Session 1.13
A/CONF.49/P-056
CONF-710901--8

NUCLEAR SYSTEMS FOR SPACE POWER AND PROPULSION

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In the brief history of the space age, man has sent instruments into earth orbit and to the near planets, he has begun to utilize space for carrying out his daily activities on earth - in meteorology, communication, navigation to name a few such uses, and man has begun directly to explore the moon. These steps, as dramatic as they have been are only the beginning of mankind's exploration and utilization of space.

As has been true on earth, our ability to move about in space is dependent upon the availability of energy. Substantial amounts have already been necessary to perform the missions that have been accomplished. Until now, non-nuclear energy sources have supplied by far the largest proportion of the energy used. However, as we move deeper into space and as we attempt to perform more complex operations in space, nuclear energy as a compact source of large amounts of energy is expected to play a larger and larger role.

My purpose in this paper is to present the manner in which we envision that role will develop and the technology needed to carry out future space activities.

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(NASA-TM-X-68341) NUCLEAR SYSTEMS FOR SPACE POWER AND PROPULSION M. Klein (Office of Space Nuclear Systems (AEC)) [1971] 14 p CSCL 18E G3/22
N72-25612
Unclas 30527

NUCLEAR ELECTRIC POWER

The electrical energy required for U. S. space exploration missions has increased 10,000 fold since the early days of its space program. Figure 1 shows the trends for three types of missions: earth orbit applications, automated scientific missions, and manned missions. Energy requirements have increased as the spacecraft lifetimes have increased and as more use is made of each spacecraft. We can expect these trends to continue and, although we cannot predict with assurance the rate, Figure 1 projects another 500 fold increase over the next 20 years.

As a practical matter, these large quantities of energy can be supplied in space only by the sun, utilizing solar energy conversion systems, or by nuclear systems. The technology of solar energy systems currently permits the generation of approximately 110-120 watts of electricity per square meter of solar array exposed to the sun. Since in low earth orbit an array is not always in sunlight, the average power output for such applications is in the 35-60 watts per square meter range. However, in synchronous orbit, power output approaches the ideal. To achieve these values the array must be pointing directly to the sun, so that precise pointing mechanisms are required or the arrays must be substantially larger. While these values are quite acceptable for many applications in the vicinity of the earth, one can see that, for power levels in the kilowatt range, the areas of solar arrays become quite large, creating significant atmospheric drag penalties.

SPACE POWER
ENERGY USAGE

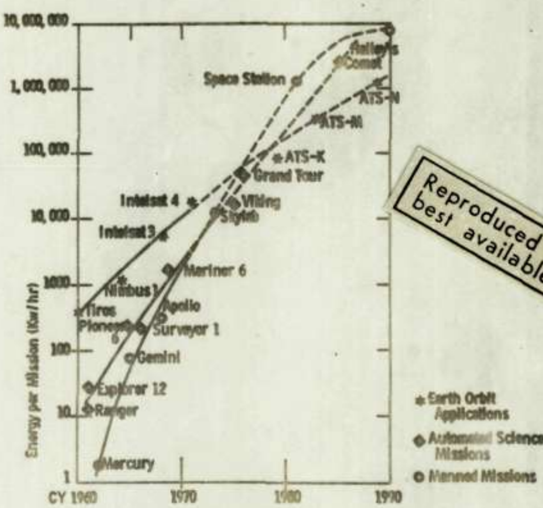

Fig. 1

The net effect of these considerations then is that in earth orbit solar energy will continue to play a major role in supplying power at the lower power levels. As power requirements rise, however, nuclear power becomes increasingly competitive. Unless there are special factors, the energy source selection for a mission will be decided by cost and reliability considerations.

However, there can be special factors. The possibility that large solar arrays will obscure view angles from the spacecraft, interfering with science and other mission needs is one such factor. Furthermore, in some missions the thermal energy byproduct of nuclear systems is advantageous. The need for very long-lived craft can also be a special consideration for low earth orbit missions; solar energy systems can be limited by solar cell degradation and also by the battery lifetime, since batteries are a necessary concomitant of solar energy sources in these applications.

When one considers missions beyond earth orbit, say lunar missions or beyond, additional factors come into play. For a long-lived mission on the lunar surface or when power is required during the long lunar night, use of solar arrays is quite limiting in terms of mission objectives. For missions deeper into space, the reduced solar flux means that larger solar array area is needed to provide a given amount of power. For example, at Jupiter, which is approximately five astronomical units from the sun, a solar array area will be more than twenty-five times that in the vicinity of the earth for a given amount of power. The problems posed by hostile or unknown planetary or space environments also tend to dictate the use of nuclear power supplies which are much less sensitive to those considerations. Indeed, we would expect that nuclear power supplies will be the dominant source of electrical power for planetary exploration.

There are, of course, two types of nuclear power supplies: one which uses the decay energy of radioisotopes, the other which uses nuclear reactors. Systems of both types have been flown in space. The first such system flown by the U. S., a 3-watt radioisotope thermoelectric generator (RTG) launched in 1961, is still producing power today, although at a substantially reduced level. The first reactor power supply flown in space was the 600-watt SNAP-10A flown in 1965, operating for 43 days before it was shutdown by a malfunction unrelated to the nuclear power supply.

Radioisotope Systems: Three currently operational missions have radioisotope power supplies. One, employing a unit called the SNAP-19, is the Nimbus III weather satellite launched in May of 1969, and still operating. Nimbus III represented a milestone in the science of meteorology, demonstrating broad new capabilities for examining on a continuing basis atmospheric behavior and effects.

On the surface of the moon two radioisotope generators, called SNAP-27, are in operation powering the two scientific stations (ALSEP) left on the lunar surface by the astronauts of the Apollo 12 and Apollo 14 missions. Figure 2 contains a photograph of the Apollo 14 generator together with the scientific instruments which it is powering. These generators, the first of which was placed in operation in November of 1969, have exhibited nearly constant power output in excess of 70 watts since deployment. Additional SNAP-27's are scheduled for launch with each of the remaining Apollo flights.

Radioisotope thermoelectric generators will also be used on several missions forthcoming in the next several years. One is the Pioneer probe to Jupiter, two of which are planned in 1972 and 1973. Another use, scheduled for launch in 1975, will be in the Viking mission to send automated landers to the surface of Mars. A third class of missions are those to the outer planets; in the late 1970's such missions are planned, including a mission we have come to call the Grand Tour. Because of an unusual planetary alignment, it will be possible to launch in the 1976 to 1979 time period, a single spacecraft which can flyby three or more of the outer planets. The power levels required for these several missions vary from approximately 70 watts after approximately 1.5 years for the Viking mission to approximately 120 watts for Pioneer over a three-year mission span to on the order of 450 watts for the outer planet missions for 7 to 10 years.

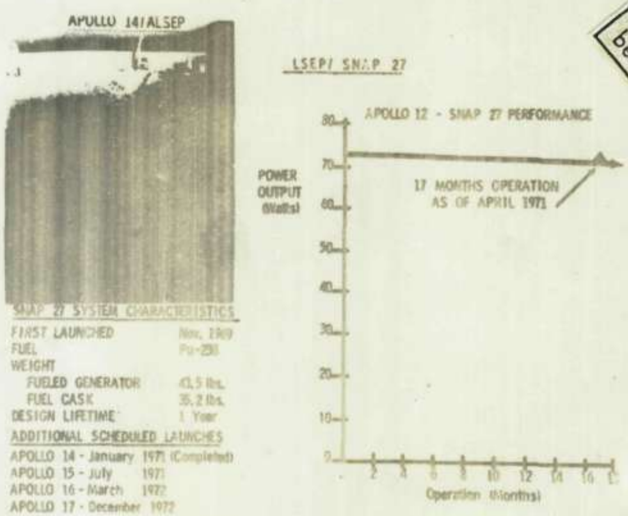

Fig. 2

The basic radioisotope thermoelectric generator consists of three elements (Figure 3): the radioisotope fuel, a container which serves to immobilize the fuel under both normal and potential abnormal conditions, and the thermoelectric material which converts the thermal energy output of the heat source into electrical energy. There are a number of candidate materials for each of these elements.

First, with respect to the fuel, in the U. S. program we are currently using plutonium-238. Plutonium-238 has a long enough half-life to provide quite suitable performance and its decay energy is primarily in the form of alpha particles, minimizing the need for shielding. It is used as the oxide because in that form it is relatively inert both chemically and biologically and has adequate thermal properties.

The radioisotope fuel is contained in a capsule for which a number of candidate materials also have been considered. In the generators flown to date, the primary structural material of the capsule has been a nickel steel superalloy. However, generators currently under development use refractory metals to provide a higher temperature capability for higher performance systems. Between that structural member and the fuel is an inner liner to facilitate manufacture and in some cases serve as a compatibility member. An exterior coating or noble metal clad is used to provide oxidation resistance. This capsule system then is placed within a re-entry body made of graphite, the purpose of which

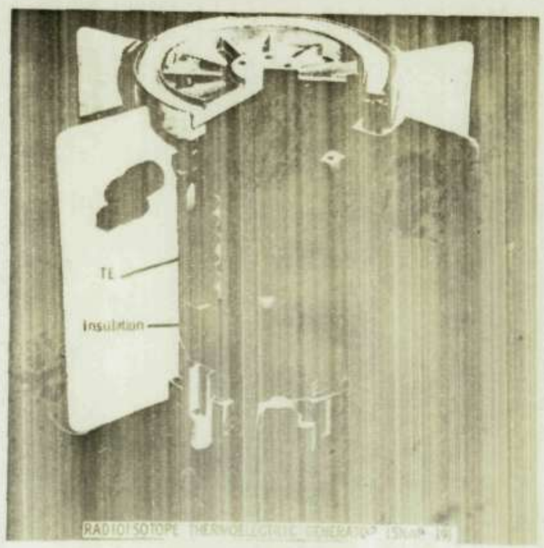

Fig. 3

is to provide thermal protection to the capsule and its contained radioisotope fuel if the heat source were to re-enter the earth's atmosphere in the event of a launch failure. Through these design features, the objective is to bring the capsule to the earth's surface intact in the event of a mission failure.

The thermoelectric materials must cover a range of operating temperature conditions. Lead telluride and its variations are used at the lower end of the temperature range of interest, up to about 1100°F, and silicon germanium up to about 1800°F.

For missions to the outer planets with their substantially longer lifetime and higher power requirements, an advancement in the state-of-the-art is necessary. Furthermore, as we look to expanded uses of RTG's, further extensions in technology are desirable, if not essential. Advancements are sought primarily in the following areas: (1) In the fuel form, reduced cost will have a major benefit since fuel is a major element in the cost of such systems, (2) Improved encapsulating materials, capable of operating at higher temperatures, can lead to higher efficiency systems, (3) Improved power conversion efficiency and reduced degradation rates through improved thermoelectric materials and structures will reduce the amounts of fuel and hence cost, system weight, and radiator area. In addition the potential exists for using with radioisotopes convertors which operate on the principle of thermionic emission; they too have the potential for improved efficiency over current thermoelectrics.

In addition to utilizing the decay energy of radioisotopes to produce electric energy, that energy is also valuable directly as a source of heat for various purposes in space flight. For example, radioisotopes were used to provide heat to the scientific package left on the lunar surface in the Apollo 11 mission in July of 1969. One-watt plutonium-238 heaters are being prepared for use on the Pioneer Jupiter spacecraft. Exploratory development is underway on a radioisotope heated system for waste management purposes.

Reactor Systems: Radioisotopes will be the source of energy for systems using nuclear energy when power levels up to a few kilowatts are needed. Above that range, and overlapping it to some extent, reactor power sources will be required. For unmanned earth orbit missions, present analyses show that reactors become more economic than solar power above a few kilowatts, the power range for such application satellites as direct broadcast television. In manned missions, such as a permanent space station, an important advantage of reactor systems is their ability to accommodate substantial growth in power demand. Finally, reactor systems of an advanced type will be needed for electric propulsion systems capable of high energy missions such as those to the far planets.

The U. S. space reactor technology program has two elements. For missions of the above types which may require reactor power in the late 1970's and the early 1980's, our reactor program is concentrated on the uranium-zirconium hydride (UZrH) reactor (Figure 4). For more advanced applications, including nuclear electric propulsion, we are working on two advanced concepts, the thermionic reactor and a high temperature liquid-metal-cooled reactor.

Several reactors of the UZrH type have been operated for as long as 10,000 hours on the ground. The SNAP-10A reactor already flown was of this type. This reactor is a moderated system in which the U-235 fuel is mixed homogeneously with zirconium, hydrided, and clad in a nickel steel alloy. Control is accomplished by means of void-backed or poison-backed drums contained in the reactor periphery. This reactor can be coupled with either of several power conversion units. The two principal power conversion systems for use with this system in our program are thermoelectrics and the Brayton gas-turbine system.

For applications requiring even higher performance and higher power, emphasis is placed on providing the technology for an in-core thermionic reactor in which reactor thermal energy from fission is converted within the fuel element assembly into electricity. Potential applications include power requirements of 100 kilowatts or more and electric propulsion, which requires systems of very low specific weight:

S8DR GROUND TEST ASSEMBLY

Fig. 4

5-30 kilograms per kilowatt compared to the hundreds of kilograms per kilowatt typical of today's technology. Of course when such systems are available, they could also be used at lower power levels. Current efforts in our program continue to emphasize work on the thermionic fuel element. The fuels being examined are UO_2 and UC, in tungsten cladding, which serves as the electron emitter. Electrically heated experimental diodes, the building block of the thermionic fuel element, have now operated for over 30,000 hours, in-pile experimental diodes for over 10,000 hours and partial length fuel elements for over 7,000 hours. At the appropriate time, the next step in this program will be to proceed with a reactor experiment to investigate fuel element interactions and study thermionic reactor operating characteristics.

NUCLEAR PROPULSION

Just as electric energy requirements have been increasing and are expected to increase further as the space program proceeds, so too is the case with propulsion energy needs.

The propulsion energy presently used in the space program is provided by chemical reactions. In the U. S. a major program for increased propulsion capability is planned for the next decade. Emphasis is being placed on means of reducing the cost and increasing the flexibility of space transportation and to this end a space transportation system has been defined. One element of this system is a reusable space shuttle to deliver payloads at low cost from the earth's surface to an orbit about the earth. This space shuttle can then return to the surface of the earth, refuel and, with a minimum amount of refurbishment, make another trip to orbit. A second major element of the space transportation system is a nuclear powered stage to go beyond the orbital range of the space shuttle. (Figure 5) This stage would employ the NERVA nuclear rocket engine.

In the nuclear rocket, by using the most efficient propellant, hydrogen, and heating it to high temperature in a nuclear reactor, the efficiency of high thrust propulsion can be increased markedly. In the first generation such system, using a solid core reactor - NERVA, a propulsion efficiency, or specific impulse, of approximately twice that of the best chemical rocket is possible.

The nuclear rocket can provide transportation of automated spacecraft for exploration of the surfaces of Mars, Venus, Mercury, some of the moons of Jupiter and certain asteroids. The return of samples to the earth will be possible in some cases. In addition, the nuclear stage could send spacecraft on fast trips to the distant planets reducing trip times by several years in comparison to other propulsion methods. When it becomes appropriate to resume manned lunar exploration, a system of the capability of the NERVA stage will be used to transport men and equipment to and from the moon. Another

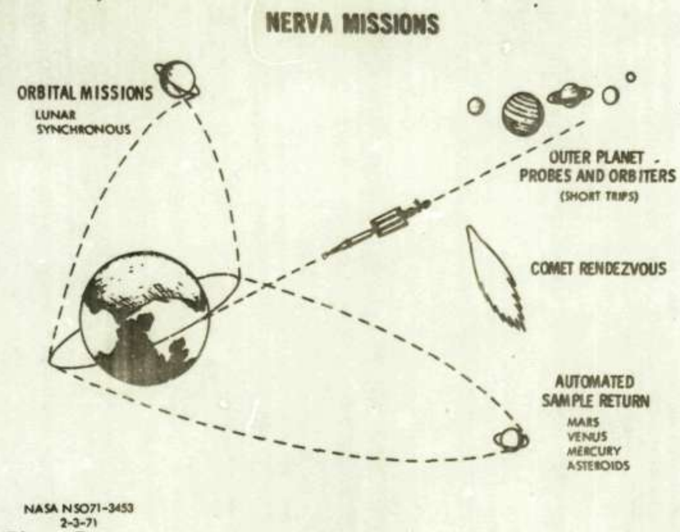

Fig. 5

application would likely be to move large payloads between low and synchronous orbit or from one orbital plane to another. While these missions are only in the planning stages, it is expected that at least some of them will occur in the 1980's.

Work to provide the technological basis for such a propulsion system began in the U. S. in the 1950's. Since that time an extensive program of analysis, laboratory work and full scale experimentation has been conducted. Eighteen rocket reactors have been operated, including the testing of experimental engines. (Figure 6). All of the necessary design and performance features required of such a system have been demonstrated.

With the successful achievement of these technological goals, the development of a flight qualified NERVA system was initiated approximately 2 years ago. This work has recently been slowed down as the U. S. space program has stretched out in time. However, we are proceeding with the development of this system at a much reduced pace with the intention of resuming full development when future mission planning dictates.

Figure 7 shows the over-all engine design as it has evolved. The thrust will be 75,000 pounds, a suitable thrust for missions of the types described earlier. Its specific impulse is to be 825 seconds compared to approximately 460 seconds for the best chemical rocket engines planned. The endurance goal of the engine is 10 hours, capable of many


GROUND
EXPERIMENTAL

Fig. 6

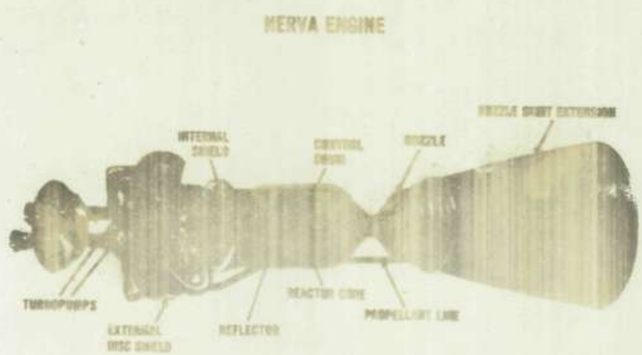
NERVA ENGINE
NOZZLE SKIRT EXTENSION
INTERNAL SHIELD
CONTROL DRUM
NOZZLE
TURBOPUMPS
EXTERNAL DISC SHIELD
REFLECTOR
REACTOR CORE
PROPELLANT LINE

Fig. 7

start and stop cycles. Such an endurance goal would permit, as an example, 10 round trips to the moon with, of course, the necessary replenishment of hydrogen propellant in earth orbit between trips.

The NERVA engine will be approximately 34 feet in length from the bottom of the propellant tank to the exit plane of the nozzle. Its largest diameter will be approximately 10 feet. It contains a reactor rated at 1500 megawatts (thermal) with a core diameter of approximately 3 feet.

Engine weight is approximately 23,000 pounds including an internal shield weight of approximately 3,000 pounds. This shield is adequate for unmanned missions and manned missions in which the payload is large and substantially distant from the engine. For certain missions additional shielding may be required depending upon the design of the payload and other spacecraft structure.

Hydrogen flows through the engine at a rate of approximately 90 pounds per second. A parallel redundant pumping system is provided for added reliability. Reactor control drums are located circumferentially around the reactor core in the reflector. Engine control is primarily accomplished through positioning of the reactor control drums, controlling hydrogen flow through certain core structural members, and controlling turbine power.

The fuel elements are made of uranium carbide in a graphite and zirconium carbide structure. It is necessary to coat the fuel elements, using materials such as niobium carbide and zirconium carbide, to minimize carbon loss.

The performance limiting feature of the nuclear rocket is the loss of carbon from the fuel elements by diffusion of the carbon in the fuel element into the high temperature hydrogen. Carbon loss reduces reactivity and structural strength and leads to an endurance limit which is a function of material temperature and fuel quality. Over the past several years, substantial progress has been made in minimizing the loss of carbon through improved fuel element materials, improved coating processes and improved process control. It has now become possible to envision a 10 hour lifetime for the reactor core. The present state-of-the-art provides fuel elements with a lifetime on the order of 5 hours.

In the controls area it has been necessary to devise methods of rapid and automatic startup as well as control of steady state operation and shutdown. The control must be accomplished while hydrogen is fed to the reactor at widely varying temperatures and pressures. An open loop automatic start from source power to the megawatt range in less than one minute is standard practice. A three decade power increase beyond that point is accomplished in less than another minute, typically using closed loop temperature and flow control.

ADVANCED SPACE NUCLEAR SYSTEM CONCEPTS

While NERVA represents a major advancement in space propulsion, structural limitations associated with solid fuel elements restrict the specific impulse of the NERVA and other solid fuel systems to about 1,000 seconds. Nuclear energy can potentially provide even greater improvements in performance. Nuclear processes yield the highest known specific energy (energy per mass of reactants) releases. Theoretically nuclear energy could provide a specific impulse of 1,000,000 seconds; however, there obviously are major technical problems that prohibit the attainment of the ultimate in performance. Nevertheless, the existence of this vast potential for nuclear propulsion stimulates a limited research program to extend technology and to explore the feasibility of new concepts for utilizing nuclear energy to the maximum practical extent.

Research and studies are being conducted to ascertain the feasibility and performance potential of nuclear fission reactors in which the fuel is in gaseous state and from which the potential specific impulse is as high as 5,000 seconds. In this concept the nuclear reaction takes place in a chamber in which the nuclear fuel is in a gaseous state and hydrogen propellant is either passed directly through this chamber or through a region separated from the gaseous nuclear fuel by transparent walls.

Still another advanced concept results from the recent advancements in pulsed lasers, together with predictions that fusion reactions could be initiated by such laser energy. Studies are being conducted of the means by which a laser ignited fusion reaction could be applied to propulsion and also to power generation for space purposes.

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In concluding this survey of space nuclear systems activities, I would like to touch upon two factors that have significant influence upon the design and development of these systems. The first relates to system reliability. Reliability concerns nearly all forms of engineering and technological activities. However, the consequences of failures in space systems are particularly costly. Therefore, the need for reliability is an extremely important element in these programs. Complicating the achievement of high reliability is the fact that there is very little room for the trial and error approach to reliability, which by design or otherwise has typified many earth-based engineering activities. In space systems, there are relatively few units used and each one must work. Attention, therefore, to the characteristics of, and to the margin in, materials, components and subsystems is the essential path to adequate reliability. We have devised new techniques for considering in detail statistical probabilities in the design of these systems.

The second major influence on the program is flight safety. This factor is considered throughout the design and development cycle in order to assure that the systems will operate safely under abnormal as well as normal conditions of launch, boost and operation in space.

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The totality of these space nuclear systems activities, in power, in propulsion and in the science and technology that these applications are forcing will pave the way to the next phases of exploration and utilization of space. Through them, the horizons of mankind will be extended and, at the same time, these greater technological capabilities will aid in improving the quality of life here on earth.

LIST OF FIGURE CAPTIONS