case of a rocket propulsion gas-core reactor, the radiated energy is absorbed by hydrogen that is rendered opaque to the radiation by the addition of seed particles like smoke.

The gas-core reactor has other potential applications (see ref. 11 and 12). It may be used for stationary electric power production by using the hot gases generated to drive gas turbines and/or making steam to drive a steam turbine. The gases can be so hot that they are ionized so that they can be used in an MHD generator to produce electrical energy. Because of the low parasitic neutron absorption that is characteristic of gas-core reactors, they may find application as breeder reactors. In this case, fertile materials may flow through moderator regions or through the gaseous core itself, in addition to being located in blankets around the reflector.

Because of the molecular or atomic population inversions made possible by the processes that occur in a fissioning plasma, it is conceivable that new lasers powered directly by fissioning atoms may be possible. Examination of these possibilities has just begun.

CONCLUDING REMARKS

Nuclear energy offers mankind many options in propulsion and power that cannot be achieved in other ways. It makes possible a more abundant and cheaper source of electrical energy; a faster more efficient waterborne or underwater shipping system; a 100 knot air-cushion vehicle transportation system that can generate new port cities and transportation centers to better distribute our growing population; an airplane that has essentially no duration or distance limit and has potential for low cost very high speed cargo transportation; finally it can make possible a 60-day round trip to Mars.

What other technology has so much to offer?

REFERENCES

1. Kosofsky, F., and Mazursky, S., "Future Dynamics of United States Flag Oceanborne Transportation," Paper 69-413, May 1969, AIAA, New York, N.Y.
2. Pitkin, M , "An Assessment of Nuclear Propulsion: A Challenge for the Seventies," SM 141-54, May 13, 1971, U. S. Maritime Administration.
3. Rom, F. E., "Nuclear Power for Surface Effect Vehicle and Aircraft Propulsion," Paper 70-1221, Oct. 1970, AIAA, New York, N.Y.
4. Anderson, J L., "A Nuclear Powered Air Cushion Freighter for the 1980's," TM X-67876, Oct. 1971, NASA, Cleveland, Ohio.
5. Rom, F. E , "Airbreathing Nuclear Propulsion: A New Look," Nuclear News, Vol. 14, No. 10, Oct. 1971, pp. 79-84, 87.
6. 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.
7. Rom, F. E., and Finnegan, P. M., "Will the Nuclear-Powered Aircraft be Safe?" Astronautics and Aeronautics, Vol. 6, No. 3, Mar. 1968, pp. 32-40.
8. Rom, F. E., "The Nuclear-Powered Airplane," Technology Review, Vol. 72, No. 2, Dec. 1969, pp. 48-56.
9. Ragsdale, R. G., "Gas-Core Rocket Reactors—A New Look," TM X-67823, June 1971, NASA, Cleveland, Ohio.
10. Fishbach, L. H., and Willis, E. A., Jr., "Performance Potential of Gas-Core and Fusion Rockets: A Mission Applications Survey," TM X-67940, Nov. 1971, NASA, Cleveland, Ohio.

11. Clement, J. D., and Williams, J. R., "Gas-Core Reactor Technology," Reactor Technology, Vol. 13, No. 3, Summer 1970, pp. 226-251.

12. Thom, K., and Schneider, R. T., eds., "Research on Uranium Plasmas and Their Technological Applications," SP-236, 1971, NASA, Washington, D.C.

TABLE I

FOSSIL AND NUCLEAR FUEL COST

	Unit Cost	$\$/10^6$ btu
Marine fuel	\$2.50/bbl	0.39
Aviation fuel	\$0.08/gal	.62
Nuclear fuel	12 \$/gm	.16

TABLE II

WORLDWIDE OPERATIONAL NUCLEAR POWERPLANTS

	1971	1976-1980
Stationary	111	256
Submarine	184	228+
Ship	6	15+
Totals	301	500+

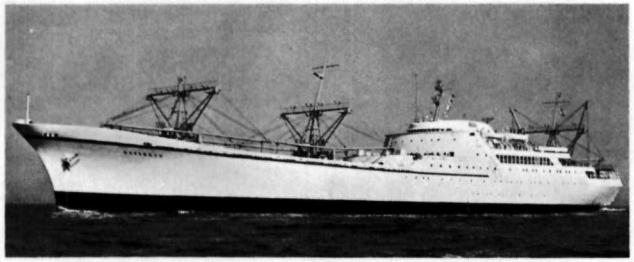
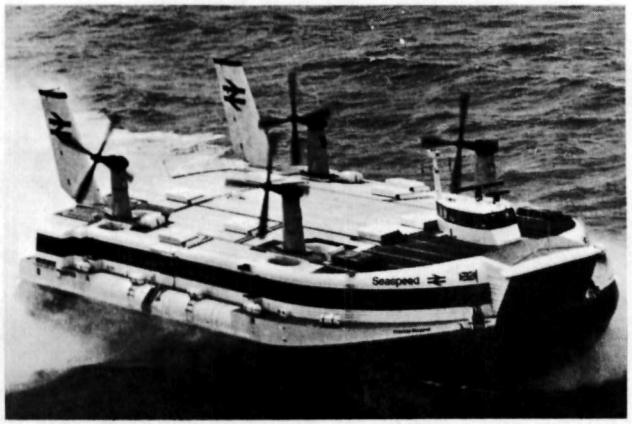


Figure 1. - NS Savannah, the world's first nuclear ship.



CS-53867

Figure 3. - British Hovercraft Ltd. SRN-4 Air Cushoin Vehicle in operation as English Channel passenger and auto ferry. Gross weight, 168 tons. Speed, 65 knots.

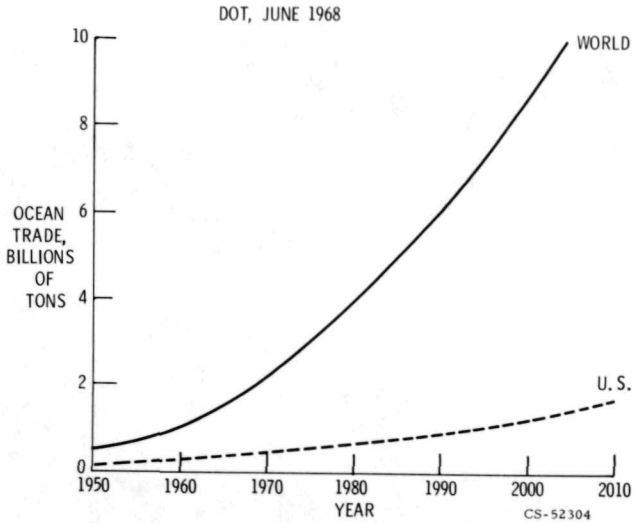


Figure 2. - Department of Transportation World Oceanborne Trade Forecast.

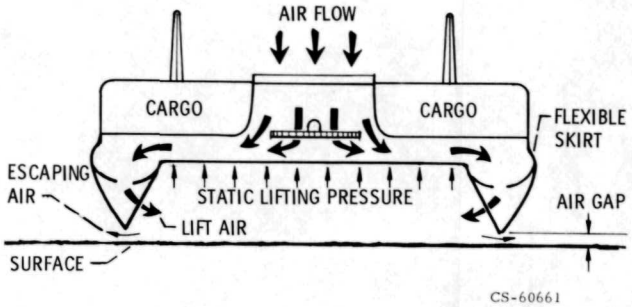


Figure 4. - Principle of air cushion vehicle.

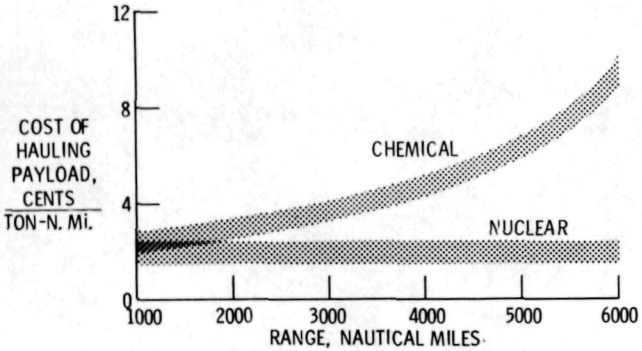


Figure 5. - Operating costs for nuclear and chemical air cushion vehicles; gross weight, 5000 tons.

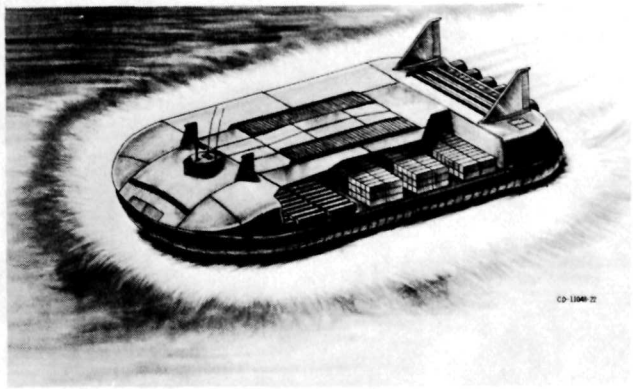


Figure 6. - 5000 Ton nuclear ACV freighter.

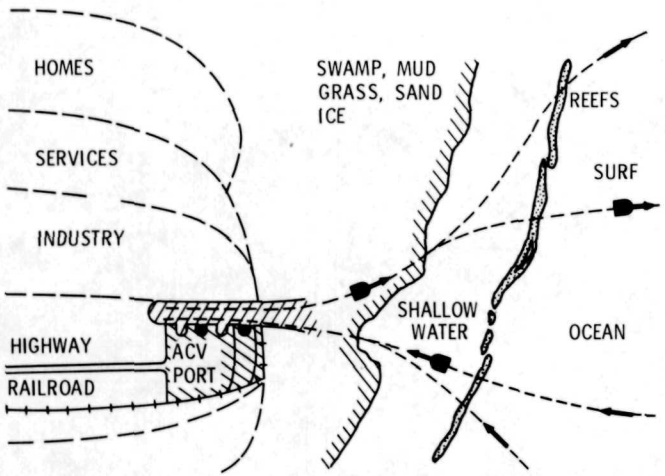
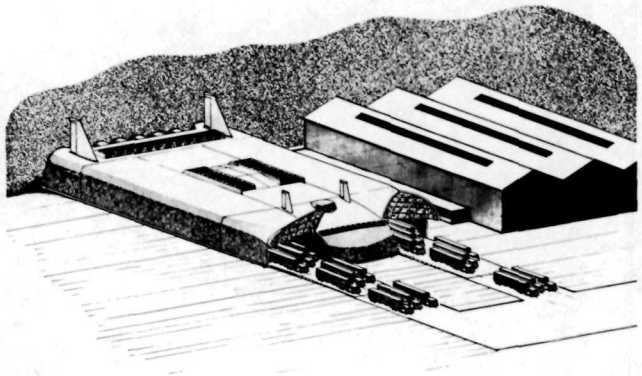
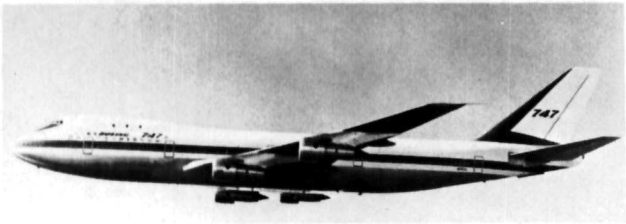


Figure 7. - Air cushion vehicle trade center.



CD-11099-02

Figure 8. - Roll-on roll-off ACV freighter.



C-71-2347

Figure 9. - Boeing 747 aircraft. Gross weight, 322 metric tons (355 tons); cruise speed, 1010 kilometers per hour (545 knots).

C-71-2346

Figure 10. - Lockheed C-5A aircraft. Gross weight, 361 metric tons (399 tons); cruise speed, 780 kilometers per hour (420 knots).

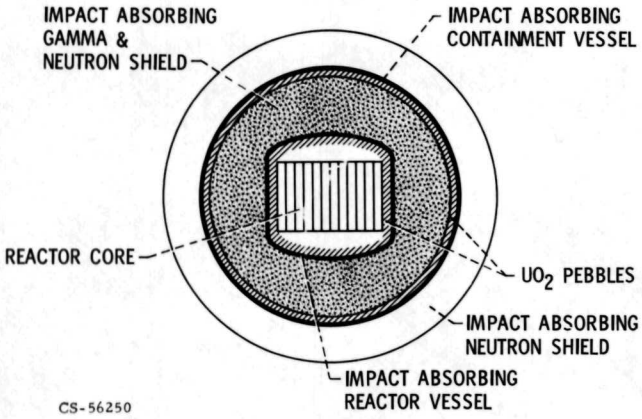


Figure 11. - Mobile reactor containment system concept.

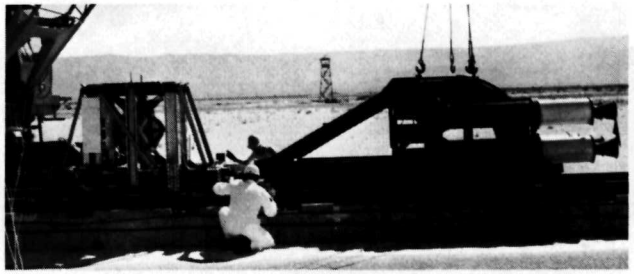


Figure 12. - Rocket sled for reactor containment vessel impact test.

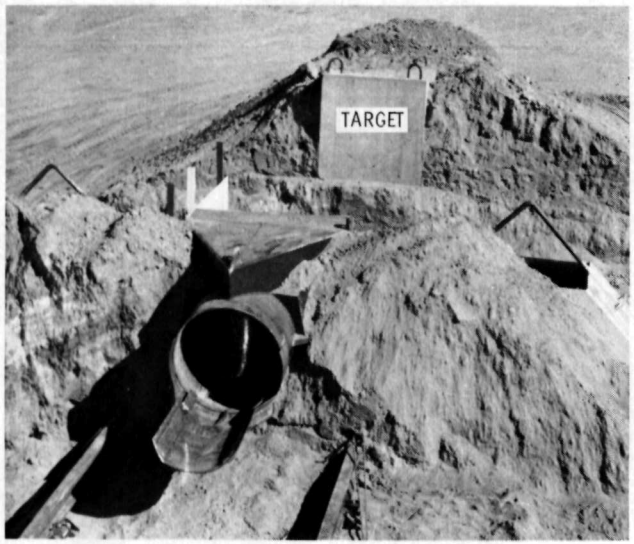


Figure 13. - Reinforced concrete target for reactor containment vessel impact tests.

Figure 14. - Spherical containment vessel after impact at 700 mph. Vessel did not split open.

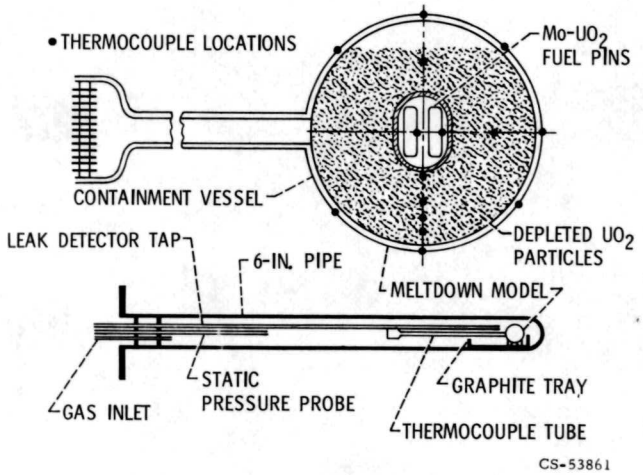


Figure 15. - Reactor meltdown containment experiment.

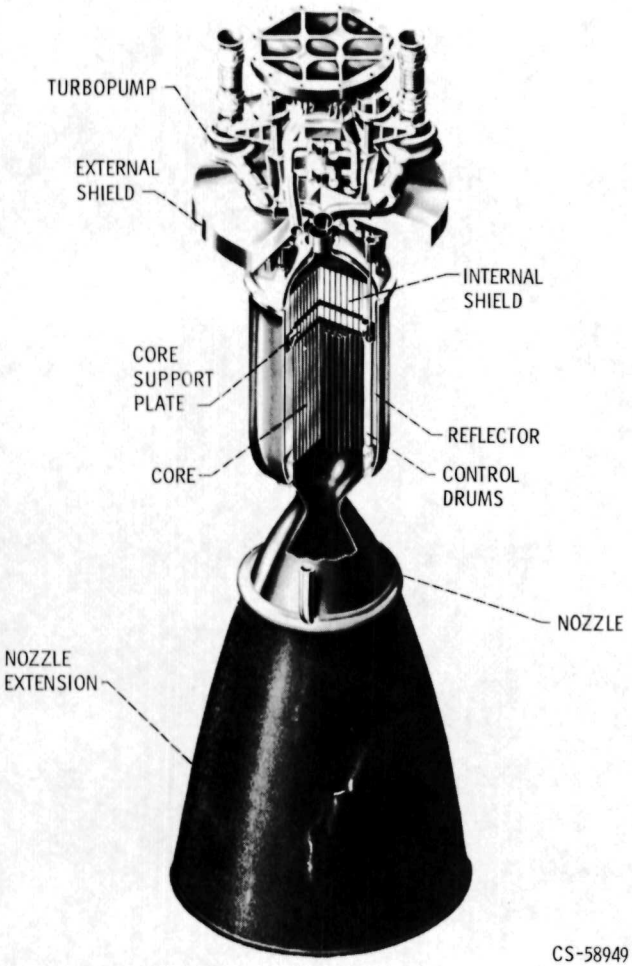


Figure 16. - NERVA graphite rocket reactor.

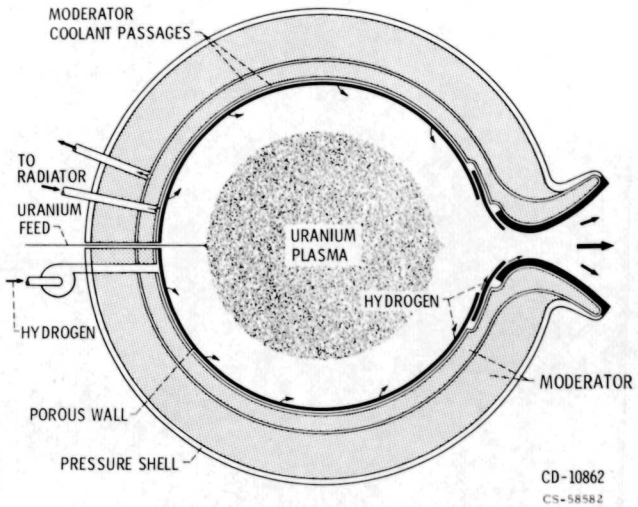


Figure 17. - Porous wall gas core engine.