NUCLEAR SYSTEMS FOR SPACE POWER AND PROPULSION

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The nuclear systems under development in the U. S. are divided into two main programs: the Systems for Nuclear Auxiliary Power (SNAP) program and the Nuclear Engine for Rocket Vehicle Application (NERVA) program. These systems are primarily the responsibility of the National Aeronautics and Space Administration and the Department of Defense. Although there are other potential users, their uses are further off in the future than for these agencies.

The two main applications for nuclear systems--electric power and propulsion--are illustrated in Fig. 1. In both cases the nuclear component is used as a heat source, for there is no magic quality of the nuclear reactor or isotope to be taken advantage of other than the generation of heat.

In the case of electric power, a reactor, or mass of radioisotopes, generates heat which by radiative heat transfer or by some kind of a plumbing system, is transferred to a static or a turbogenerator system that generates electricity. Not shown in this sketch is the large thermal radiator, which is required to dispose of the excessive heat produced whenever a thermodynamic power generation cycle operates.

In the space propulsion cycle liquid hydrogen is the most effective propellant. The propellant is pumped through a reactor in a system that is described as the NERVA rocket. The expanded liquid hydrogen then flows out the rear through the nozzle to create thrust. The advantage is that with a nuclear propulsion system you can use molecular hydrogen. Since hydrogen is the lightest molecule available, the hydrogen for a given temperature can achieve a high specific impulse.

I. Space Power Systems

Figure 2 shows about where various power competitors fit in space. On the vertical axis the power level is shown in kilowatts, and on the horizontal axis the lifetime is shown in hours. Generally speaking, the isotope, solar and reactor systems are used for the longer lifetimes of up to 10,000 hours. The isotope and solar systems are used where the power requirements are low (up to a few kilowatts), whereas reactors are used when the power requirements are above a few kilowatts.

The dynamic chemical systems, the fuel cells and primary batteries, have a shorter lifetime chiefly because of their higher weight as a function of total energy. Generally, if to be used for several weeks, the batteries (the

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Fig. 1--Nuclear energy for space power and propulsion.

Fig. 2--Space power sources for various lifetimes and power levels.

primary batteries) and fuel cells become quite heavy. The chemical dynamic system is for a few hours' use in a high-power application of some type, such as a radar-jamming device.

Reactors are quite heavy at low power because they require a certain critical mass plus some heat-transfer machinery and a shield. Once we get that minimum weight assembled, the use of a reactor can result in a considerable amount of additional power for about the same weight or a small increase in weight, and thus they become more attractive for the higher power applications.

Costwise, the solar and the isotope systems are quite expensive. The plutonium-238 fuel systems that we are now using, and which are now considered to be qualified for space, cost several thousand dollars per electrical watt, with the 5 per cent conversion efficiency that we have today (thermoelectrics). The cost of solar systems rises in direct proportion to the power level, but they are not quite as expensive as isotopes with the current 5 per cent power isotope-thermoelectric conversion efficiency. A small reactor system might cost a million dollars, and for a higher-power system that million-dollar investment can give more power; hence, the cost per kilowatt comes down. The nuclear system is competing with the solar system (generally the photovoltaic system today) for the long lifetime missions.

If solar cells are used in places where the spacecraft goes into the shade, such as behind the earth or behind the moon or in trajectories far from the sun, battery energy storage will be required. A cyclical recharge for secondary batteries can be used; and the cost, weight and other penalties associated with the batteries must be considered.

Weight, size, cost and availability of the isotopes are important. Plutonium-238, which is the currently qualified isotope, is in fairly short supply. Although we do not now see any urgent shortage during the 1960's, we are using essentially all that we can make. One way to overcome any shortage is to develop and learn to use cheaper and more readily available isotopes, such as strontium-90. Strontium-90 is used in some of the terrestrial SNAP systems for navigation buoys, weather stations and other remote earth-and-sea applications.

The size and area of a power system are important. The solar system has to have a certain total area to intercept enough energy from the sun. The photovoltaic device operates at about 10 or 11 per cent efficiency, and total area is a direct function of the power level.

With the thermodynamic power systems which characterize the use of the isotopes and reactors, system size depends largely on the area of the thermal radiator needed to dispose of excess cycle heat. If we are willing to sacrifice a little efficiency, we can have a higher-temperature radiator, which will reduce the size of the power system. Area becomes important also with higher-power systems because of the problem of packaging radiators with large surface areas in available spacecraft or launch vehicles.

There are other special mission factors such as distance from the sun or the time during which a craft has to be within the shadow of the moon or the earth. A prime example is the surface of the moon, which has a night-

time period of about 350 hours. For that reason nuclear power will be especially useful on the surface of the moon.

These relevant factors lead us to a group of development objectives, which ties together this development program of power systems and power conversion devices. The objectives are shown in Table I.

TABLE I

Space Nuclear Power Systems Technology Objectives

1. Increase Heat Source Temperature
2. Develop More Efficient Power Conversion Concepts
3. Demonstrate and Improve Reliability
4. Reduce System Costs
5. Improve Methods for Assuring Safety

First, because the thermodynamic power device has to dispose of the excess waste heat in space by thermal radiation, the radiator must be at a high temperature relative to space, yet must be at the low temperature point of the heat cycle. Thus, the heat source will have to be at high temperatures to attain a respectable Carnot efficiency. Therefore, it is one of the main objectives in the several reactor and isotopic fuels programs to develop higher temperature capability.

The second development objective is to get higher efficiency power conversion devices. For the lower-power systems, the inventory of isotopes in the heat source which is the expensive, scarce item of the power system is reduced when efficiency is increased.

In the case of the higher-power devices which will have reactor heat sources, the size of the reactor determines the size and weight of the shield. This reactor-shield assembly plus the radiator account for about two-thirds of the weight of some of the advanced power systems. Again efficiency, which could limit the size of the reactor and the size of the radiator, is an important factor.

Methods of analyzing for safety have to be improved. A large part of the total analysis and experimental effort still goes into the various considerations of safety in all of the missions for which power systems are being developed today. As more is learned, less new research and development is required; but the competitors with which we have to compare have no safety problem. Because these devices are launched into space, and eventually many come down--and looking at it in the worst possible way, they can come down anywhere--we have to constantly check and improve our methods for insuring safety. Reliability is also vital in order to get useful systems, and cost is always important.

Now let's look at the various SNAP power systems being developed, or that have already been launched, and also look at the advanced technology

program to see how these fit into the picture. First, up to now, six SNAP devices have been launched. Five were radioisotope devices, and one was a small reactor.

A. Radioisotope Power Devices

The first two radioisotope devices were SNAP 3A units producing about three watts each. SNAP 3 was the unit President Eisenhower showed before national television on his desk in 1959. The first unit launched on the DOD Transit experimental navigation satellite has been in orbit for six years (since June 29, 1961), and as of today has the record for uninterrupted generation of power in space. The second SNAP 3 device operated for about eight or nine months, and then a failure quieted the whole satellite. As far as we know, it is generating voltage with an open circuit right now.

Three SNAP 9A units were launched in 1963 and 1964. They were 25-watt units, also using plutonium-238 with thermoelectrics. Two of the units are still working in orbit, and the third failed to orbit when the rocket guidance system failed. That third one was important because it came down over the Pacific Ocean and burned up due to re-entry heating as designed. The small amount of plutonium-238 that was released is being counted around the world today by the AEC fallout monitoring program. It is being dispersed safely, exactly as designed.

Generally speaking, we are going away from the burn-up re-entry devices and are moving in the direction of devices designed to re-enter intact. In that way we achieve safety without having to disperse and distribute isotopes into the atmosphere.

Figure 3 shows the SNAP 19 unit, which has two 25-watt generators in tandem for a total of 50 watts. It will be mounted as shown on the sensing ring of the Nimbus-B Satellite, a NASA meteorological experimental system. Two of the Nimbus satellites have been launched. The next one to be launched will be this one with the first nuclear unit aboard. Those large solar paddles generate an effective average power of about 200 watts initially, but only about 80 watts is left to power the experiments after accounting for the housekeeping load. So the 50 watts end-of-life minimum power that the new SNAP 19 units will generate becomes a substantial part of the total power capability of the system.

Figure 4 shows a cutaway of SNAP 19, illustrating the simplicity of the low-power isotope thermoelectric devices. A capsule containing plutonium dioxide fuel is mounted in the center of the device. It radiates heat to a bank of lead telluride thermocouples. The extra heat is conducted to the fins which in turn radiate it to space.

The power generator elements can be wired in series and parallel to give the desired optimum combination of voltage and current and to assure against open-circuit failures. The solar cells have this advantage, too. Because there are so many of them, it is easy to wire them in such a way that the electrical circuit is simple and reliable.

Fig. 3--Radioisotope electric generator on Nimbus-B satellite (SNAP-19).

SNAP 19 RADIOISOTOPE ELECTRIC GENERATOR

DESIGN POWER OUTPUT 25 WATTS
DESIGN WEIGHT 30 LBS

NASA RN67-1273
12-22-66

Fig. 4--Cutaway diagram of SNAP-19 radioisotope electric generator.

Radiator area is not important in the low-power systems, but it becomes important in the high-power systems such as SNAP 27 shown in Fig. 5. This is a 70-watt unit that will be launched on the Apollo mission that makes the first landing on the moon. Figure 6 shows an artist's concept of the lunar excursion module (LEM) which has landed on the moon. The astronaut is about to remove the experiment package that he will leave on the moon, called the Apollo Lunar Surface Experiments Package (ALSEP). The generator and the various pieces of the experiment station that will be left on the moon are shown in their storage racks.

The LEM carries the plutonium-238 capsule for the SNAP 27 in a graphite container mounted on the side of the vehicle, as shown. This is done in order to simplify the thermal design of this system since the generator is not fueled until required. In case of an abort early in the mission in which the device comes back inadvertently into the earth's atmosphere, this graphite container will protect the fuel so it will not disperse; it will re-enter intact.

Figure 7 shows an artist's view of the astronaut returning after emplacing the generator and several experiment packages. The experiment package is being developed by Bendix and the SNAP 27 generator by General Electric. There is a unit now in ground testing in Valley Forge, Pennsylvania; and one flight unit will be delivered to Bendix at Cape Kennedy later this year.

Figure 8 shows one of several advanced technology programs that we have under way which we call the "Lightweight" thermoelectric panel. The small pellets of lead telluride in the center are thin elements. Used in a system, this optimized panel should result in a low-weight thermoelectric generator. Again the thermoelectrics give an efficiency of only about 5 per cent, which is not good when using scarce, expensive fuels. The conversion system (the generator, in contrast to the heat source) weighs about one-half of the 1 pound per watt of the current isotope systems. This new concept will cut that down to where the conversion system weighs about 20 per cent of the total weight of the system or possibly a little less. With attendant improvement in heat-source technology, we hope to reduce the weight of the isotope devices from 1 pound per watt to about one-third or one-half pound per watt.

Figure 9 is a phantom view of SNAP 29, a several hundred watt unit, showing the generator and radiator assemblies. In this case to meet the requirements of DOD short-lived missions, we are going to use in space for the first time polonium-210, which like plutonium-238 is an alpha emitting isotope. Polonium-210 has a high-power density but only a short half-life of about 138 days. The system which will be ground tested in the late 1960's (probably the end of 1969) will be good for about three to five months in several types of earth orbital missions for DOD or NASA.

The isotope Brayton cycle is shown in Fig. 10. To get higher efficiency, this concept uses more complex power conversion equipment. This is the cycle which NASA hopes will produce about 5-1/2 kW electrical using a 25 kW thermal plutonium-238 radioisotope heat source. It heats a gas working fluid, probably argon or some optimized mixture of inert gases, which drives a turbine-compressor alternator by a recuperative Brayton cycle. The excess heat is ultimately disposed in a liquid-filled radiator loop. NASA has requested the AEC to furnish a heat source, and we are developing the 25 kW thermal plutonium-238 heat source.

Fig. 5--SNAP-27 radioisotope electric generator, showing the large radiator area required for high power systems.

Fig. 6--Artist's concept of the lunar excursion module (LEM), which has landed on the moon, showing astronaut about to remove the experiment package.

Fig. 7--Apollo lunar surface experiment package (ALSEP) with SNAP-27 radioisotope electric generator.

Fig. 8--"Lightweight" thermoelectric converter panel being developed under one of the advanced technology programs.

Fig. 9--Phantom view of the SNAP-29 radioisotope electric generator, showing the generator and radiator assemblies.

Fig. 10--Radioisotope--gas turbine electric power system (Brayton cycle).

Twenty-five thermal kilowatts is equivalent to a large part of the plutonium-238 that will have been produced up to the 1970's, when delivery is needed. The advantage of this cycle is that, although the weights are not remarkably better than current systems, the efficiency of the Brayton cycle will be somewhere between 20 and 30 per cent instead of the 5 per cent that we now have available. So for a given electrical power, the radioisotope requirement should be only one-fourth to one-fifth of that required with present thermoelectric systems.

B. Reactor Power Devices

Turning to the use of reactors for the higher power devices, Fig. 11 shows the SNAP 10A system and heat cycle. The bare reactor is 8 inches in diameter and 16 inches with the reflectors, which serve as the reactor control. To start the reactor the reflectors are rotated. The reactor heats NaK to 1050° F and pumps it with a static pump. This is an electromagnetic pump which generates its own power using the heat contained in the liquid. No external power is required, and there are no moving parts. The liquid flows from the pump into the supporting legs, where the power is generated by thermoelectric conversion and after the temperature drops about 150° F, the NaK returns to the reactor for more heat.

The thermoelectric conversion system for SNAP 10A which is shown in Fig. 12 represents another improvement in thermoelectrics. The liquid metal from the reactor flows through the tubes, transferring heat to the thermoelectric units. Each unit has its own radiator plate for getting rid of excess heat.

A SNAP 10A unit was launched in April, 1965, and operated in space for 43 days, generating a little over 500 watts of electrical power. It was designed to operate for a year. The satellite voltage control system failed after 43 days, and the reactor shut itself down as it was designed to do.

An exact copy was operated on the ground for 10,000 hours in California. The system was designed to be passively self-controlling, i.e., after the initial start up and stabilization of performance, the whole control system was turned off; and the reactor operated on its negative temperature coefficient for the full one-year design life, dropping in average NaK temperature by about 20 to 30 degrees during that time and generating a minimum of 500 watts in the process. However, the control system could be turned back on and more reactivity inserted by means of the control drums at any desired time. After operating one year on the ground in the test system, we did insert some reactivity just to prove we could get it back up to the 1050° F initial condition. It worked, and we operated it for another two months and then shut it down. The system was taken apart, and it was apparently as good as when it started.

This SNAP 10A system was a zirconium hydride fuel matrix with uranium-235 fuel. The big brother of the SNAP 10A is the SNAP 8. Whereas the SNAP 10A reactor in that application operated at about 40 kW thermal, SNAP 8 can put out about 600 kW.

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Fig. 11--SNAP-10A reactor power system and heat conversion cycle.

Fig. 12--Advanced direct-radiating thermoelectric concept for the SNAP-10A system.

Figure 13 shows the next reactor of the SNAP 8 program. We ran an experimental reactor at full power for 10,000 hours. When we took the system apart, we found cracked fuel elements. We believe we now know why they cracked and how to prevent them from cracking, and we are now assembling the core which will be operated with complete space-configured reactor paraphernalia. The reactor location is in a pit about five stories down. An expanded view of the reactor and experimental shield is also shown. The piping around the pit takes the heat from the reactor into a heat dissipation cycle which will probably be an air blower heat exchanger.

The SNAP 8 system power will be about 10-30 kW with the electric systems or 30-100 kW with the NASA mercury turbine system. We hope to run the second SNAP 8 reactor at power starting next spring.

For the high power levels (hundreds to thousands of kilowatts) there are two main approaches to reactor power systems. The first is the one that was called, until recently, SNAP 50. This system is designed to have a bigger and better reactor and a higher temperature power conversion system than SNAP 8. The cycle is illustrated in Fig. 14. A fast reactor, powered with uranium nitride fuel, operates at a temperature of 2200° F. Heat is transferred by molten lithium to the heat exchanger (boiler) where steam at 2150° F is produced to drive the turbine generator. The cycle has a separate liquid-loop radiator. There is no immediate need for this system, so we are now only in a research phase learning to use the materials required for the high temperatures that will be needed.

Systems for the power levels that will be useful in the various types of missions under consideration are also being studied. These include the advanced auxiliary power, i.e., station-keeping electrical power requirements and the advanced electrical propulsion requirements of the 1980's.

The other advanced high power concept is the in-core thermionic reactor in which the emitter is heated by reactor fuel in the center of the diode. The emitter is a metal surface which boils off electrons, resulting in a flow to a colder collector plate. The electron flow is the electrical power. Thermionics offers the advantage of no moving parts for reliability, but has the disadvantage of requiring high temperatures. Whereas we have been operating it at 1000 to 1300 degrees in our hydride reactors, and the Rankine system will require 2000 degrees, the emitter of a thermionic device for good performance should operate above 2600° F, preferably about 3000° F.

We are now in the stage of building fueled diodes, learning to use them and learning to build them reliably. The next step (which we hope will be in the early seventies) will be to put these diodes together in one of several possible configurations for operation as the core of a reactor. Then, in concept, we would have a pot out of which would come electric power. The cycle will require a radiator into which liquid metal will flow to be cooled; but it will be able to operate at quite high temperatures; and this is one of the advantages of the thermionic system.

A summary showing the growth of isotopic space power technology is given in Table II.

Fig. 13--SNAP-8 ground test facility. Cutaway of system with expanded view of reactor and experimental shield.

Fig. 14--Fast reactor--advanced Rankine electric power system.

TABLE II
Isotopic Space Power Technology Growth

	<u>Power/Unit Electric Watts</u>	<u>Efficiency Per Cent</u>	<u>Specific Power Pounds/Watt</u>	<u>Available</u>
SNAP 9A, SNAP 19	3 - 30	4 - 5	1.0	Today
SNAP 27	50	4 - 5	0.6	1968 (Apollo)
SNAP 29	500	4 - 5	1.0	1970 (Ground Test)
Isotope - Improved Thermoelectric	--	7 - 9	0.3 - 1.0	1970 (Ground Test Capability)
Isotope - Organic or Mercury Rankine	2,000 - 10,000	10 - 20	0.3 - 0.5	Early 70's (Ground Test Capability)
Isotope - Brayton	5,500	20+	0.15 - 0.25	Early 70's (Ground Test)

The present systems, SNAP 9A and SNAP 19, are operating at about 4 to 5 per cent efficiency; and they weigh about 1 pound per watt. The best systems under development for isotopes will, hopefully, operate at higher than 20 per cent efficiency and will weigh between one-fourth and one-half pound per watt. The target date for these is the early seventies.

The growth of reactor space power technology is presented in Table III. The SNAP 10A and SNAP 8 units of the current systems can produce power up to about 50 kilowatts and will weigh about 300 to 1000 pounds per kilowatt. The advanced liquid-metal and the in-core thermionic reactors will put out megawatts and will weigh as little as 20 to 100 pounds per kilowatt. The weight of reactor systems is always highly dependent upon the geometry of the system. In space one tries to use shadow shielding for the reactor. There are no atmosphere or protruding objects as on earth to scatter neutrons back into the payloads, so we build a shadow cone which hides the reactor from the personnel or devices to be protected.

If the spacecraft is long and narrow, a light shield results because the frustrum of a cone which contains the shield is a small volume. All of the low-weight conceptual systems (20 pounds per kilowatt) are based upon a long, narrow, optimized geometry.

TABLE III

Reactor Space Power Technology Growth

	Fuel Surface Temperature °F	Power Electrical kW	Weight Objective Pounds/kW
SNAP 10A - 8 Gas-Cooled Reactor w/Brayton	1300 2200 - 2700	Up to 50 100 - 200	300 - 1000 100 - 200
Liquid Metal Reactor w/Potassium Turbo- generator	> 2000	100 - 10,000	20 - 100
In-Core Thermionic Reactor	2800 - 3400	100 - 10,000	20 - 100

III. Space Propulsion Systems

Turning now to space propulsion systems especially for the advanced high-energy missions of the future, one of the most important factors to be considered in the rating of a propulsion system is the specific impulse. Specific impulse is a number expressed in seconds which tells the thrust in pounds that can be generated by a given propulsion system for a given flow rate in pounds per second of propellant.

Since everything used in propellant systems after the system is in space has to be launched initially from the earth, the propellant requirements for some of the complex advanced missions of the future are quite large. Take a manned vehicle with large mass, that has to go all the way to Mars, for instance. It must leave the earth from a parking orbit, correct its position and its direction along the way, and slow down at Mars to do useful things there. Then it must inject itself back into an earthbound trajectory, make course corrections along the way, and finally slow itself down for recovery at the earth. The entire operation requires a large amount of contained propulsion capability.

As for conventional chemical systems, the best of them mixes oxygen and liquid hydrogen in the rocket to give a specific impulse of about 440 seconds, i. e., 440 pounds of thrust per pound per second of propellant flow. The nuclear rocket, because it can use H_2 , a light-weight molecule, can get much more effective use of the propellant for a given temperature. Specific impulse feasibility on the order of twice the 440 value is being demonstrated for the nuclear rocket system that is now being tested.

This is the advantage of the nuclear rocket. A typical manned interplanetary mission of the future that is in the process of being planned (the manned Mars mission) would require with chemical propulsion about 6,000,000 pounds of propellant to be launched into earth orbit. Using a nuclear rocket about one-third that much would be required. When you consider that a Saturn V, which is our largest launch vehicle, costs about one hundred to two

hundred million dollars per launch and puts up about a quarter of a million pounds, this saving amounts to tens of Saturn V's or billions of dollars per interplanetary mission.

The evolving NERVA engine is shown in Fig. 15. The reactor is about the size of an office desk--4 or 5 feet in diameter. The one that we are now starting to develop will have a thrust of 200,000 to 250,000 pounds and a power of 5,000 MW--roughly the power of Hoover Dam or the installed electrical capacity of the country of Denmark. It has a chamber temperature of about 4500° R which is about the temperature we are working on today.

Figure 16 shows this engine incorporated into the whole rocket. The reactor has a graphite fuel matrix. The hydrogen is contained in the large tank shown in the picture. It flows first through a pump, then into the walls of the nozzle for a regenerative heating cycle. The cold liquid hydrogen cools the nozzle shell and then flows into the reactor, through the reactor and exits the reactor at 4500° R. The turbine that is required to operate the pump is driven by a small bleed of gas from within the high-temperature plenum.

Several reactor and engine tests have been conducted. A typical test is illustrated in Fig. 17. It takes only about 30 minutes of total propulsion time for each reactor in a manned Mars mission. Several reactors have been run for 10 to 40 minutes under conditions that will give, in the large thermal reactor which we are now developing, the 800-850 seconds of specific impulse that is wanted. Hydrogen is pumped into the nozzle shell first and from there through the reactor and out vertically. All together eight or nine reactor tests have been run, mostly at power outputs of about 1100 MW.

The propulsion module concept with the NERVA engine behind a large tank of propellant is shown in Fig. 18. In these views modules are individual or clustered for use in the several typical candidate missions shown. The basic module can be used with a fairly small tank of hydrogen for a lunar direct mission or for an unmanned space probe. For a manned Mars flyby one NERVA engine is used.

The manned Mars landing requires much more velocity change. Five NERVA modules are planned: three for the first stage which would be the stage which leaves the earth orbit, one for the slowing down at Mars, and one for returning to earth.

In summary, several nuclear power systems have been used in space. Nuclear systems technology is now competitive with solar systems in certain specialized space applications. We are now developing a family of long-life isotopic and reactor power systems which will supply up to 50 kW for use in the early to mid-seventies, and we are working on the better technology required for systems in the more distant future. This technology effort is concentrated in several areas designed to give us a higher temperature capability and higher efficiency power conversion for better performance and higher reliability.

In the nuclear rocket program we are now preparing to enter into a program to develop a NERVA engine, and in due time, a nuclear propulsion module--a complete nuclear stage--to be used in a wide variety of space missions.

NERVA ENGINE

- THRUST
200,000 - 250,000 LB.
- POWER
4,000 - 5,000 M.W.
- CHAMBER TEMPERATURE
4,500°R
- SPECIFIC IMPULSE
825 SEC.

NASA NPO67-49
REV. 1-23-67

Fig. 15--The evolving NERVA engine.

Fig. 16--Propulsion module concept using NERVA engine.

Fig. 17--Stationary NERVA reactor and engine test system.

VERSATILITY

BASIC PROPULSION MODULE

NASA NPO 65-1874
12-14-65

Fig. 18--Proposed propulsion systems for various missions utilizing basic NERVA module.

DISCUSSION

QUESTION: Mr. LaFleur, can you comment on the use of thulium in isotope powered devices?

ANSWER: There are two isotopes of thulium that are potentially attractive. Thulium-170 with a half-life roughly like polonium-210, about 128 days, is attractive potentially for shortlife missions. It normally requires more shielding than polonium-210 but may not under some conditions of use. Until recently, it has not been available because stable thulium-169 from which it is made has not been available. Today, there are companies that claim they can furnish enough thulium-169 to make it possible to make significant quantities of thulium-170. This thulium-169 is apparently a byproduct of the color television industry. One of the big advantages, as compared to polonium-210, is that it has a stable high-temperature oxide form that makes it potentially safer.

Thulium-171 resulting from adding a neutron to thulium-170 with about a 2-1/2 year half-life is almost an ideal isotopic fuel but is practically impossible to generate and to separate economically.

QUESTION: Is there any concern with the radiation damage in the thermoelectric materials themselves?

ANSWER: Not much. Of the two classes of thermoelectrics--the lead telluride which is good at low temperatures and the silicon-germanium at higher temperatures--the silicon-germanium is more prone to damage than the lead telluride. Both telluride and silicon-germanium are quite impure as compared to the semiconductors used in transistors. For that reason they can sustain a large amount of radiation reactions in their matrix without deteriorating in performance.

If there are transistors in the payload, the shielding requirements are orders of magnitude lower for the generator than for the payload.

QUESTION: You showed the graphite reactor in a propulsion system. What is the status of the competing or advanced fast reactor propulsion system?

ANSWER: We could possibly get higher performance with a tungsten-family fuel. However, it would not be much higher and would be much more expensive to develop. Because we have had so much experience with graphite, we have not started a large-scale program with tungsten.

Argonne did a lot of good work a few years ago to develop techniques for using the tungsten fuels but has no program right now and no plan to leave the graphite and start with the faster reactor systems.