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SURVEY OF ELECTRIC POWER PLANTS FOR SPACE APPLICATIONS

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Lewis Research Center
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TECHNICAL PAPER presented at Fifty-Eight
National Meeting of the American Institute of Chemical Engineers
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ABSTRACT

The extent to which man will realize his ambition to explore space may ultimately be limited by his ability to develop suitable electric generating systems for spacecraft. Space power systems are required to operate in an extreme and hostile environment. Space vacuum, storms of particulate matter from micrometeorites to high-energy protons, near-abolute-zero temperature, and difficulties of logistics and maintenance all exert their influence on the type of powerplant which can be selected for a given mission.

The natural tendency is to think in terms of exotic new solutions to meet an exotic requirement. The space program, however, is based on modifying existing technologies and techniques to meet the special requirements of space environment. This paper reviews the broad spectrum of powerplants that are currently under development including solar cells, batteries, fuel cells, thermoelectric generators, thermionics, and nuclear and solar mechanical systems. These systems are described in terms of their similarities to conventional devices rather than their differences. In almost every case, it can be shown that the concept being used, whether new or old, came into being because of its commercial potentiality rather than space power requirements. However, the space program has supplied the impetus for the research and

development now being conducted to improve and understand these existing techniques. The result will ultimately be a general across-the-board improvement or upgrading of all power systems. These improvements undoubtedly will reflect themselves in advantages to all of us.

INTRODUCTION

The extent to which man will realize his ambition to explore space may ultimately be limited by his ability to develop suitable electric generating systems for spacecraft. To assure oneself of the truth of this declaration, one has only to realize that all major components and subsystems of spacecraft conceived to date are either powered or controlled by electricity. Without electrical power there could be no communications, data transmission, navigation, life support, or control; in short, no useful mission could be performed. Since each mission has its own peculiar requirements, it is not then surprising to find a number of different powerplants under development.

Many factors influence the selection of a powerplant. Foremost among these are performance characterisitcs and availability of the system or technique for use at the time required, but other considerations influence the choice. The general factors that are considered in the selection of a power system for a mission are weight, volume, area requirements, cost, reliability, availability, safety (nuclear), and operational restrictions.

For any aerospace application the natural tendency is to consider weight as the predominant selection criterion. Were this the sole significant criterion, selections could be made by simply referring to a chart of the type shown in figure 1, which is based on weight and area considerations alone. However, in any practical situation, other factors may prevail. While a system may be suitable from a weight standpoint, volume or area requirements may prevent its use. The choice is often made on the basis of availability, safety, cost, or reliability factors, or because a particular device places fewer design or operational restrictions (i.e., orientation requirements, stowage of complex shapes, deployment requirements, nuclear shield design, etc.) on the spacecraft. Thus, powerplant selection is a trade-off procedure involving all of these criteria in relation to the specific mission and spacecraft requirements.

Space power systems are required to operate in an extreme and hostile environment. Space vacuum, showers of particulate matter (from micrometeorites to high-energy protons), near-absolute-zero temperature, and difficulties of logistics and maintenance all exert their influence on selection. To meet this broad spectrum of requirements, NASA is currently developing a large inventory of space power systems including solar cells, batteries, fuel cells, nuclear thermoelectrics, thermionics, and nuclear and solar mechanical systems based on both the Rankine and Brayton cycles. From the foregoing, we might conclude that space power systems represent a specialized art which is completely divorced from the mundane commercial power sources to which we are exposed every day. Nothing could be further from the truth. All these systems, whether new or old in concept, have come into being because of their commercial potentialities. Indeed, if we go through this list we find that most of the power conversion techniques mentioned earlier exist in everyday applications. This paper will review the type of power systems being considered for space application in terms of their similarities to everyday earth-bound powerplants, rather than in terms of their differences.

SOLAR CELLS

Solar cells are semiconductor devices that are capable of directly converting the energy of incident sunlight to electricity.

Figure 2 shows three different types of solar cell. The selenium cell on the left has been known for some 80 years. This low-efficiency (0.3 percent) cell responds to light in the same manner as the human eye or photographic film and is therefore useful in photographic light meters. The low-conversion efficiency makes this type of cell unsatisfactory for space use since 3 square feet of cell area would be required to produce a single watt.

The backbone of the space power program at the present time is the silicon solar cell. This cell is prepared by adding controlled amounts of specific impurities to high-purity silicon crystals. Addition of phosphorous produces an n-type silicon whose potential decreases on exposure to sunlight. The use of p-type impurities such as boron causes the potential to rise when incident sunlight strikes the crystal. If, for the two types of silicon, the number of electrons is related to the number required to fill the valence band, n-type silicon has an excess of electrons and p-type a deficiency. If such dissimilar materials contact one another, surplus electrons flow from the n-type material to the p-type and the result is a contact potential between the materials and an electric field at their junction. This field is so oriented as to aid the flow of electrons from the p to the n side and resist it in the opposite direction. If silicon containing a p-n junction is exposed to sunlight, some incident photons will have sufficient energy to transfer an electron from the valence band to the conduction band; if this occurs near the junction between the p- and n-types of materials, the electric field created by the junction will cause the electrons to move and thereby will cause a useful current to flow. The combination of p- and n-type layers within a single crystal produces the maximum voltage difference. This is about 0.5 volt. For space applications, the silicon crystal cell delivers efficiences of 9 to 11 percent in outer space. This is the most efficient type of solar cell made to date, and occasional single samples deliver 14 percent efficiency. The silicon cell has two major disadvantages: it is expensive (figures commonly used are $250 to $300 per W unmounted and $1000 per W assembled into an array), and they are small (typically 1×2 cm) rigid crystals requiring both a rigid supporting structure and many electrical connections in order to deliver a usable quantity of power. The cost picture is improving, however, and figures as low as $400 per watt for oriented arrays may be achieved.

The thin-film cadmium sulfide cell is an attempt to overcome these problems. Its efficiency at present is 4 to 5 percent for areas measuring a few square centimeters. However, these thin cells have the advantage of being light-weight and flexible and can potentially be made in large areas. The flexibility of this cell is illustrated in figure 3. Although the ultimate efficiency of large areas of the material may be about $3\frac{1}{2}$ percent, the cost per watt may drop as low as $10 to $50 per watt compared with a potential cost of $100 per watt for silicon cells. It is expected that large areas of the material may be packaged into small containers for launching and then be unfurled when needed.

Solar cells are an ideal power source when small quantities of power are needed in remote sunny areas where stringing power lines is impractical from the cost or logistic standpoints. The satellite or space probe is a perfect example of such a situation, but there are others here on Earth. One striking example is the use of pole-mounted silicon solar cells to charge the batteries that power an emergency radio-telephone network on a Los Angeles freeway. Solar cells are the most economical means of maintaining these installations.

CHEMICAL BATTERIES

The silicon solar cell is an attractive energy source from the standpoints of availability and reliability, but it suffers from the serious drawback that it requires sunlight to operate. If sunlight is available part of the time, as in a day-night Earth cycle or in a satellite passing through the Earth's shadow during an orbit, some form of energy storage is required if the power output is to be continuous. Batteries offer the means for meeting this need.

The commercial battery business is generally a high-volume, low-margin, cost-conscious industry. The designs and manufacturing techniques used to meet commercial markets could not meet the stringent requirements placed on them by the space program. Because NASA needed batteries that could withstand the high vacuum of space without losing volatile materials, hermetically sealed cells had to be developed. The need for a cell free from irreversible gas formation during operation and able to supply thousands of short (90 min) charge-discharge cycles precluded the use of the lead-acid battery. In addition, spacecraft batteries must deliver power for both high and low drain rates. The LeClanche (flashlight) cell could meet very low-rate needs only. As a result, it was necessary for the government to support the development of several battery types which were not new but, for economic and application reasons, were not available in a form suitable for space use.

As with commercial applications, the aerospace field requires two types of batteries, primary or nonrechargeable and secondary or rechargeable. The silver oxide - zinc cell is used to meet almost all the primary battery needs for space. The performance characteristics of this cell are shown in table I. The silver cell is the highest energy-density battery in service today. The watt-hours delivered per pound of total cell weight range from 35 watt-hours per pound at the 10-minute-discharge rate to 75 watt-hours per pound at the 100-hour rate. In one flight application, a silver battery produced slightly over 100 watt-hours per pound during a 3-month discharge. By comparison, the LeClanche cell used in flashlights may deliver 40 watt-hours per pound at the 100-hour drain rate and 67 watt-hours per pound for a 1-month discharge. A major difference also exists in cost, with the LeClanche cell delivering energy at $0.03 per watt-hour compared with $2 per watt-hour for the silver oxide-zinc system.

Secondary battery development has relied heavily on the nickel oxide - cadmium system which was originally pioneered in Europe and is now finding a large commercial market in the United States for such applications as electric toothbrushes, household appliances, hand power tools and children's toys. Currently, the silver oxide - cadmium cell is being readied for flight use. It offers a higher energy density, but shorter cycle life than a comparable nickel-cadmium cell. The relative performance of these cells and the projected future capability are shown in tables II and III. As the depth of discharge, or fraction of rated energy capacity, increases, the cycle life tends to decrease. Current technology, based on a 25-percent depth of discharge, shows a 67-percent improvement in energy density for the silver - cadmium battery over nickel-cadmium, while the latter offers more than three times the cycle life. Surprisingly, although the silver-cadmium battery is expected to have a 60 percent greater total watt-hour per pound capacity, experts currently predict that the nickel-cadmium cell, because of its ability to sustain greater discharge depths, will ultimately deliver energy densities equivalent to the silver-cadmium cell while offering several times the cycle life. A substantial improvement would be realized if the silver-zinc battery could be operated in a rechargeable mode. Though it is presently able to deliver three times the energy density of the nickel-cadmium cell, the cycle life is limited to a few hundred cycles at a maximum. Work on solution of the problems that limit the cycle life of the silver oxide-zinc cell is currently underway, with much of the effort being supported by NASA and other government agencies. This support is necessitated since suitable markets, which would justify industry's bearing the expense of this development, are lacking. This is another example of the fact that while government support has been needed to obtain batteries for space use, the basic technology required was in existence prior to the inception of the space effort. The space program provided the incentive and financial support to advance this technology.

FUEL CELLS

The main limitation of primary batteries is that they contain a relatively high mass-fraction of inactive components such as an electrolyte, separators, an electrode support structure, a case, terminals, and connectors. If a greater quantity of energy is required, some improvement might be obtained by building larger cells. Once the practical limits of cell size is reached, increased energy demand results in no improvement in energy density. The fuel cell is an electrochemical cell into which the reactive material is continually fed and from which the reaction product is continuously withdrawn, as shown in figure 4. When the chemical content of the battery at the left is expended, it must be replaced. The fuel cell, on the other hand, maintains a constant condition within the cell due to the controlled product and reactant flows. As a result, the cell continues to operate as long as flows are maintained, and the mass fraction of inactive material for the system decreases as the required operating time increases. In time, the delivered energy density approaches the value of the reactive materials alone as a limit.

Like many "new" aerospace components, the fuel cell is over a century old. During the period following World War II, research increased, with the impetus supplied by the prospect of vehicle or central station power through fuel-cell means. In order to achieve the goal of a hydrocarbon-burning cell, it was necessary to study electrode processes using pure hydrogen as an idealized fuel. Pure oxygen was likewise used in order to define the electrochemical processes occurring at air electrodes.

Happily, this combination has a theoretical energy density of over 1600 watt-hours per pound, and practical cells can be built which deliver over 1000 watt-hours per pound. Putting it conversely, the fuel consumption of hydrogen-oxygen fuel cells is 1 pound per kilowatt-hour or less. Thus, when 2-week missions requiring 1 to 2 kilowatts of electrical power came along, the hydrogen-oxygen fuel cell had undergone sufficient study to show that its development was feasible.

The fuel cell has already been chosen for the Gemini, Apollo, and Biosatellite missions by NASA. It is also a prime candidate for the Air Force's Manned Orbiting Laboratory and shows potential for several other future applications. The various types of fuel cells being developed for space are described in more detail in another paper. In general, their fixed weight, exclusive of tankage and reactants, varies from 70 to 150 pounds per kilowatt. These values are conservatively expected to drop to about 50 pounds per kilowatt in the near future. A more significant improvement will be obtained by lowering the fuel consumption. This is ultimately expected to be lowered to 0.75 to 0.80 pound of total hydrogen and oxygen per kilowatt-hour produced.

THERMOELECTRIC GENERATORS

The thermoelectric generator performs the direct conversion of heat to electricity. In this respect it is like the solar cell which directly converts sunlight to electricity. Thermoelectricity is based on the Seebeck effect. Two dissimilar materials are joined on one end, heat is supplied to this junction while the opposite end, the cold junction, is connected through an external load and maintained at some lower temperature. As heat flows through the dissimilar legs, a thermoelectric potential appears across the cold junction. This effect is completely reversible. An electric current forced in the reverse direction through this device results in a flow of heat from the cold to the hot junction. Both effects have wide application in industry and the home, ranging from the familiar thermocouple and special purpose refrigerators to pilot-light sensors and automatic shutoff valves in home water heaters and furnaces.

The power output of a thermoelectric unit will be a function of the heat flow, temperature difference and the combination of materials selected. The intensive search for increased performance has resulted in the discovery of many suitable high-performance materials as shown in table IV. It is interesting to note that each of these three materials has a range in which its performance is superior to the others.

The relatively small size, long life, and wide temperature range make thermoelectrics a natural choice for small space power systems using thermal energy. Although they are adaptable to many thermal energy sources, their use in space has so far been with radioisotope and reactor power systems. The SNAP 9A (Systems for Nuclear Auxiliary Power) generator which powers a Department of Defense satellite as shown in figure 5. Four of these systems have been launched to date. They utilize the radioactive decay of plutonium 238 in conjunction with lead-tellurdie thermoelectric elements to produce 25 watts of electric power. The first unit launched has now accumulated nearly $4\frac{1}{2}$ years of continuous operation. Table V shows several other generators of this class that are currently in use for both space and terrestial applications. From table V, it is apparent that these devices are finding application where reliable long-term unattended operation is a primary requirement. The first nuclear-reactor power system, designated SNAP 10A (fig. 6), was launched into orbit on April 3, 1965. This system used silicon-germanium thermoelectric elements. The hot junction was heated by liquid metal (NaK) which was circulated through the nuclear reactor. This system performed continuously for 43 days, and the malfunction that prematurely shut down the reactor system is not attributed to a failure in the power system.

The advanced state of thermoelectric technology, coupled with its proven flight capability, may make these systems attractive for multi-kilowatt manned applications where availability rather than performance is a major consideration.

RANKINE CYCLE

The old standby of the electric power generating industry has been and still is the Rankine cycle. It is only natural that, with the wealth of background, operating experience, and technology available, the Rankine cycle would receive significant interest for application to high-power space systems. In addition there are several desirable features which make the Rankine cycle particularly advantageous for space. These features can be summarized as:

(1) Of the mechanical cycles, the Rankine cycle comes closest to achieving Carnot efficiency.

(2) Heat addition and heat rejection are accomplished at essentially constant temperature.

(3) There is a wide range of working fluids from which one can choose to meet specific design objectives.

(4) Rankine cycle hardware has demonstrated a highly reliable endurance capability in service on Earth.

Figure 7 is a schematic of a typical Rankine cycle system that utilizes a reactor heat source. The example shown in a two-loop system; that is, a liquid loop that uses a liquid metal as the heat-transfer fluid between the reactor and the boiler, and a two-phase loop in which a liquid metal is vaporized, expanded through the turbine producting power, condensed in the radiator, and pumped back to boiler pressure by the condensate pump. The temperatures shown are typical of a high-power Rankine space power system.

Since heat rejection in space must be accomplished by radiation, the heat rejection rate is inversely proportional to the fourth power of the absolute temperature, thus making it desirable to operate the radiators at as high a temperature as possible. Liquid metals offer the advantage of high condensing temperatures in comparison with water, which is used in the conventional ground powerplant. The significant current programs utilize mercury and potassium as the working fluids. Mercury has been used as one of working fluids in binary central powerplants for many years.

The mercury Rankine cycle is under development for low- to relatively high-power applications, up to approximately 60 kilowatts. The turbine inlet temperature level of up to 1300° F is consistent with the temperature capabilities of current nuclear reactor and material technologies. Table VI summarizes the development status of this class of systems. These systems exploit a variety of potential energy sources. SNAP-1 was to have utilized the radioactive decay of the isotope Ce-144 as the energy source. SNAP-2 and SNAP-8 use reactor heat sources. (The SNAP-8 system is shown in fig. 8.) The Sunflower system was to have operated with solar energy using a solar collector to concentrate the solar energy to a mercury boiler.

For electrically propelled, manned, interplanetary spacecraft, extremely high-powered, light-weight systems will be required. For this application, alkali-metal Rankine cycle technology, based on potassium as the working fluid, is being pursued by NASA. The overwhelming effect of powerplant specific weight on mission payload capability for an electrically propelled spacecraft is graphically illustrated in figure 9. This indicates that, for desirable missions to be performed, powerplant specific weights in the range of 20 pounds per kilowatt must be achieved. It should be noted, however, that this figure is typical of the trends exhibited of powerplant specific weight on vehicle mass requirements. The absolute numbers are highly dependent on the assumptions used. Hence, this type of data should not be used indiscriminately. Other studies of this type have indicated useful missions at somewhat higher specific weights. Since radiator weight comprises a significant proportion of the total powerplant specific weight, it is instructive to look at the effect of turbine inlet temperature on relative radiator-area requirements. Figure 10 indicates that, in order to achieve the required low specific weights, the high-temperature, alkali-metal system may be required.

The predominant characteristics of the high-temperature Rankine cycle would then be:

(1) Applicability over a wide range of powers up to the very high (megawatts) power levels required for electrical propulsion

(2) Low radiator area and weight

(3) Moderate thermal efficiencies

(4) Adaptability for use with a diversity of heat sources

(5) Wealth of background related to terrestial technology

(6) Difficult technology because of high temperatures, two-phase flow problems and corrosive nature of the working fluids

BRAYTON CYCLE

The Brayton cycle has received considerable interest as a space powerplant and is currently being investigated by NASA. Interest stems primarily from the fact that the Brayton cycle can utilize inert-gas working fluids such as argon, neon, or even mixtures such as helium-xenon. The use of these inert working fluids should effectively eliminate problems relating to corrosion, turbine erosion, and compatibility, as well as two-phase fluid mechanics problems in zero gravity. The Brayton cycle offers desirable performance potential with conversion efficiencies ranging from 20 to 30 percent. In addition, the Brayton-cycle development program can draw heavily from the wealth of existing gas-turbine technology developed for the familiar turbojet engine.

Figure 11 depicts shematically a Brayton-cycle space powerplant. In this cycle, the working fluid remains in the gaseous phase throughout. Cold gas is compressed in the compressor and passes through a recuperator where it is preheated by the hot turbine exhaust gas. The gas is heated to its maximum temperature by the heat source (a reactor in this diagram) and is then expanded through a turbine, which drives the compressor, and an electric generator. Then, the gas passes through the recuperator, where it gives up some of its heat to the compressor discharge stream. More heat is given up in the radiator where it is radiated to space. The cold gas then reenters the compressor, completing the cycle. Since the sensible heat of the gas is rejected, the radiator is not isothermal as in the Rankine cycle.

Operating between the same temperature limits, the Brayton cycle is less efficient and requires a larger radiator than the Rankine cycle. However, higher efficiencies are obtained by operating the Brayton cycle across a wider temperature range than is practical for the Rankine cycle. The resulting radiator area is still much greater than for the Rankine cycle. It is for this reason that the Brayton cycle is not generally considered competitive with the potassium Rankine cycle at very high power levels.

The Brayton cycle has been studied for a variety of missions and energy sources. NASA is currently testing the components of a nominal 8 kilowatt-electric Brayton system utilizing argon as the working fluid. A conceptual drawing of such a system is shown in figure 12. This technology program is directed toward the use of a solar concentrator.

Since a solar Brayton cycle must operate continuously in orbit about the Earth whether in sunlight or in shade, heat storage is required during the sun part of the orbit to provide heat for continuous operation during the shadow portion of the orbit. The solar collector focuses the sun's energy on a cavity receiver consisting of a gas heat exchanger and a heat storage medium. Lithium fluoride is used as the heat storage medium. Its melting temperature of 1560° F permits the higher turbine inlet temperature required for desirable performance of the Brayton cycle.

The predominant characteristics of Brayton cycle for space power are summarized below relative to the Rankine cycle:

(1) High efficiency

(2) Large radiator area and weight

(3) Applicability over a wide range of power levels, but not competitive with the Rankine cycle at very high powers

(4) Compatibility with the same diversity of heat sources

(5) Comparable background of related terrestrial technology

(6) Considerably less difficult technology because of inert, single-phase working fluid.

THERMIONICS

Of all the power systems discussed here, the one perhaps most deserving the title of an exotic power-conversion device is the thermionic generator. This device, which was little more than a laboratory curiosity, has received its primary impetus from the space program. The concept itself is not a new one since Thomas Edison was one of the early observers of the phenomenon of thermionic emission. The effect still bears his name, the "edison effect."

The principle of operation of this device is relatively simple. A thermionic converter consists of a high-temperature electron-emitting surface and a low-temperature electron-collecting surface. As the emitter is heated to extremely high temperatures, typically 3000° to 3500° F, sufficient energy is imparted to the electrons to permit large numbers of them to escape the surface and traverse the gap to the cooled collector, so that a charge builds up on the collector surface. If the collector and emitter are then connected through an external load, a flow of current is sustained by the potential difference between the emitting and the collecting surfaces. The collector surface is maintained by coolant at approximately half the temperature of the emitting surface. In the simplest of these devices, a vacuum is maintained between the two surfaces. However, as the electron current builds up, a repelling space charge develops which inhibits further emission from the cathode surface, compromising the performance of the device. Figure 13 shows what is termed a "plasma diode," in which an electrically conducting ionized gas is introduced into the interelectrode space. The purpose of this plasma is to neutralize the space charge.

The plasma most used in thermionic diodes presently is cesium vapor. In the cesium diode, the vapor actually performs two functions; it suppresses the space charge effect, and it reduces the work function of the collector, which is the energy required to stop an electron from the material surface. This increases the potential or voltage output. The range of interelectrode spacing currently being utilized in the cesium diode is of the order of 0.005 to 0.010 inch. Table VII summarizes the status of current thermionic-diode technology.

Several ways exist in which termionic converters can be integrated into a system incorporating solar, chemical, or nuclear (both reactor and isotope) energy sources. Since thermionic devices are inherently high-power-density devices, the most promising way of developing thermionic power appears to be the integration of converters into a nuclear reactor core integral with the fuel elements. Figure 14 schematically illustrates one concept for accomplishing the integration. In this device, the cylindrical emitter surface is the container for the fissionable reactor-core material. The core is fabricated of fuel elements with are, in effect, integrated thermionic diodes. Surrounding these emitter fuel elements would be the collector. A liquid metal coolant such as lithium would be used to transfer the heat to the heat-rejection system. Figure 15 illustrates the basic components required for integrating this concept into a reactor-thermionic system. Considerable in-pile testing of thermionic diodes has been accomplished which demonstrates the feasibility of this approach. However, before this system can become a reality, numerous engineering problems must be resolved. Problems associated with nuclear fuels operating at these high temperatures, seals, insulating materials, and fabrication techniques must be investigated to assure that converters can operate reliably for long periods of time. Also, as indicated above, little work has been done on systems of converters. In a typical reactor system, hundreds or thousands of these converters will be connected in a series-parallel network. In addition, thermionic converters are typically low-voltage, high-current devices. Reliable, light-weight, and highly efficient power-conditioning equipment will be needed. All the areas mentioned are currently receiving attention. The predominant characteristics of the thermionic system can be summarized as:

(1) Applicability over a wide range of powers, including the very high power levels
(2) Low radiator area and weight
(3) Moderate thermal efficiencies
(4) Adaptability to a diversity of heat sources
(5) Multiplicity of small elements in large systems, thus the possibility of increased reliability
(6) Low-voltage, high-current devices
(7) Very difficult technology with little established background to draw from; Bizarre materials, elaborate and minute details of construction, all within a reactor core where the problems cannot be separated as in the Rankine and Brayton cycle

The potential for inherently reliable diodes of high performance with low weight and area requirements warrants their continued development not only for space power applications, but also for energy conversion from nuclear power in ground applications, perhaps in the form of a topping unit for a conventional steam powerplant.

CONCLUSION

In conclusion, it is apparent that space power systems are really hybrid devices, being neither new exotic systems developed only for space use nor familiar everyday ground-type powerplants. Space power systems represent a logical modification or extension of ground-power technology to meet a special set of operation requirements.

Modification of familiar power systems to meet special earthbound applications is not new. For instance, the tendency is to build large steam powerplants near a water source which can act as a heat sink. There are applications on earth, however, where water is not available as a heat sink, and ambient air is used through the medium of specially designed heat exchangers. On the other end of this spectrum, in certain locations in New Zealand and Italy underground hot springs are used as the heat source for Rankine cycle powerplants. It is not surprising, therefore, to find that in space the selection of heat source for a power system is made on the basis of the environment encountered and the heat sources that are compatible with the particular mission requirements.

The natural tendency is to think in terms of exotic new solutions to meet an exotic requirement. In fact, however, the space power program is based on the modification of existing techniques and technologies to meet the special requirements of the space environment, just as they are often modified to meet special requirements on earth. While the existing technology in commercial powerplants has served as a jumping-off place for the development of space power systems, the space program has supplied the impetus for conducting research and development to improve and to better understand these existing techniques. The result will ultimately be a general across-the-board improvement or upgrading of all power systems. These improvements undoubtedly will reflect themselves in advantages to all of us.

TABLE I. - PRIMARY ZINC-SILVER OXIDE BATTERY

[Anode, zinc; electrolyte, potassium hydroxide; cathode, silver (II) oxide; nominal voltage, 1.5 V; operating voltage (av), 1.4 to 1.5 V]

Discharge rate, hr to 0.9 V	Energy density		Usable temperature range, °F	
	W-hr/lb	W-hr/in.^{3}	Upper	Lower
1/6	35	2.1	165	80
1	40	3.5	165	32
30	60	4.5	165	0
100	75	6.0	125	-40

TABLE II. - PRESENT AND PROJECTED NICKEL OXIDE-CADMIUM BATTERY PERFORMANCE

Depth of discharge, percent	1965		1968		1975	
	Effective capacity W-hr/lb	Life, thousands of cycles	Effective capacity, W-hr/lb	Life, thousands of cycles	Effective capacity, W-hr/lb	Life, thousands of cycles
25	3	10	----	50	--	100
50	--	4	6.5	15	--	30
75	--	2	----	5	11	30
100	12	--	13.5	--	15	---

TABLE III. - PRESENT AND PROJECTED SILVER OXIDE-CADMIUM BATTERY PERFORMANCE

Depth of discharge, percent	1965		1968		1975	
	Effective capacity, W-hr/lb	Life, thousands of cycles	Effective capacity, W-hr/lb	Life, thousands of cycles	Effective capacity, W-hr/lb	Life, thousands of cycles
25	5	0.30	--	0.50	--	1.00
35	--	.25	8	.35	--	0.70
45	--	.20	--	.25	11	.40
100	20	----	22	----	24	----

TABLE IV. - THERMOELECTRIC MATERIALS

Material	Hot junction temperature for best efficiency, °F	Efficiency at temperature shown, percent
Bismuth telluride	500	4
Lead telluride	1100	7
Silicon-germanium alloy	1500+	7

TABLE V. - SNAP ISOTOPE THERMOELECTRIC SYSTEMS
[Lead Telluride T/E Elements]

Unit	Power, W	Isotope fuel	Weight, lb	Application
SNAP-3	2.5	Plutonium-238	5	DOD satellite
Sentry	4.5	Strontium-90	----	Arctic weather satellite
SNAP-7A	10		1870	Light buoy
SNAP-7B	60		4600	Lighthouse
SNAP-7C	10		1870	Antarctic weather station
SNAP-7D	60		4600	Ocean weather station
SNAP-7E	7		6000	Deep-sea acoustic beacon
SNAP-7F	60		----	Oil platform beacon
SNAP-9A	25	Plutonium-238	27	DOD satellite

TABLE VI. - MERCURY RANKINE CYCLE PROGRAM

Unit	Heat source	Power, kWe	Cycle efficiency, percent	Test results
SNAP-1	Isotope	0.5	10	System, 2500 hr, continuous
SNAP-2	Reactor	3	8	Components, 25,000 hr, total
Sunflower	Solar	3	10	Turbomachinery, 4600 hr, continuous
SNAP-8	Reactor	35	8	Turbomachinery, 830 hr, continuous pumps, > 9500

TABLE VII. - TYPICAL THERMIONIC DIODE PERFORMANCE (OUT OF PILE)

[Emitter temperature, ~1800° C; demonstrated life, > 7000 hr.]

Spacing, mils	Collector material	Emitter material	Power density, W/cm^2	Efficiency, percent
10	Niobium	Tungsten	7 to 20	7 to 15
8	Molybdenum	Tungsten	7 to 10	~ 13
5	Niobium	Tungsten	13 to 15	14 to 20

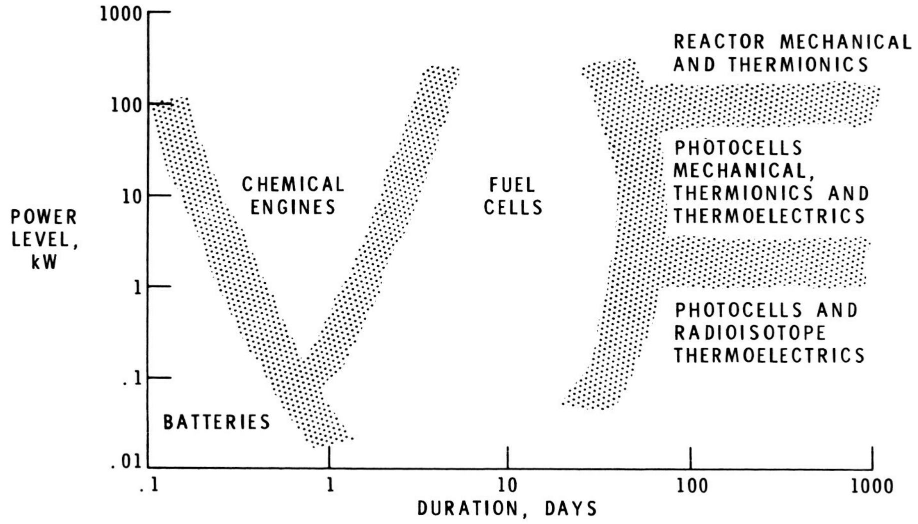

FIGURE 1. - ELECTRIC POWER SYSTEMS FOR EARTH ORBIT.

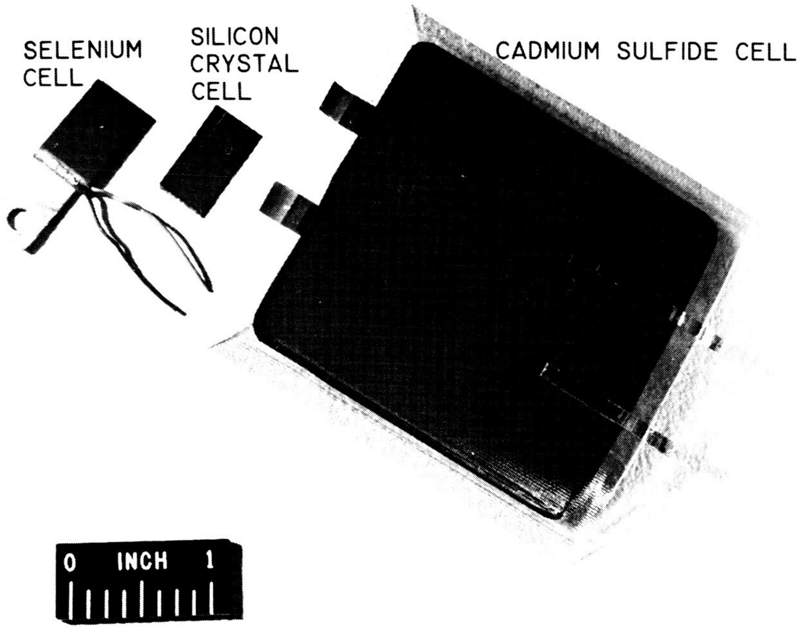

FIGURE 2. - THREE SOLAR CELLS.

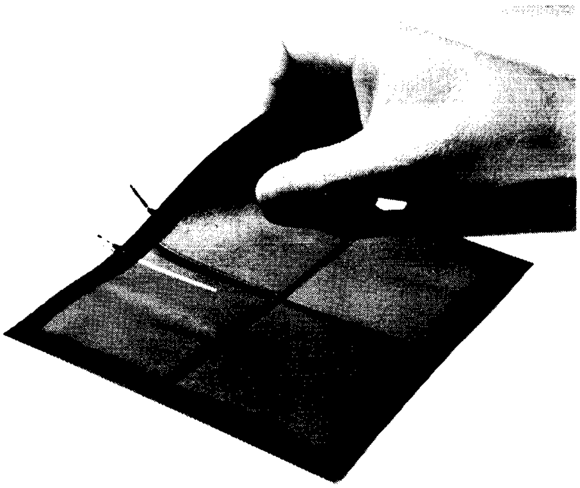

FIGURE 3. - FLEXIBLE THIN-FILM CADMIUM SULFIDE PHOTOVOLTAIC CELL.

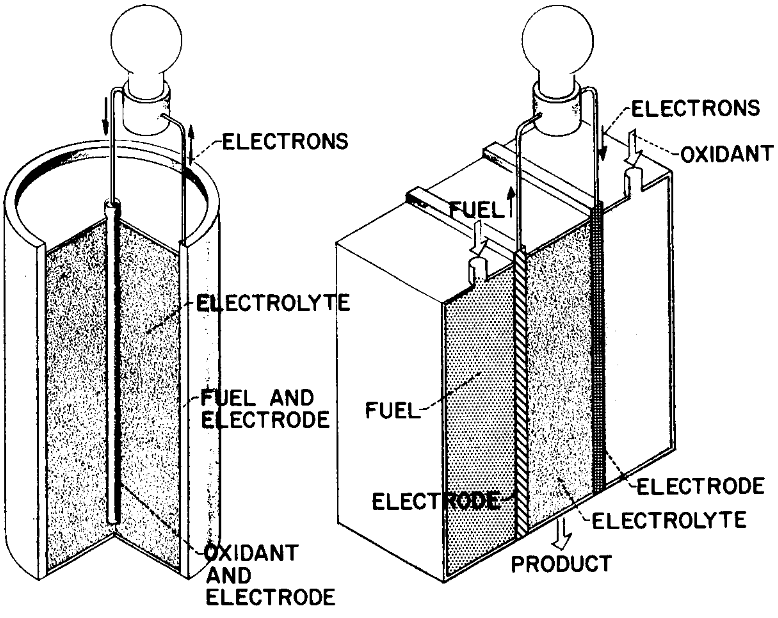

FIGURE 4. - COMPARISON OF BATTERY AND FUEL CELLS.

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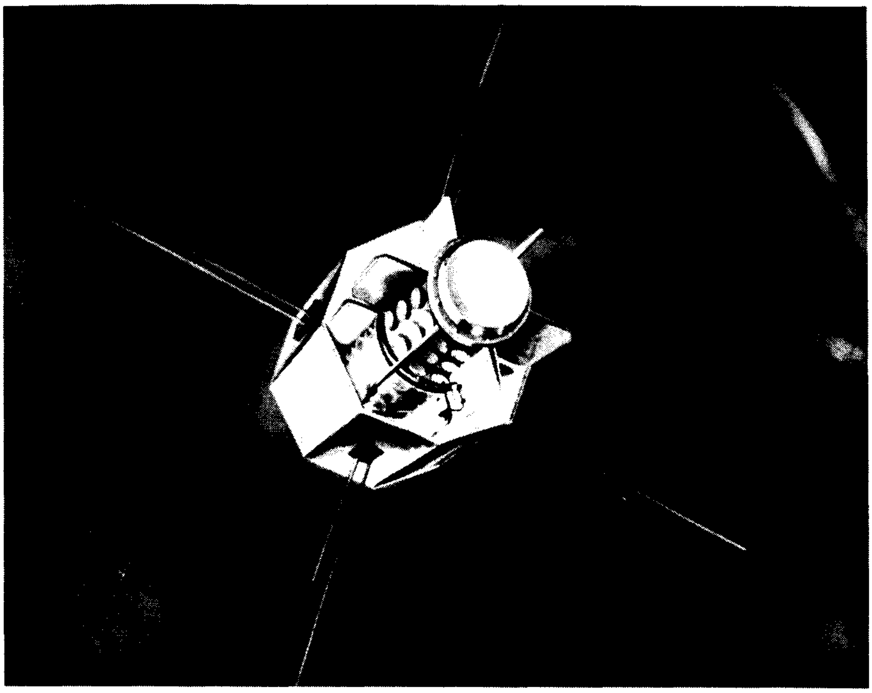

FIGURE 5. - SNAP-9A.

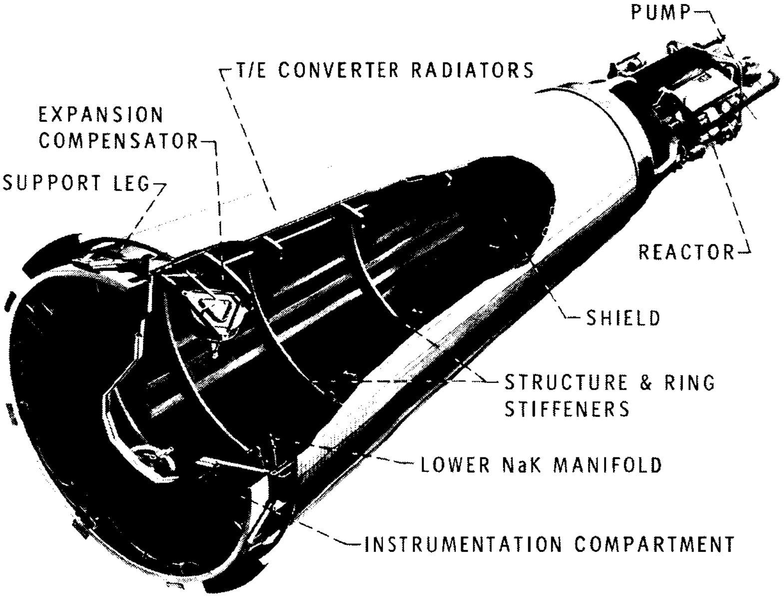

FIGURE 6. - SNAP-10A SYSTEM.

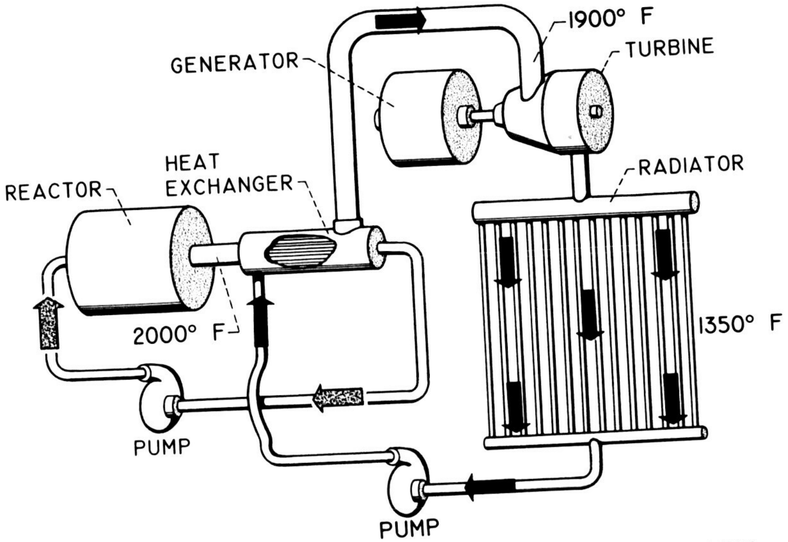

FIGURE 7. - SCHEMATIC OF RANKINE CYCLE SPACE POWER SYSTEM.

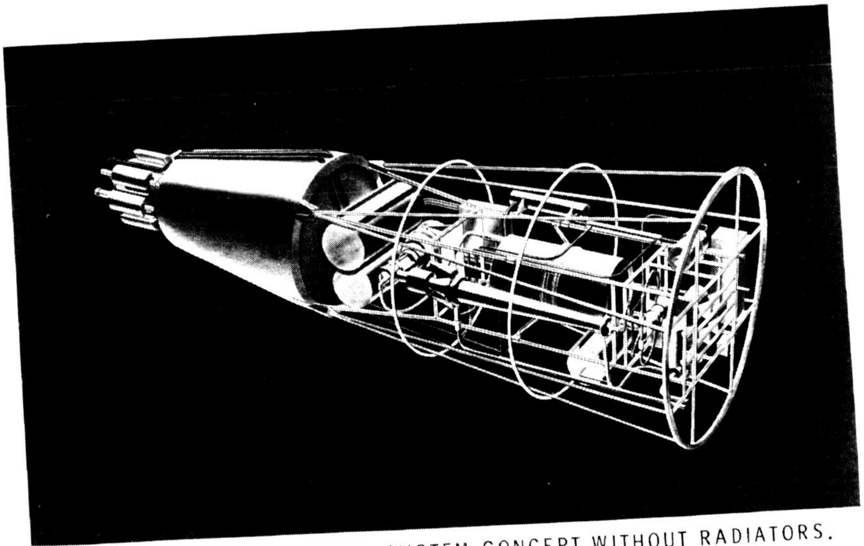

FIGURE 8. - SNAP-8 POWER SYSTEM CONCEPT WITHOUT RADIATORS.

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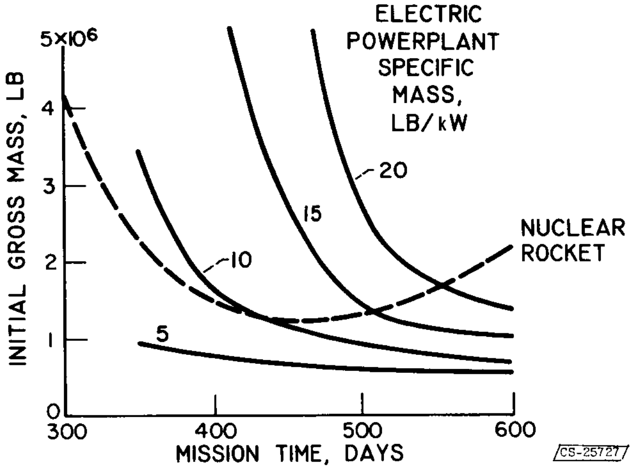

FIGURE 9. - STUDY OF SEVEN-MAN MISSION TO MARS; CREW SHIELDING FOR 100 REM, DOSE; METEOROID SHIELDING FOR $P_0 = 0.999$.

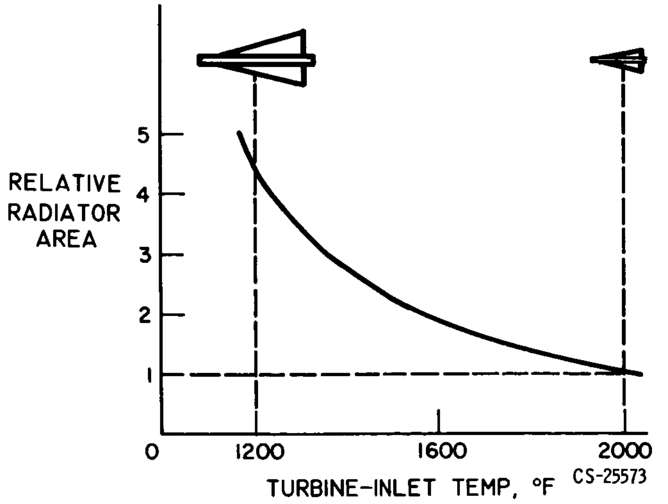

FIGURE 10. - EFFECT OF TURBINE-INLET TEMPERATURE ON RADIATOR AREA.

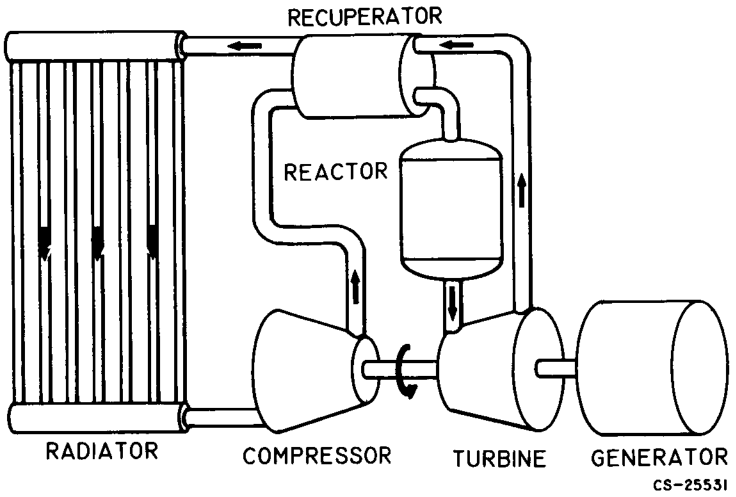

FIGURE 11. - SCHEMATIC OF RECUPERATIVE BRAYTON CYCLE SPACE POWER SYSTEM.

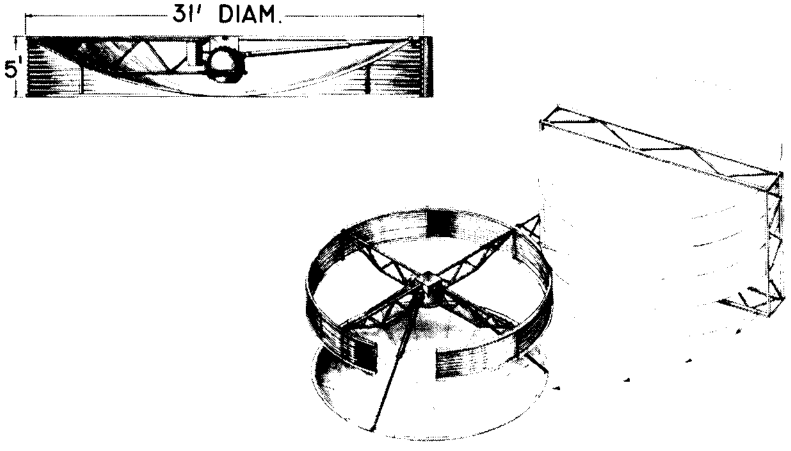

FIGURE 12. - SOLAR BRAYTON CYCLE POWER SYSTEM.

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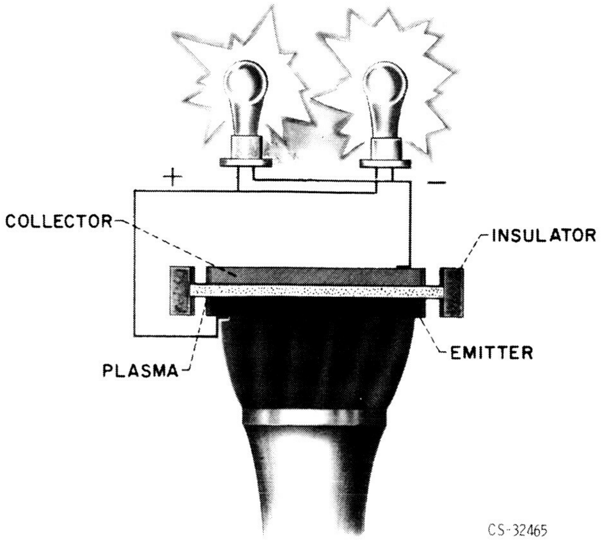

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FIGURE 13. - PLASMA DIODE.

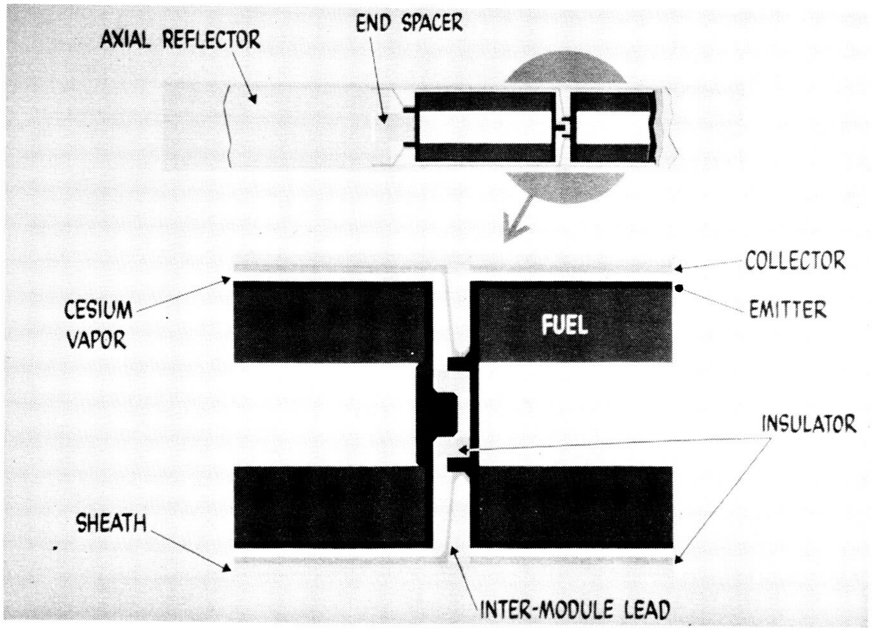

FIGURE 14. - CONCEPTUAL THERMIONIC REACTOR FUEL-ELEMENT DESIGN.

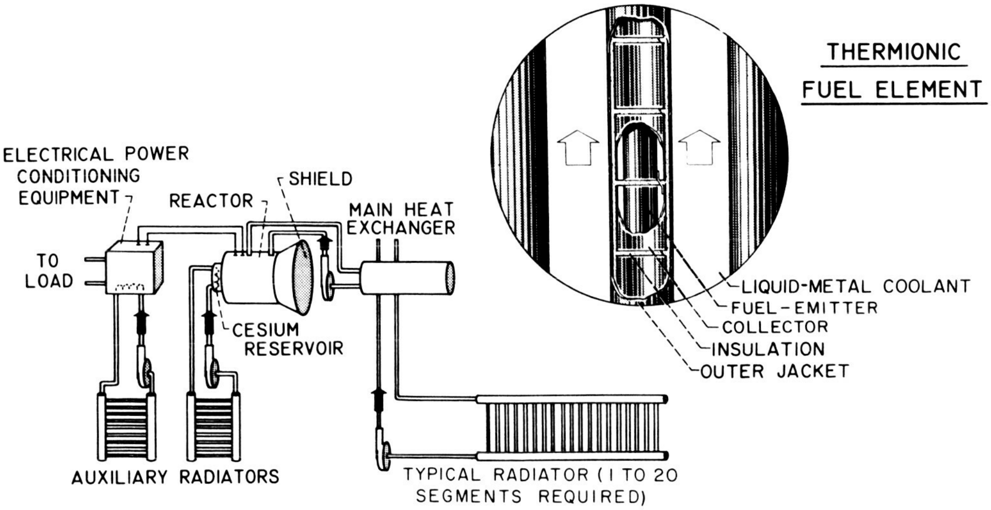

FIGURE 15. - SCHEMATIC OF NUCLEAR THERMIONIC POWER SYSTEM.