NUCLEAR SPACE PROPULSION SYSTEMS

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Since the first space flights in 1957, a large number of rockets have been launched by the United States and the U.S.S.R. to place various scientific and technological experiments into space and to permit man to take his first voyages into space. New information on the earth, its nearest neighbor, the moon, and Venus has been obtained. The first relatively close look at Venus has been taken and further examination of this neighboring planet as well as of Mars will be carried out. The moon is an object of attention in providing a better understanding of the origin of the earth and Ranger-7 has provided our first close look at that satellite of the earth. The Van Allen belts of radiation around the earth and the shape of the earth are now known and the complex electromagnetic seas in which the earth moves around the sun are being better defined. The development of space technology provides improved weather forecasting, communications, and navigational aids through the satellites that are in use and that are being developed. In addition to the large amount of information accumulated in this relatively short period using advanced instrumentation and measuring techniques, the first steps have been taken to understand the capabilities of man in space so that he can apply his judgment and versatility to enhance the accumulation of scientific information and understanding of space. As a major technological as well as scientific undertaking, the United States has undertaken the Apollo program aimed at landing men on the moon in this decade.

All of these space missions that have been conducted so far and that are now under development have used chemical combustion rocket systems to provide the propulsive energy needed. Such rockets were available when the space program started, their technology and operation was understood, and improvements including the development of larger rockets and systems using the high-energy hydrogen-oxygen propellant combination could be provided in reasonable times with sufficiently improved performance to permit conduct of even manned landings on the moon. Thus, the dependence of the space program on chemical combustion propulsion was natural in providing the quick birth and early growth of activity in this new area of exploration.

However, the missions conducted so far in these early years of space exploration have required relatively low energies. The chemical-bond energies available in these chemical-combustion rocket systems became inadequate for the performance of deep-space, high-payload missions. We can visualize high-energy missions in space, to the planets, close in to the sun, and far out of the plane of the planetary orbits that will require that higher energy sources be utilized for propulsion. The use of nuclear energy in space is therefore an inevitable requirement if mankind is really to have the capability to travel freely in this new environment with both instrumented and also with manned vehicles so that he may know and understand this relatively unknown region in which our earth lives and if he is to benefit from this new knowledge and the resources that may derive from it.

In describing the work on space nuclear propulsion it must first be recognized that there are many nuclear systems having application in space exploration. These nuclear propulsion systems include nuclear reactor rocket propulsion using solid-fuel-element reactors, electric propulsion using nuclear reactor electric power generation, liquid- and gaseous-core nuclear rockets, nuclear pulse propulsion, and others. The interest in all of these systems arises from the eventual need to provide large amounts of energy for the performance of deep-space, high-payload missions.

In the United States major emphasis has been devoted to the first two of these nuclear propulsion systems, the solid-reactor-core nuclear rockets and the nuclear electric propulsion, with a smaller research effort on all of the other nuclear systems that have been proposed and are under consideration.

A cross-section drawing of a solid-core nuclear rocket propulsion system is shown in Fig. 1. Liquid hydrogen is stored in a large propellant tank and serves as the propellant for this open-cycle system. The liquid hydrogen is pumped from the tank and is used to cool the walls of the jet nozzle. The hydrogen passes through the reflector and then through the reactor core where it is heated to high temperature by contact with the fuel elements containing the fissionable uranium fuel. The high-temperature hydrogen gas is then ejected through the jet nozzle where it is accelerated to velocities several times greater than the values possible in chemical-combustion systems. These high velocities result in specific impulses (thrust per pound of propellant flow per second) two to three times the values that may be achieved with chemical combustion rocket systems. Specifically, specific impulse of 800 sec is reasonable and higher values may ultimately be achievable with nuclear rockets. This value compares with the 300 to 450 sec possible with the chemical combustion systems now being applied and under development.

Solid-core nuclear rockets, with special emphasis on the reactor systems that use graphite as the structural and fuel moderator material, are undoubtedly in a more advanced state of development than any of the other nuclear systems. Their performance potential has been demonstrated by short-time reactor tests. Longer-time tests are planned during this calendar year and next. Engineering and technology work is well underway. Nuclear rockets offer substantial performance improvement; they offer very high specific-impulse capabilities; they offer a wide range of thrust capability. They utilize much technology that is already being developed or is already available in hydrogen-oxygen chemical rockets, since many of the components are similar to the hydrogen-oxygen components; they can be developed using general methods similar to those understood in chemical rocket development. Nuclear rockets offer the ability to perform a wide range of missions and they are particularly advantageous for advanced missions beyond Apollo. They do require advancement in nuclear reactor and nonnuclear component technology and test facilities, but they do not require the development of fundamental new scientific principles or con-

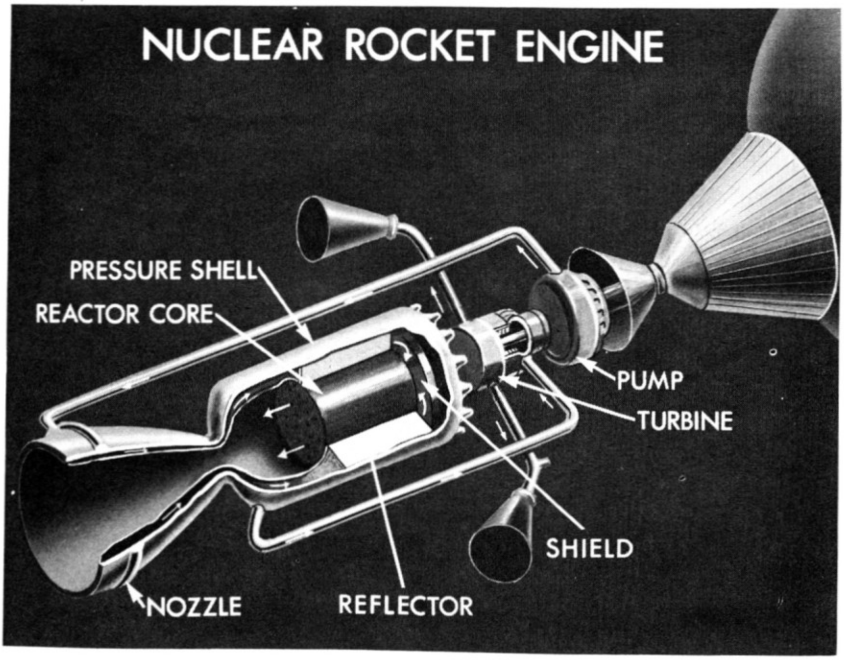


Figure 1. Nuclear rocket engine.

cepts. We therefore believe that solid-core nuclear rockets will be the first advanced nuclear propulsion systems developed for space missions and we can assess their applicability and availability with greater assurance than is the case for any other nuclear propulsion system. The United States program in this area is directed toward establishing or extending the technology in the important reactor engine and vehicle areas and establishing design information and operating capabilities so that nuclear rockets can be made available and utilized quickly when advanced space missions requiring their high-performance capabilities are more clearly defined.

After several exploratory reactor tests and extensive laboratory research on materials, physics, cryogenics, heat transfer, etc., initiated in 1955, the Los Alamos Scientific Laboratory successfully tested a nuclear rocket reactor in May 1964 at powers and temperatures close to the design values. I would like briefly to review the history, progress, status, and future plans of this effort in the United States to provide nuclear propelled rockets for space exploration missions.

The Rover program (the general name of the nuclear rocket propulsion development program) was started at the Los Alamos Scientific Laboratory in 1955 with laboratory research that led to the KIWI-A reactor tests (named after the nonflying New Zealand bird because of the research nature of these tests) in 1959 and 1960.

A photograph of the KIWI-A reactor is shown in Fig. 2. These tests and later tests of the KIWI-B1 reactors conducted in 1961 and 1962 provided important information on the design techniques, materials properties, cold-to-hot neutronic factors, verification of the suitability of controlling the fission power generation of the reactor by rotating drums in the reflector portion of the reactor, and demonstration of the ability to start and operate such reactors using liquid hydrogen as the coolant or propellant. In November 1962 the KIWI-B4A reactor was tested at our Nuclear Rocket Development Station in Nevada. This reactor (Fig. 3) was our favored design for use in the NERVA (Nuclear Engine for Rocket Vehicle Application) engine, which will be our first nuclear rocket engine.

The KIWI-NERVA reactors are graphite-based reactors using graphite fuel elements impregnated with uranium carbide. The reactor core is made up of clusters of these fuel elements and is supported by both a lateral and an axial support system. These support systems must accommodate large changes in core dimensions arising from thermal expansion of the core as they provide for the static and dynamic loads imposed on the core. In order to achieve as close to uniform temperature distribution throughout the core as possible, the uranium loading and flow distribution are adjusted radially across the core. The outer reflector cylinder in both reactors is made of beryllium and is cooled by liquid hydrogen from the regenerative cooling passages of the jet nozzle. Twelve rotary control drums, made of beryllium with a boral sheet subtending 120° of arc, are used to control the reactor.

A short movie taken during the KIWI-B4A test in November 1962 shows flashes in the jet exhaust that indicated that graphite damage was occurring in the reactor core. On disassembly, extensive fuel element cracking and core damage was found.

During 1963 extensive redesign, analysis, component testing, subsystem tests, and cold flow tests of the KIWI-B4A and KIWI-B4B reactors demonstrated that the damage of the KIWI-B4A reactor was caused by vibrations that were flow induced and not associated with fission power. This extensive work also indicated that the design approach being taken by Los Alamos and Westinghouse (the NERVA reactor subcontractor) to avoid these vibrations would lead to a stable structural design.

In February 1964 a cold-flow version (in which no fission energy is generated) of the Los Alamos redesigned reactor was tested and indicated that this redesigned reactor successfully avoided the vibrations that had been encountered in the KIWI-B4A reactor.

In March and April 1964 the NRX-A cold-flow reactor was run by Westinghouse and Aerojet-General (the NERVA contractors) and indi-

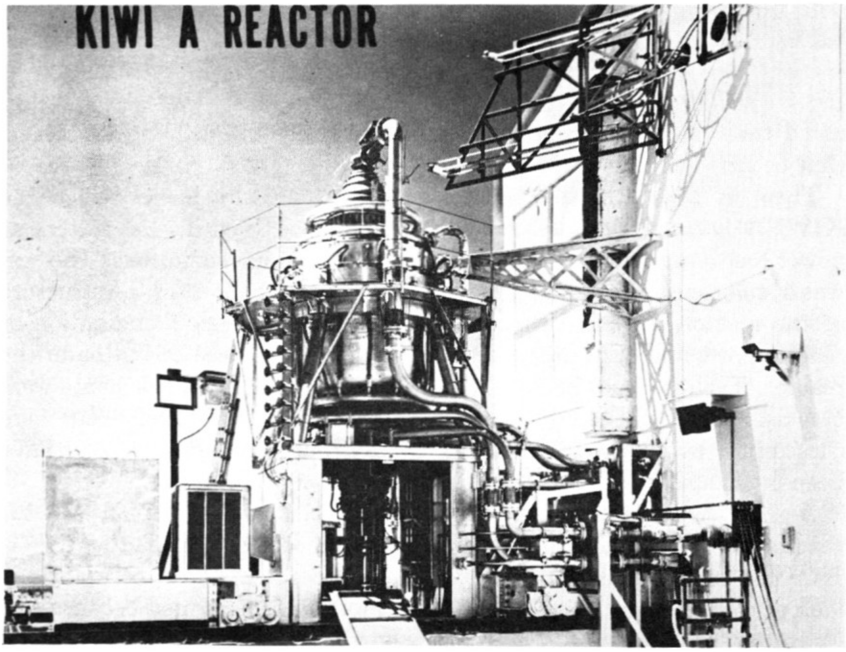


Figure 2. KIWI-A reactor.

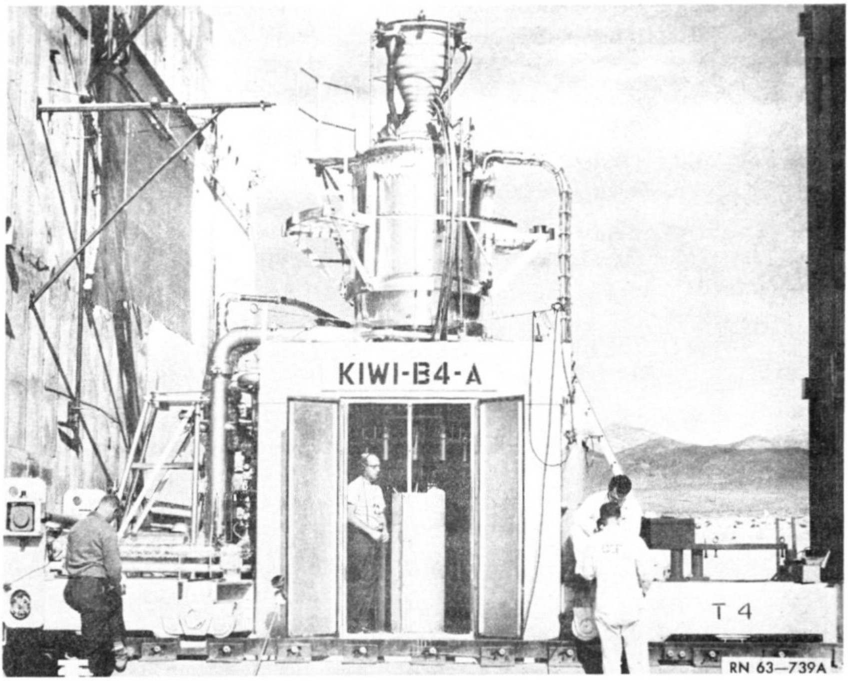


Figure 3. KIWI-B4A reactor

cated that this Westinghouse design successfully avoided the vibrations that occurred in the KIWI-B4A reactor.

Then on May 13, 1964, a major milestone was achieved when the KIWI-B4D reactor was tested by the Los Alamos Scientific Laboratory at power and temperature conditions close to the design conditions. The test was of sufficient duration to provide a significant proof test of the structure of the reactor, as well as many other reactor features. Examination of reactor parts and data analysis have indicated successful operation of the reactor. The structure behaved as it was designed. No fuel elements were cracked; the vibrations encountered in the November 1962 tests were successfully avoided. We can safely say that our structural problems have been overcome.

A short movie taken during the power operation of the KIWI-B4D reactor shows how clean the exhaust jet is compared to the earlier KIWI-B4A test run. This indicates the successful operation of the core and the lack of core damage. The test time was shorter than planned because of a hydrogen leak that occurred in the jet nozzle causing a fire around the reactor. Fortunately, this nozzle failure did not compromise our test objectives; the reactor continued to operate stably after the leak occurred and it was shut down in a normal controlled way. Although we are concerned about the jet-nozzle problem, it is not an area that affects the basic developability or availability of nuclear rockets.

Further reactor tests will be run during the remainder of this year, on the KIWI-B4 and NRX-A reactors. In addition, tests will be run next year on the KIWI-sized versions of the Los Alamos Phoebus reactors as well as additional NRX-A reactors. These reactor tests, supported by laboratory work, are intended to fully evaluate the effects of longer operating times, particularly on reactor fuel elements, and to investigate the potential of increased power operation.

The reactor test work will lead to tests of experimental engines which should fully evaluate the operating characteristics of nuclear rocket engines to a point that flight system development for use in the various potential future missions can be undertaken with a high level of confidence and with an accurate basis for anticipating technical problems and for estimating development time, cost, facility, and manpower requirements. This is a technology effort that will lead eventually to the development and application of these systems in space missions.

To summarize our work on nuclear rockets, a major forward step was taken in the KIWI-B4D nuclear rocket reactor experiment. This test provides good reason for confidence in the successful execution of the tests to be conducted this year and next and provides a good basis for confidence in the availability of nuclear rockets when they will be required for the performance of advanced space missions. The availability of these nuclear rocket propulsion systems will give us a propulsion capability far advanced over any other rocket propulsion system available.

ELECTRIC PROPULSION

Electric propulsion is the second area of nuclear propulsion that is receiving substantial research work and development attention in the United States. A schematic drawing of an electric propulsion system is shown in Fig. 4 to indicate the major parts of the system. Thrust is generated by a thrustor engine which may be one of several types but which basically accelerates the propellant by application of electrical energy to generate heat, electrostatic fields, or magnetic fields. The electrical energy required by the thrustor is provided by an electric power generating system which, for large electric-propulsion systems used to propel spacecraft over large distances, will use nuclear reactors as the primary source of heat energy.

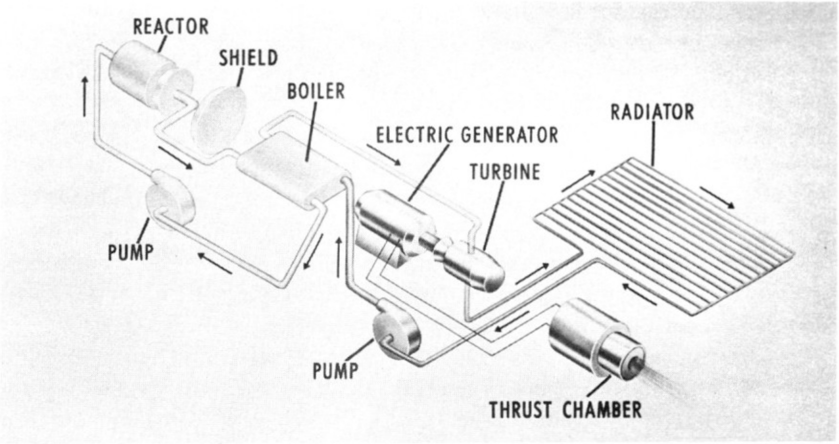


Figure 4. Nuclear-electric power and propulsion system.

While the primary applications of nuclear rockets are in the manned missions in space, it appears from the results of our advanced mission studies and the theoretical performance estimates that the earliest applications of nuclear electric propulsion will be in unmanned scientific and satellite applications missions involving high velocity increments. Among these unmanned missions, electric propulsion will probably be applied first as small, attitude-control, and orbital-position-keeping engines, where power already available in the satellite would provide the electrical energy needed for the electric propulsion thrustor. The electric accelerators or thrustors for such applications could be provided in a relatively short time. Beyond these earliest electric-thrust applications we can anticipate propulsion for unmanned spacecraft deep into space. Among the unmanned scientific missions for which electric propulsion may be required are the solar probes that would be aimed at delivering spacecraft, weighing at least a few hundred pounds, close to the sun or probes to high angles out of the plane of the planetary orbits. Ideal velocity increments for these missions will reach 75,000 ft/sec. They, therefore, provide a potential application for electric propulsion.

Beyond the unmanned spacecraft propulsion, we can anticipate manned planetary exploration based on nuclear electric propulsion, or more probably, combinations of electric propulsion and nuclear rocket propulsion. The possible use of electric propulsion in the second stage of an earth-orbit departure vehicle (with a nuclear rocket first stage) is based on the performance potential of high power (approximately 5 mw) nuclear electric systems but is not yet based on real data that demonstrate the feasibility of obtaining low system weights (10–20 lb per electrical kw) with operating times of 10,000 to 20,000 hr reliably. It is of interest to point out that if electric propulsion is to be used as the sole propulsion system from earth orbit to the planets in manned missions, electrical power levels of tens of megawatts would be required.

It is essential that data from our technology development programs be obtained to assess the performance that will eventually be achievable in these various high-power electric propulsion systems. Because the technology of such systems is not yet available and because much research information remains to be accumulated, electric propulsion is at a much earlier stage of development than is the case with the nuclear rockets that were described earlier.

Our work on electric propulsion is divided into two main parts since the system itself can be divided into two principal portions—the system that generates electric power and the thrust system that uses that electric power to accelerate the propellant, producing thrust.

ELECTRIC THRUSTOR TECHNOLOGY

There are three main types of electric thrustors, pictured schematically in Fig. 5: the electrothermal jet (shown as an arc jet here), the ion jet (electrostatic), and the plasma jet (electromagnetic or MHD). They differ principally in the method used to accelerate the propellant. For example, the propellant in an electrothermal jet is accelerated by heating it in an

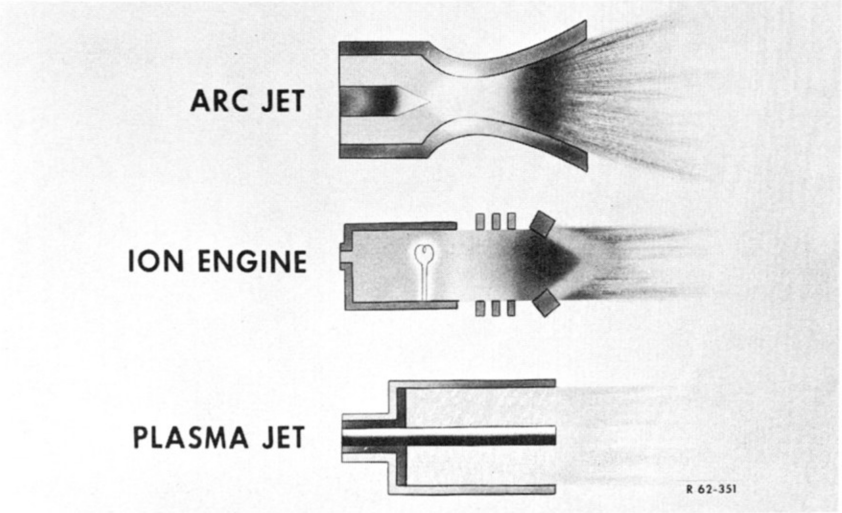


Figure 5. Electric thrust chamber program.

arc discharge or in an electric resistance heater and expanding it through a jet nozzle. The ion and plasma jets develop thrust by means of reactions between the propellant in an ionized state and electrostatic and electromagnetic fields respectively.

Our major emphasis has been and still is on the electrostatic ion engine although work is also proceeding on the electromagnetic and electrothermal engines. A very significant milestone in this part of our program was achieved on July 20, 1964, when the SERT I (Space Electric Rocket Test) spacecraft was flown on a Scout vehicle from Wallops Island, Virginia (Fig. 6). The SERT spacecraft carried two ion engines; one having a thrust of 0.001 lb and the other a thrust of 0.006 lb. The objective of this SERT flight test was to answer conclusively the questions concerning neutralization of the exit ion beam required to avoid a buildup of space charge in the electrostatic ion engine system, which would deteriorate the thrust capability of the system. Ground-test data had indicated that ion beam neutralization could be accomplished by injecting electrons in the exhaust jet; however, the infinite expanse of space cannot be duplicated in any of the contained ground vacuum chambers. In this test the thrust of the system was indicated by the spin rate of the vehicle since, as shown in Fig. 7, the thrust was directed in a tangential direction. Only the 0.006-lb thrust engine operated during the test but its operation was so successful that neutral-

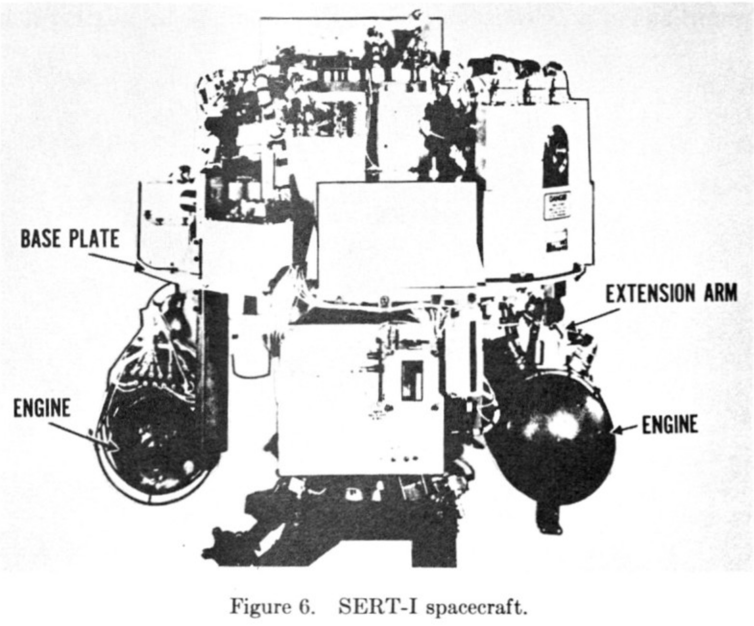


Figure 6. SERT-I spacecraft.

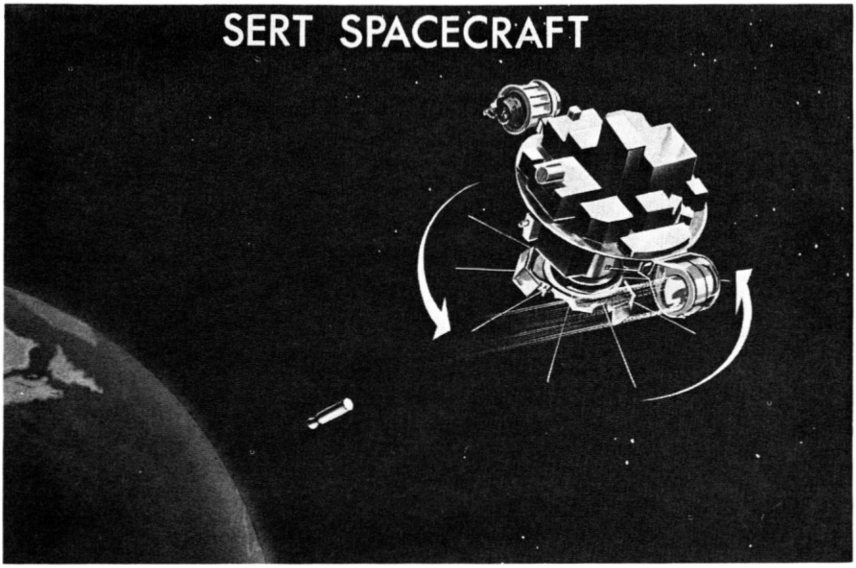


Figure 7. SERT spacecraft.

ization was clearly demonstrated and the ability to start, shut down, and restart these engines in space was also demonstrated.

The extensive data that we have obtained in ground-test facilities and in the SERT flight indicate that the technology of low-power ion engines is available. The technology of the high-powered (megawatt) engines for the propulsion of large manned and unmanned spacecraft is not yet available. It appears now that the most practical way of achieving increased thrust with electric thrustor systems is by clustering a number of smaller thrustors. Accordingly, we have been testing a 9 module cluster of 3-kw ion engines shown in Fig. 8; also a single 30-kw engine shown in Fig. 9 as the next step toward achieving our ultimate goal of megawatt size thrustors. This work aimed at increasing the thrust while maintaining high efficiency and long life is a major portion of our electric propulsion program.

NUCLEAR REACTOR ELECTRIC POWER

Although much more work must be done to assure the availability of thrustors having efficiency, life, thrust, and frontal area that will be required in space missions, the most difficult and pacing element of electric propulsion is the development of high-power, long-life, low-specific-weight, nuclear-reactor electric generating systems. The two systems that are being investigated for electric power generation rely on the Rankine cycle, alkali

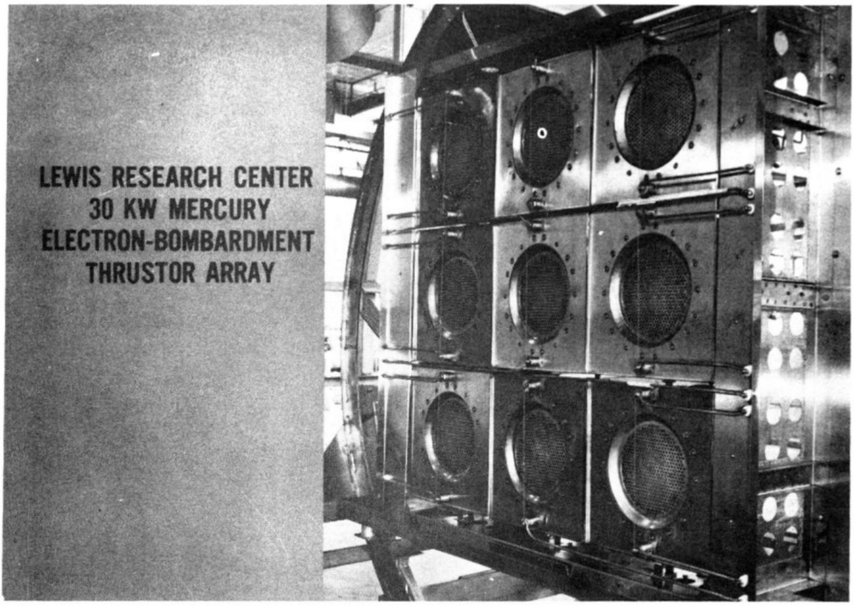


Figure 8. 30-kw mercury electron-bombardment thrustor array.

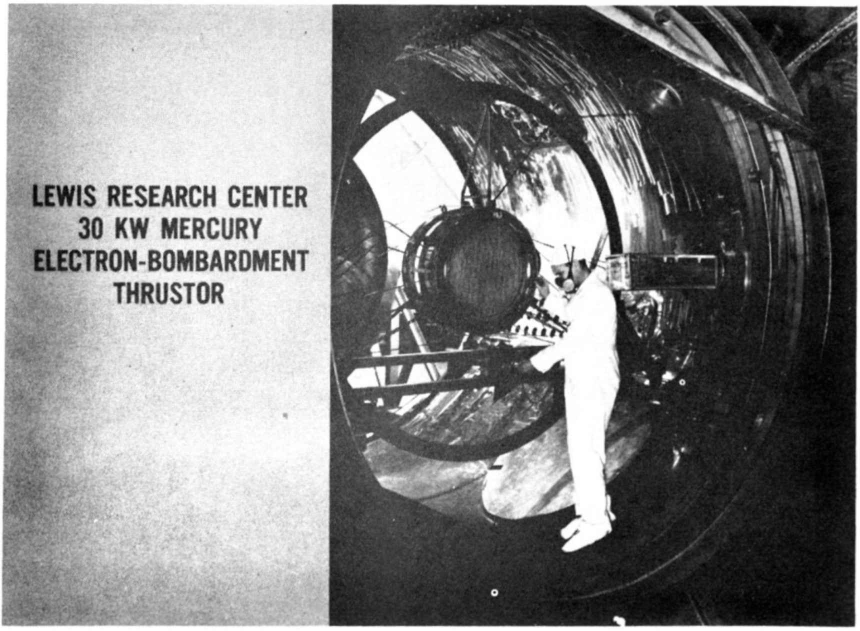


Figure 9. 30-kw mercury electron-bombardment thrustor.

metal working fluid, turboalternator concept shown in Fig. 10 and the thermionic direct conversion concept shown in Fig. 11. In the turbogenerator system, heat from the nuclear reactor is converted to electrical energy in a liquid-metal working fluid cycle operating at temperatures in the neighborhood of 2000°F in order to achieve the extremely low weight capability required for electric propulsion. In the thermionic direct conversion system being investigated, nuclear fission energy is used to heat a cathode which emits electrons at its surface. The electrons flow across a small gap to a cool anode and then deliver power to the external load. Both of these systems are complex; they are beyond our current technological capability even though we are generally more familiar with, and many feel more at home with the general class of components in the Rankine cycle, such as turbines, pumps, etc.

As part of our work we are well along on finding the basic properties of the working fluids that will be used. Such information was not available when we started this work in the late 1950s. In addition, long-time material tests are underway and physical property data on refractory materials that are suitable for use in these systems are being obtained; corrosion test loops are now beginning to provide data; a large fund of boiling and condensing heat-transfer data is being accumulated; turbine-test facilities have been built and turbine tests are being initiated with potassium vapor; ground tests of low-speed meteoroid impact conditions with candidate, lightweight radiator materials have been run (although with somewhat

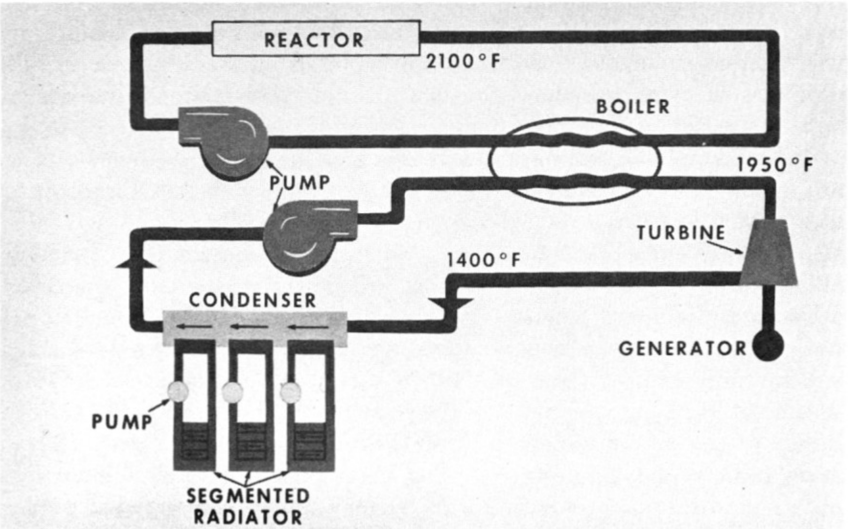
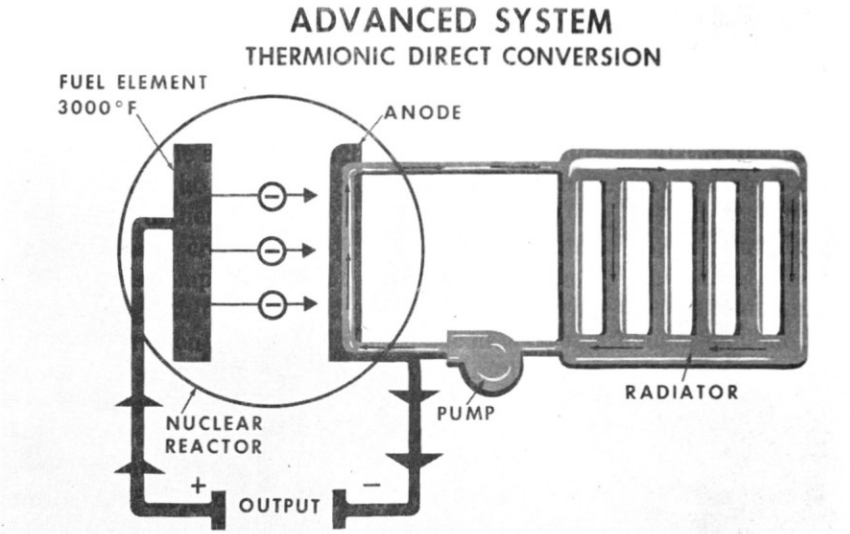


Figure 10. Advanced system—turboelectric.



m—thermionic direct conversion.

discouraging results); the space meteoroid puncture models are now better defined than was the case when we started the program. With regard to the thermionic emitter systems, much information on material properties is being accumulated, but many materials problems remain and new ones have been identified. Long-time emitter tests have been run, including a very limited bit of test operation up to 8,500 hr outside of a reactor. The problems of operating these emitters are better understood and designs aimed at avoiding the major ones are being defined.

Some examples of our work in this area and the results we have obtained are indicated in the next several slides. Figure 12 indicates the property data that have been obtained for potassium and sodium liquid and vapor as a result of our work in comparison with the information that was available before our program started. You will note that there are significant areas in which there were no previous experimental data. You will also notice that the range of temperatures over which data are now available is substantially greater than that which was available earlier. Such information on the basic properties of the materials is obviously essential in the design of any power system utilizing these working fluids. Figure 13 indicates some of the single-tube boiling heat-transfer data that have been obtained with potassium over a wide range of quality, presented as percent of vapor. With helical inserts, extremely high heat-transfer coefficients are obtained even into the high-quality region. Figure 14 shows the turbine-

PROPERTY	STATE	METAL	PREVIOUS DATA	DATA FROM THIS WORK (°F)
VAPOR PRESSURE	VAPOR	POTASSIUM	1100-1850	900-2100
		SODIUM	1500-2000	900-2100
DENSITY	LIQUID	POTASSIUM	150-1300	300-2100
		SODIUM	200-1500	300-2500
	VAPOR	POTASSIUM	**NONE**	900-2100
		SODIUM	**NONE**	900-2500
PRESSURE VOLUME TEMPERATURE	VAPOR	POTASSIUM	**NONE**	900-2100
		SODIUM	**NONE**	900-2500
SPECIFIC HEAT	LIQUID	POTASSIUM	150-1500	32-2100
		SODIUM	200-1650	300-2100
	VAPOR	POTASSIUM	**NONE**	300-2100
		SODIUM	**NONE**	300-2100
VISCOSITY	LIQUID	POTASSIUM	150-1300	150-2100
THERMAL CONDUCTIVITY	LIQUID	POTASSIUM	800-1140	200-1500
	VAPOR	POTASSIUM	**NONE**	900-2100
SURFACE TENSION	LIQUID	POTASSIUM	150-900	200-2100

Figure 12. Property measurements.

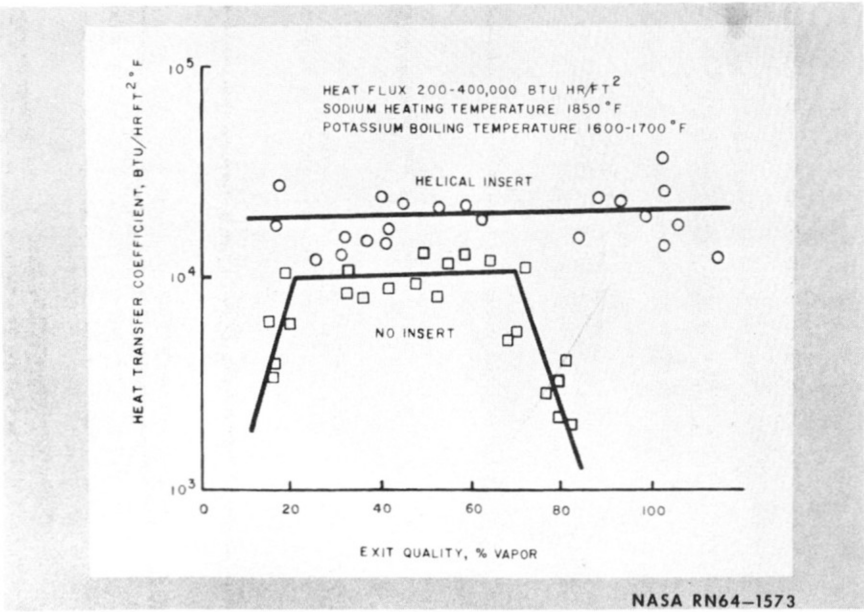


Figure 13. Potassium single-tube boiler test data.

test installation at General Electric that is now being used for turbine tests under contract with NASA. Information on the effects of moisture on both the erosion characteristics and performance characteristics of the potassium turbine will be obtained in this test installation. Additional turbine research work is underway at the NASA Lewis Research Center.

Because of the large weight associated with radiators in high-power nuclear electric power supplies and the importance of reducing overall system weight to assure that the performance potential of electric propulsion may be achieved, considerable effort is being devoted to evaluation of the design and resulting weight of radiators. One of the major uncertainties is and has been the protection required on radiator tubes to assure that they will not be penetrated by meteoroids during a space-flight mission. Evaluation of the meteoroid environment in space and development of models to predict the penetration resulting from meteoroids have, therefore, been investigated. As indicated earlier, the meteoroids penetration model correlations have been substantially improved during the past year. However, the selection of a lightweight material for use in fabricating the radiator is still under investigation. Figure 15 shows the relative radiator weights for the various materials that have been considered. You will note that beryllium is by far the lightest material for such application.


POTASSIUM TURBINE INSTALLED ON TEST STAND

Figure 14. Potassium test turbine installation.

However, as shown in Fig. 16, beryllium tends to crack when it is impacted by projectiles simulating meteoroid projectiles. It should be noted that in this case a ⅛-in.-diameter glass projectile with a velocity of 25,000 ft/sec impacted the beryllium tube sample. These velocities are substantially lower than the meteoroid velocities that would be encountered in space. Because of this cracking problem, the use of beryllium is at this point

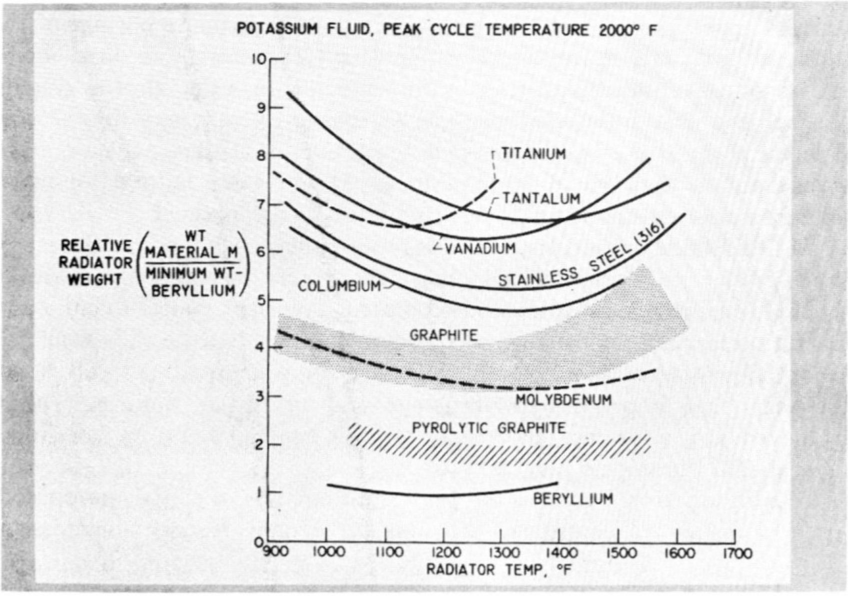


Figure 15. Radiator relative weight.

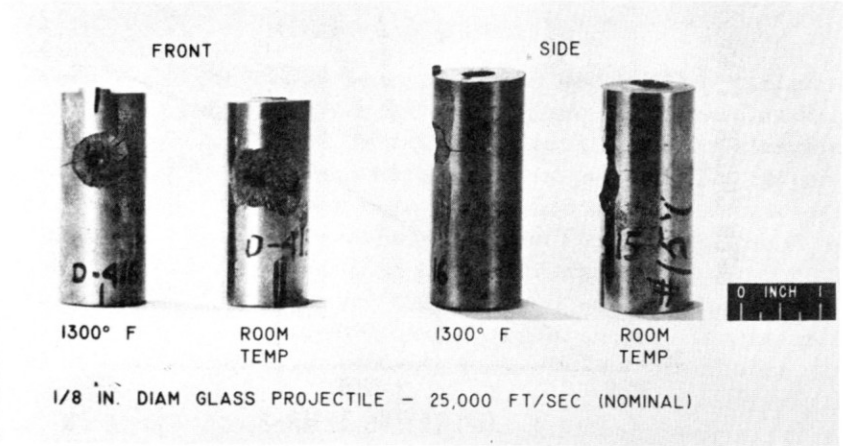


Figure 16. Impact into beryllium tubes.

uncertain and it is conceivable that more ductile materials may be required in our radiator structures. Should this be the case, the weight of nuclear electric power supplies may increase substantially above the values that would be desired to achieve the full performance potential of electric propulsion.

Interesting information has also been obtained with regard to thermionic direct conversion systems. As shown in Fig. 17, it has been found that in certain concepts in which the emitter or the hot cathode portion of the thermionic emitter encopsulates the nuclear fuel material, an open circuit will lead to a substantial increase in the temperature of that emitter system. To achieve maximum power output of these systems, it is desirable to operate them at the highest possible temperature. Designs are now under consideration that would attempt to avoid this large margin for open-circuit emitter temperature that would have to be provided.

As I indicated earlier, considerable progress has been made with respect to converter life. Figure 18 lists some of the results of single cell electrically heated converter tests in the United States. To orient you as to our goals, useful performance consistent with the units shown on the slide would be about 10 watts/cm^2 ideal power with efficiency of about 20 percent. It can be seen that impressive performance and operating times are being achieved. It is a far cry, however, from these simple laboratory tests to an operational thermionic reactor.

In addition to this work on the nonreactor portions of electric propulsion, it is important to emphasize that the US Atomic Energy Commission,

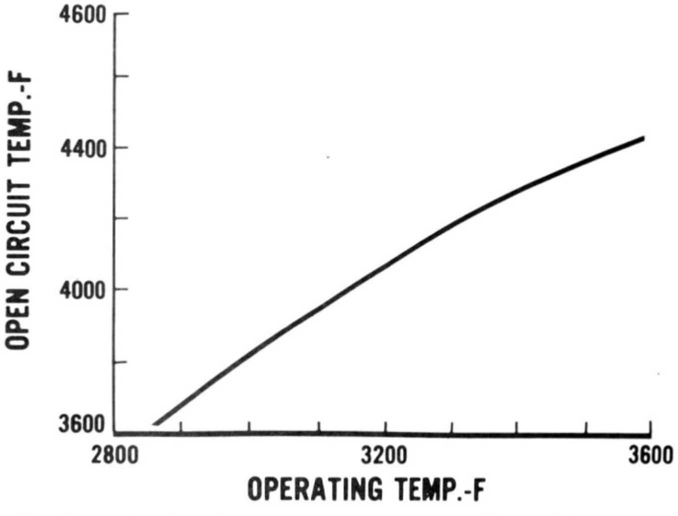


Figure 17. Open-circuit emitter temperature vs. operating emitter temperature.

Converter Designation	Emitter Temperature °C	Collector °C	Gap mils.	Ideal Power Density Watts/cm^2	Efficiency %	Time Hrs	Remarks
301	1810	700	10	9.2	12.9	2215	Continuing on test
303	1790	610	10	9.5	12.4	916	Failed due to emitter leak
402	1725	650	10	6.2	----	3650	Continuing
403	1730	700	10	7.2	----	1812	Continuing
405	1780	700 (Ni Collector)	10	15	----	1175	Continuing
406	1825	710	5	13.0	----	1915	Continuing
LC-1	1800	700	10	8.5	12.0	1250	Continuing
LC-2	1700	700	10	8.5	14.0	200	Continuing
OC-4	1750	650 (C_b)	11	5.0	9.2	1351	Stopped for examination
OC-5	1800	700	10	11.0	16.0	260	Cell broken during instrument replacement

Figure 18. Out-of-pile converter tests.

working closely with NASA and the US Air Force, is establishing the basic technology for the reactors that will be required in generating electric power for electric propulsion. The AEC is investigating various fuel forms, their burnout characteristics, the power output and power distribution that results from various reactor configurations, and, in general, all other research and technology factors leading to the actual development of reactors for such systems.

ADVANCED CONCEPTS

In addition to the solid-fuel-element nuclear rockets and electric propulsion, I have indicated earlier that there are several advanced nuclear concepts that are not yet well defined but are receiving research attention to evaluate their feasibility and real performance potential. The gas core reactor nuclear rocket is one of these systems. One of the several gas core reactor concepts that is being studied is shown in Fig. 19. The objective in this kind of a nuclear rocket is to avoid the temperature limit that results from the use of solid-fuel-element materials. In this concept the uranium fuel is held in a highly concentrated core in a gaseous form. Various force fields have been suggested to accomplish this uranium concentration. In the case shown, the uranium is held in place by centrifugal force. Hydrogen would be heated to extremely high temperatures so that specific impulses above 1,500 sec may eventually be achievable.

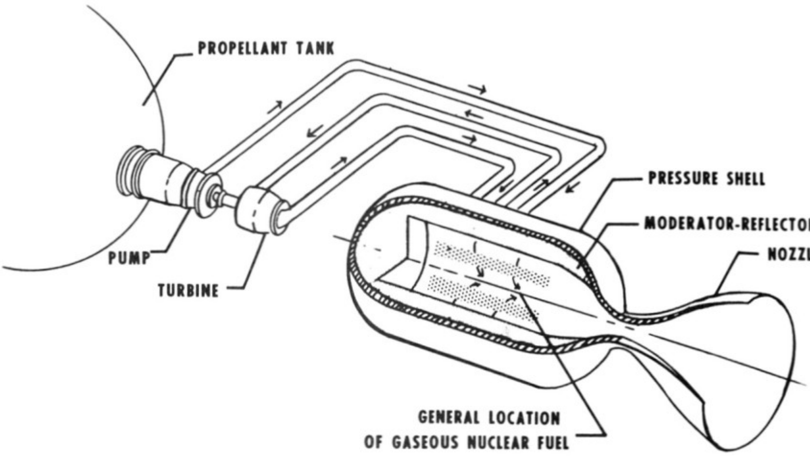


Figure 19. Gaseous-core nuclear rocket.

Another advanced propulsion concept receiving some attention is the Orion concept illustrated schematically in Fig. 20. In this concept a rapid succession of nuclear explosions below the pusher plate imparts an upward force through a shock-absorber system to a large space vehicle. Analytical work and some high-energy explosive testing have been conducted on this concept. No nuclear tests have been undertaken.

There are, in addition, several other concepts that are being studied, but I must emphasize that although the performance that has been theoretically calculated for these various systems offers some advantage, the attainability of this performance potential and the feasibility of developing these systems are not yet established.

SUMMARY

Space propulsion using nuclear energy sources offers a capability for accomplishment of high-energy increment, high-payload missions in space beyond the capability of the chemical combustion propulsion systems when considering practical operating limitations. Work now underway in the United States indicates that nuclear rockets can be anticipated for earliest use in the space program. Reactor tests being conducted during this year should provide a firm technical basis for system development. Electric propulsion using the nuclear reactor energy source offers promising storable-propellant performance if lightweight, long-life power supplies can be developed. Technology investigations are now underway to evaluate the

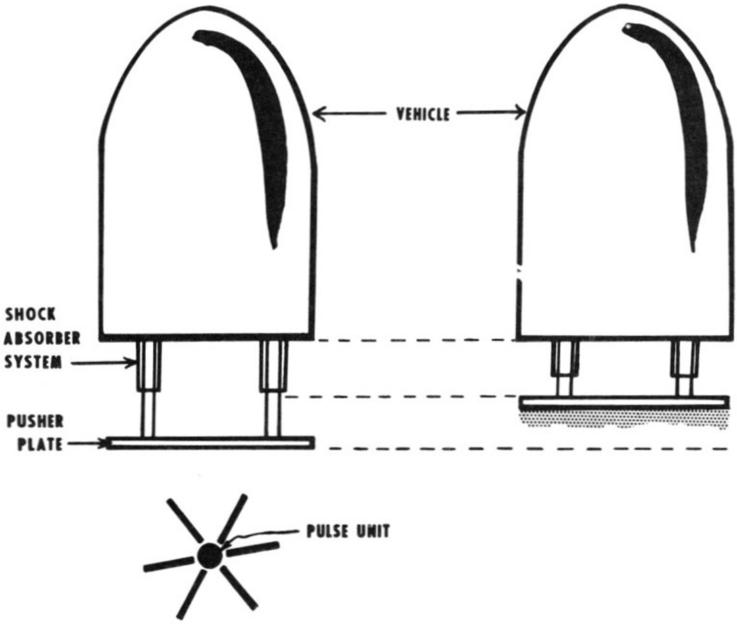


Figure 20. Orion pulse propulsion system.

feasibility of achieving the required performance. This work will simultaneously provide the information that is required to provide large amounts of electric power for nonpropulsive purposes in space. Beyond these systems, a host of new and advanced concepts have been proposed. These are not well enough defined or evaluated to assure that their high performance potential can actually be achieved. Some research work is underway on these systems.