ELECTRIC PROPULSION FOR MANNED MISSIONS

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INTRODUCTION

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Missions of Interest

Electric propulsion is of interest for manned interplanetary missions, primarily because it offers the potential of delivering and returning relatively large payload fractions from the planets. This can be achieved because of the high specific impulse obtainable when the propellant is accelerated by electrical means rather than thermally, as in chemical and nuclear rockets.

The benefits of reduced propellant consumption are not, however, obtained without cost. For a given thrust level, increased electrical power must be put into the exhaust jet to obtain a higher specific impulse, and the powerplant weight increases correspondingly. When thrust level and specific impulse are optimized in order to balance propellant weight and powerplant weight while achieving a maximum net payload, the vehicle acceleration is typically found to be on the order of 10^{-3} to 10^{-4} g for most interplanetary missions. As a result, the electric spacecraft cannot take off from a planetary surface but must be boosted into orbit by a high-thrust engine. In addition, as a result of the low thrust, the electric vehicles require relatively long propulsion times to perform the missions of interest. In contrast to high-thrust operation, which consists of short power bursts followed by long coast periods, the electric system operates for long periods of time to provide equivalent velocity increments.

Electric Engine Defined

A typical electric engine is shown schematically in figure 1. It consists of an electric thrustor having a propellant feed system, the electrical power-conditioning equipment, and the electrical power supply. A powerplant consists of the latter two.

The electric thrustor accelerates the propellant to a high velocity, which produces specific impulses in the 1000- to 40,000-second range. The propellant feed system stores the propellant and controls its flow to the thrustor. Typically, the system consists of the tankage, a pressurizer, the flow-control provisions, and, in most cases, a propellant vaporizer. The electrical power-conditioning equipment converts the power supply output to the voltage and frequency required by the thrustor. It consists of inverters, transformers, rectifiers, and circuit breakers in the more complex installations. The electrical power supply consists of a heat source, an energy-conversion system, and a means of rejecting waste heat into space.

General Engine Specifications

The interest in an electric engine depends on its competitiveness relative to other propulsion schemes. The nuclear rocket appears to be the next major advance in propulsion, so a comparison of nuclear rockets and electric propulsion can serve as an illustration of the performance required of the electric engine. In figure 2 relative initial payload is plotted against mission time for a Mars round trip for nuclear rockets and electric propulsion. Three nuclear rocket curves cover [redacted]orable launch dates (1971, 1986, 2001, etc.), a less f[redacted]0), and specific impulses of 800 and 900 seconds. The [redacted] of the electric engine is shown parametrically as a function of powerplant specific weight for only one launch date as, in general, changes in launch dates have little effect on missions with high-specific-impulse engines.

From the comparison, it is apparent that low-specific-weight (10 to 15 lb/kw) electric engines capable of operating reliably for 400 to 500 days are required to compete successfully with nuclear rockets for the Mars mission. For longer higher energy missions, planetary missions (such as Jupiter or Pluto), or where large quantities of electric power are required at the destination, the electric engine is competitive at even higher specific weights.

The electrical power levels of interest for manned interplanetary flight vary, depending on the mission profile, payload requirements, and specific weight of the engine. A typical 450-day Mars mission for a net weight in Mars orbit of 170,000 pounds and a return weight to Earth orbit of 120,000 pounds can utilize a 20-megawatt, 11-pound-per-kilowatt power system. If heavier shielding weights are required for crew protection, the power requirements could increase. Or, if specific weights of the powerplant are lower, the power may increase. In general, the power levels for electric propulsion missions can be crudely estimated by assuming that one-third of the spacecraft weight in orbit will consist of powerplant, one-third of propellant, and the remainder of structure and payload. It appears that the power range of interest for the manned Mars mission is 5 to 40 megawatts, where the 5 megawatts correspond to missions with small spacecraft using electric propulsion from Earth escape and the 40 megawatts are for larger spacecraft starting from Earth orbit.

While it is likely that large electric engines, if developed, will be designed for manned missions, there are many useful unmanned missions that could be performed during the powerplant "man rating" phase and after the engine is developed. The power levels of interest for the unmanned missions are related to booster capability. Typical examples are:

(1) Starting with a Saturn C-5 payload of about 200,000 pounds in Earth orbit, 5 megawatts of electric power can be used to provide a large Jupiter satellite.

(2) With a Saturn C-5 payload of 60,000 pounds placed beyond Earth escape, 1 megawatt of electric power can be used for a smaller Jupiter orbiter.

(3) With a Saturn C-1B, 28,000 pounds can be placed in a 300-mile orbit. A spacecraft of this size with about 400 kilowatts of electric power can be used to perform missions such as a solar orbiter or Mercury orbiter missions.

In general, the unmanned missions are longer, requiring 700 to 800 days for Jupiter orbiters and up to 1200 days for Pluto probes. For these higher energy missions, the electric engine can compete successfully with a nuclear rocket with powerplant specific weights up to 30 pounds per kilowatt.

Preliminary analysis indicates that the engine should, also, be of modular construction and that a useful module size is about 5 megawatts electric. One module would consist of many thrustors, a single reactor, and one or more power-conversion systems. Two to four 5-megawatt-electric modules could then be used for a manned mission, and one 5-megawatt-electric module at rated power or derated module for the unmanned missions.

Other general requirements for the electric engine can be inferred from these mission considerations. To operate in the space environment, the engine must tolerate vacuum conditions, meteoroid impacts, and space radiations. It can only reject waste heat by thermal radiation in the vacuum. As most space power systems must reject 7 to 10 kilowatts of thermal energy for each kilowatt of electric power generated, the radiator becomes prohibitively large at high powers unless operated at high temperatures. As an example, if heat is rejected at 600° F, approximately 1 acre or 40,000 square feet of radiating surface are required per megawatt of electric power generated. While at 1500° F, only 2000 square feet are required. Since radiators typically weigh 1 to 5 pounds per square foot, the achievement of lightweight power systems requires that heat be rejected in a 1200° to 1800° F temperature range. The high heat-rejection temperatures in turn imply a requirement for high heat source temperatures of 2000° to 3500° F, depending upon the power-conversion system.

An electric engine must utilize a nuclear heat source. Chemical heat sources are too heavy for the long missions. Solar heat sources require large collectors (about 70 sq ft/kw), which are much heavier than nuclear sources at higher powers. Isotopes are not available in sufficient quantities for manned missions, and a fusion reactor is not yet conceivable. Thus, the nuclear fission reactor heat source is the only one of interest.

A closed-cycle power system that incorporates its own heat-transfer media must be used. While small quantities of propellant are continually exhausted from the engine, a simple thermodynamic calculation will disclose that the propellant weight flow is insufficient for transferring heat in any adequate power-generating system because of the inefficiencies in the electrical and thrustor systems.

The stringent reliability requirement for manned missions, coupled with the need for long life at high temperatures, imposes a severe burden on the engine. It is doubtful whether this reliability and life can be achieved without extensive redundancy and in-flight repairs.

In summary, the general requirements for the electric engine, based on both manned Mars and unmanned missions, are tabulated in table I. The following discussion describes current thrustor and electric powerplant concepts, summarizes their development status, and outlines some of the problems to be resolved.

ELECTRIC THRUSTORS

Thrustors of Interest

To attain high specific impulses without the need for the extremely high exhaust-gas temperatures of nuclear rockets, the thermal energy of the nuclear heat source is first converted to electrical power at more manageable temperatures. This power is then used to produce vehicle accelerations by energizing electric thrustor devices. As a result, the impulse-producing momentum of the expellant is determined by electrical rather than thermal considerations, and much higher exit velocities and lower propellant mass-flow rates result. On the other hand, thrust levels are low for the same energy consumption, which results in long thrusting times.

Electric thrustors are not limited in their capability to generate high specific impulses. However, mission optimization has indicated a need for thrustor devices that operate over a wide range of specific impulse (1000 to 20,000 sec). It is doubtful whether such a range can be covered efficiently with a single type of thrustor. Consequently, a variety of electric thrustor devices is currently being considered.

For thrust generation, three classes of devices are currently being investigated - electrothermal, electrostatic, and electromagnetic. Potentially, electromagnetic accelerators should be competitive, at least, in the low-specific-impulse range of 1000 to 5000 seconds. This is because the integration of ionization and acceleration processes promises the efficient utilization of the ions produced. However, the operating efficiencies of these devices to date have been relatively low (10 to 30 percent), and developmental problems exist in an area where there is little experience. Electrothermal thrustors (resisto jet and arc jet) and electrostatic thrustors (contact ionization and electron bombardment ionization) have demonstrated much higher operating efficiencies, and, for this reason, only the electrothermal and the electrostatic thrustors will be discussed in detail.

Thrustor Descriptions

The electrothermal thrustor devices heat the propellant electrically and expand it through a nozzle to produce thrust. On the other hand, the electrostatic devices ionize the propellant and accelerate the ions electrostatically. Variations of these thrustor concepts are shown in figure 3. Electric heating of the propellant in the electrothermal devices may be accomplished by using a resistance heat exchanger or by striking an arc to heat the propellant to high thermal energy levels.

The electrostatic thrustors develop thrust by accelerating the ionized propellant by using electric fields. The production of ions in the electrostatic device can be achieved either by contact ionization, which occurs on hot surfaces, or by bombardment of the propellant with high-energy electrons to detach electrons from the propellant atoms.

To achieve high-specific-impulse performance, the electrothermal devices utilize hydrogen or ammonia as the propellant. The heating surfaces in the resisto jet are refractory metal coils and operate at temperatures of about 4200° F. The contact ionization thrustor utilizes cesium propellant vapor and produces ions by diffusing cesium through a 2000° F porous tungsten plug and forming ions on the surface of the tungsten. The electron bombardment ionization thrustor has been demonstrated with mercury, cesium, argon, and xenon as the propellant. Both cesium and mercury have been used in operational prototype devices. Cesium appears to be more attractive because cathode sputtering is reduced and propellant utilization is higher, and, as a result, longer life and higher overall rocket efficiency are promised. The noble gases are being considered primarily to reduce the materials corrosion problems.

Although the electrothermal devices that have been operated have produced only low-level specific impulse (850 to 1050 sec) and have not demonstrated high efficiencies, they remain attractive because they produce a specific impulse in this range, and their electrical power input requirements are characterized by low voltages and high currents. On the other hand, the electrostatic devices have produced specific impulses ranging from 5000 to 7600 seconds with power efficiencies ranging from 62 to 82 percent but require direct-current voltages on the order of a few thousand volts.

Development Status and Problems

Prototype versions of the four thrustor devices that have been described have been operated in the laboratory. Actual performance figures, or realistic performance estimates believed possible within the next year or less, are given in table II. It is seen that a wide spectrum of specific impulses is being successfully pursued ranging from 1000 to about 10,000 seconds and at power efficiencies up to 82 percent. The specific areas are about 0.001 square foot per kilowatt for the electrothermal thrustors and about 0.1 square foot per kilowatt for the electrostatic devices. Specific weights as low as $\frac{1}{4}$ and $1\frac{1}{2}$ pounds per kilowatt for the electrothermal and the electrostatic thrustors, respectively, are indicated. Lifetimes of a few hundred hours have been demonstrated by complete thrustors, and some of the more critical components have shown lifetimes of a few thousand hours.

The thrustor specific areas that appear feasible indicate that some deployment of ion thrustors will be necessary to propel manned spacecraft after launch to Earth orbit or escape. Probably, a minimum specific area will occur for 30- to 50-kilowatt thrustor modules and will be about 0.1 square foot per kilowatt.

The specific weight of the electrostatic thrustors is higher than desired, the lightest being 1.3 pounds per kilowatt. This thrustor is the only one in table II that was designed with weight in mind, and even lighter designs are thought to be possible. (This unit, although designed, has yet to be built and tested.) The mission analyses performed to date at the Lewis Research Center have assumed that thrustor weights will be about 5 percent of the powerplant weight. If the thrustor should weigh more, the power supply will have to be correspondingly lighter.

Each thrustor device has its own requirements for new technology, which result because of life, power efficiency, or propellant utilization deficiencies, or various combinations of the three. Problems related to the four devices of interest will be discussed separately.

Electrothermal thrustors. - As an electric propulsion device, the resisto jet is promising for several reasons: (1) It is electrically simple, (2) it can be adapted to almost any power supply voltage (a.c. or d.c.), and (3) it does not produce electrical noise. Unfortunately, the temperatures to which the propellant must be heated approach the melting point of tungsten. The high temperatures and high flow velocities make erosion a serious problem for long lifetime.

Development of the arc jet has been emphasized more than that of the resisto jet. Because the devices are similar, many of the materials and component problems, which are common to both, are being investigated.

Electrically, the arc jet is more complex than the resisto jet, but less complex than the electrostatic thrustors. The arc jet is more difficult to start and operate stably, largely because of the negative resistance characteristic of the arc. It produces more electrical noise and is not as flexible in adapting to power supplies as the resisto jet. Because of the low specific impulses produced by the electrothermal devices, arc jets are not presently being considered as serious candidates for manned interplanetary missions, but rather for Earth satellite attitude control or lunar ferries. Because they may eventually even be attractive for manned missions, arc jets appear in this discussion.

Electrostatic thrustors. - The contact ionization thrustor is probably the oldest concept for electric propulsion. This concept is simpler, electrically, than the electron bombardment thrustor, and its propellant utilization can potentially approach 95 percent. The power efficiency for this device is severely limited because heat is radiated from the ionizer surface directly to space. Since the heat loss is essentially constant for a given ionizer temperature, it is necessary to operate at a high specific impulse to raise the ratio of beam power to total power input. This implies that for the contact ionization thrustor a lower limit of specific impulse exists below which its power efficiency is not acceptable. In order to improve the power efficiency, it is desirable to operate the ionizer at a high current density to minimize its heat radiating area. Unfortunately, this leads to an increased loss of un-ionized propellant. This balance between the propellant loss and the heat loss occurs near 95 percent propellant utilization.

Operation of the ionizer at high temperatures brings about serious, irreversible property changes in the ionizer. The porous material continues to sinter and, as the pore sizes increase, propellant losses increase.

The propellant loss is of consequence for two reasons: The first is the payload weight penalty, and the second, and most serious, is due to the existence of neutral particles in the exhaust beam. When un-ionized atoms exist in the accelerator space, a predictable portion of these neutrals interacts with the high-velocity ions, and charge exchange results. As a result, an ion having essentially zero velocity suddenly appears at a place in the accelerator space where it should have a very high axial velocity along the line of thrust. Thus, the new ion can only accelerate toward the accelerator structure where it impacts at high velocities and causes erosion and subsequent loss of the critical electrode shape. This damage can limit the life of the accelerators to a few hundred hours. Much research is being conducted in each of these areas, and progress is being made.

The electron bombardment thrustor is being developed because it avoids the high-temperature ionizer problems and is not as sensitive to current density as the contact ionization thrustor. It does, however, introduce other almost as serious problems.

Propellant utilization is not as good as with the contact ionization thrustor, typically ranging from 80 to a little over 90 percent. Poor propellant utilization introduces similar problems with the electron bombardment thrustor as with the contact ionization thrustor.

Thrustor Performance Potential

The thrustor devices that are currently being developed promise to meet a whole spectrum of specific impulse requirements for various missions. A comparison of power efficiency plotted against specific impulse for the devices that have been discussed is given in figure 4. Although a specific impulse of only 1000 seconds has been experienced to date, the electrothermal devices have the potential capability of 1500 seconds. For the contact ionization devices, porous tungsten ionizers capable of producing higher current densities along with possibilities for improved propellant utilization promise to provide efficiencies approaching 90 percent. Improved electron bombardment emitters and possibilities for improved propellant utilization promise efficiencies up to 90 percent for the electron bombardment devices. Experience with prototype electron bombardment thrustors indicates that specific weights may be 1 pound per kilowatt or less. Specific areas for ion thrustors are currently about 0.1 square foot per kilowatt, which appears applicable to manned missions if provisions are made to deploy some of the thrustor modules.

In summary, three thrustor concepts are nearing engineering phases of development. The two electrostatic thrustors are scheduled for flight testing in 1963 and 1965; the first test is scheduled for summer 1963. Ion accelerating efficiencies are near theoretical, but there is much room for improvement in the process of propellant ionization. Efforts to improve ionization and propellant utilization efficiencies to reduce power requirements and increase payload and life capability, respectively, are being performed under several NASA contracts. In addition, heater coil, nozzle, ionizer, and electron bombardment cathode material capabilities are being investigated by NASA.

The most troublesome problem has been the electron emitter lifetime. Long-life emitters have been built, but they represent the results of a very rugged brute-force approach, and poor power efficiency has resulted. A NASA contract currently exists to develop a cesium electron bombardment ionization source, which employs a cesiated cathode. Since the propellant is also cesium, the cathode can be self-heated by bombardment with energetic cesium to maintain its temperature. Such a device promises long-life performance, but has yet to be demonstrated for more than a few hours.

Flight Test Programs

Within the next 2 years and beginning this summer, flight tests of electrostatic thrustor devices are planned. The first, SERT-I, is to determine thrust capability and the possibility of neutralization of the departing particles in space. Next, the SERT-III test will check out the attitude control capability of ion thrustors by incorporating them in a 24-hour synchronous satellite. Third, the SERT-II test is not as well defined, but current plans are to incorporate it into a 180-day Earth orbit satellite to study long-term effects of the space environment. The tests will incorporate 0.5-, 1-, and 3-kilowatt ion thrustors, respectively. SERT-I will have a contact ionization and an electron bombardment thrustor on board, SERT-III will include several contact ionization thrustors, and SERT-II is presently scheduled to be a contact ionization thrustor. Because electron bombardment thrustors are progressing rapidly, they may be used for the SERT-II test instead.

ELECTRIC POWERPLANTS

Power Supplies of Interest

The electrical power supply is the heaviest subsystem of the electric engine, potentially the least reliable, and the most difficult to develop. At present, there is no power system flight hardware under development that approaches the performance required for electric propulsion applications. There are, however, technology programs, such as the Air Force's SPUR, the AEC's SNAP-50, and NASA's advanced system, that may some day provide sufficient data to design such hardware.

Three nuclear-reactor-powered space electric-generating systems are under development: the SNAP-10A, the SNAP-2, and the SNAP-8. The SNAP-10A is a 500-watt, 900° F nuclear reactor system incorporating thermoelectric power conversion and weighing about 800 pounds per kilowatt. SNAP-2 is a 3-kilowatt, 1200° F nuclear reactor system with a mercury Rankine cycle power-conversion system and weighs approximately 250 pounds per kilowatt. SNAP-8, a 35-kilowatt, 1300° F mercury Rankine cycle system, is similar to SNAP-2 and weighs about 150 pounds per kilowatt. All these specific weights include nominal shielding for electronics. The specific weights and power levels are summarized in figure 5, where they are compared with the requirements of the advanced powerplants. It is apparent that considerable advance in the state of the art is needed to achieve the performance required, which for electric propulsion is less than 30 pounds per kilowatt at temperatures exceeding 2000° F.

Because the power supplies of interest all require a nuclear reactor heat source, the primary difference between power supplies is in power conversion. Power-conversion schemes of potential interest are the Rankine cycle, the Brayton cycle, thermionic conversion, thermoelectric, and magnetohydrodynamics. Of these five schemes, only the Rankine cycle, thermionic, and magnetohydrodynamics presently show promise for manned missions. The Brayton cycle requires relatively low radiator temperatures, and, consequently, the powerplant is too heavy. The thermoelectric-conversion scheme operates at low temperatures, is relatively low in efficiency, and is consequently too heavy. Magnetohydrodynamics shows promise, but the technology is presently not far enough advanced to be discussed realistically.

Rankine Cycle Powerplant

The Rankine cycle appears to be the best dynamic conversion scheme for space electric propulsion applications because: (1) It has relatively high efficiencies closely approaching the Carnot efficiency, and (2) it rejects and adds heat at constant temperature, which reduces the weight of the heat-rejection system Rankine cycle. Disadvantages are: (1) the requirement of relatively active cycle fluids for operation at high temperatures, and (2) the introduction of problems of two-phase flow in zero gravity and moisture handling in the turbomachinery. Figure 6 is a schematic of a typical Rankine space nuclear powerplant incorporating multiple turboalternators and radiators. Based on limited present-day knowledge, this version of the Rankine cycle appears to be the best choice for an advanced nuclear space electric system and should be considered only as a reference cycle. Other combinations of the components are possible, and, as technology advances, this reference concept may change.

Powerplant description. - The basic Rankine cycle consists of a boiler, a turbine for converting high-pressure vapor into mechanical energy, a condenser, and a pump to recirculate the condensate to the boiler. Potassium, sodium, cesium, and rubidium are potential cycle fluids. To date, although a particular cycle fluid has not been selected, the emphasis in the technology programs has been on potassium.

The heat source in the reference cycle is a liquid-cooled fast reactor with the coolant circulated by a motor-driven rotating pump. Lithium appears to be the most promising coolant for the heat source. A liquid-cooled fast reactor is incorporated in the reference cycle because it provides the most compact, lightweight reactor and shield combination.

The reference cycle incorporates a liquid coolant loop for the primary heat-rejection system. It cools the condenser and transfers the heat to the radiator, where it is rejected into space. This coolant loop is desirable because it facilitates segmenting of the radiator, which thus reduces the probability of failure due to meteoroid puncture. The coolant loop also simplifies powerplant startup and spacecraft integration by reducing the requirements for preheating the radiator to provide high condenser pressures needed for pumping and should concentrate the handling of two-phase flow in a few relatively small heat exchangers. Sodium potassium (NaK) and lithium are the more likely candidates for the fluids for all coolant loops. Lithium has more desirable heat-transfer characteristics, and NaK has advantages because its lower melting temperature should reduce freezing problems previous to startup.

The powerplant will also require a number of secondary heat-rejection loops for cooling the alternator, controls, power conditioning, reactor shield, reactor reflector, pump, reactor control-drive motors, and bearings. These loops may incorporate segmenting for redundancy to improve reliability.

The powerplant requires a control system for startup to compensate for reactor burnup, control reactor-outlet temperature, prevent overspeed of the turboalternator, and control alternator frequency and voltage. Although an extensive study of the control problem has not been made, it appears that a control concept similar to that used on SNAP-8 may be suitable. This involves reflector control that varies neutron leakage to control the reactor power level and compensate for burnup. Frequency and turbine rotational speed are controlled by a parasitic electrical load control that varies the alternator electrical load. Voltage is controlled by varying the field current in the alternator windings.

An additional difficulty that will be encountered on long missions at high powers is excessive burnup in the reactor. The powerplant may have to be operated at low power (idled) during coast phases of the trajectory rather than operated at full power with excess electrical energy dissipation in the parasitic load to minimize burnup. While controls for idling have not been investigated, there is a possibility of incorporating a control valve at the boiler inlet, which along with suitable reactor control would reduce boiler flow and the reactor power required to maintain a given outlet temperature during the idle phase.

The startup system is not shown in figure 6, primarily because this area has not yet been investigated. Startup in the Rankine cycle powerplant is particularly complicated as it is necessary to start the powerplant in orbit to satisfy nuclear safety requirements, and many of the fluids used in the powerplant freeze at temperatures above the space equilibrium temperature. An additional start problem results from a pump requirement for a reasonable inlet pressure before starting. For the cycle fluids of interest, this requires a condenser temperature in excess of 1000° F. It appears that a startup concept similar to that being investigated for SNAP-8 will be suitable for the advanced Rankine system, but, as the problems are considerably more severe with alkali-metal cycle fluids, this area still requires considerable investigation.

Development status and problems. - Reactor: The AEC has two programs at Pratt & Whitney, the Lithium Cooled Reactor Experiment (LCRE) and the SNAP-50, that should provide technology for a high-temperature, high-powered, fast, liquid-metal-cooled reactor capable of operation in space. The LCRE is a ground experiment designed to demonstrate the operation of a high-temperature, lithium-cooled, UO_2-BeO fueled, fast reactor with a power output of about 10 megawatts thermal. SNAP-50 is similar to the LCRE; but, instead of being designed for a ground experiment, SNAP-50 is being developed for space by reducing weight and auxiliary requirements.

Boiler and condenser: There is presently sufficient background in boiling and condensing to design heavy boilers and condensers that can operate successfully. They are heavy because there are limited data on both boiling and condensing heat-transfer coefficients, pressure drops, and the stability of alkali metals. This lack of data requires that the component be overdesigned, which increases weight. However, data that should remove this limitation are being obtained in these areas from at least five major heat-transfer programs.

Turbine: Alkali-metal turbines can now be designed by using the same techniques as presently used for steam, mercury, and gas. The higher temperature must be considered in the structural design, and the increased problems of moisture, handling, and erosion effects must also be considered. Before optimum efficiency and life are obtained, considerable turbine testing will be required. To date, there are essentially no test data on alkali-metal turbines, but two turbine test rigs are scheduled to start operation this year that should provide some of the required test data.

Pumps: There is considerable experience under the Aircraft Nuclear Propulsion (ANP) program on the pumping of high-temperature alkali metals that can be applied to an advanced Rankine cycle system. An extension of these data is required, however, for a better understanding of the cavitation problems that can occur in a Rankine system where low pump inlet pressures at high rotational speeds are encountered. This problem might be circumvented by the use of booster pumps, subcooling, higher condensing pressures, and lower rotational speeds, if the additional complexity and weight could be accepted.

Radiators: In large space powerplants, the radiator, because of its large surface area and the meteoroid protection required, becomes the heaviest single component in the electric engine. High-temperature (1600° F) radiators can be fabricated today out of common materials (steel and/or copper with high-emissivity coatings). Lower temperature radiators (700° F) can be constructed of aluminum. With these radiators, the meteoroid protection would be provided by armor. With conventional materials, even at high temperatures, armored radiators are quite heavy; thus, development is proceeding on improved radiator materials, such as beryllium, niobium, and molybdenum, and better protection techniques that could reduce weight.

Little is presently known about meteoroid flux, meteoroid composition, or the effect of hypervelocity impact on materials and structures. An extensive program is under way in this area that includes space experiments, greater use of ground observations, and an extensive impact program. It is expected that within 3 years sufficient engineering data will be available to engineer a design for meteoroid protection. At present, meteoroid data vary by several orders of magnitude.

Power-generating and -conditioning equipment: The major electrical components are the alternator, the transformer, and the rectifiers. The magnetic and insulating materials currently available limit the alternator and transformer to operating temperatures of 500° to 800° F. State-of-the-art semiconductor materials limit solid-state rectifiers to operating temperatures of 180° to 230° F. These components must reject approximately 6.0, 0.8, and 1.5 percent of the energy they handle as waste heat, respectively. Any increase in operating temperature capability will ease the heat-rejection problem, especially for the alternator, because of its higher inefficiency.

To achieve increases in allowable operating temperatures, magnetic materials with improved high-temperature permeability and physical strength, insulating materials with improved high-temperature dielectric strength, and semiconductor or gas-filled rectifiers capable of operation at high temperatures must be developed. Programs to investigate and develop such material and devices are being conducted under NASA and Air Force contracts.

The integration of the alternator into a turboalternator unit poses several development problems. State-of-the-art alternator technology is only adequate for the development of moderate-speed, low-temperature components. To simplify the integration, it is desirable to develop high-rotational-speed machines along with the higher temperature capability discussed previously. Alternator and power-conditioning design studies are being performed under a NASA contract.

Thermionic Powerplant

Thermionic conversion currently appears to be the best static conversion scheme for space electric propulsion applications. Thermionic converters consist of two electrically insulated electrodes, one hot and one cold, as shown by figure 7. Electrons are emitted from the hot surface, transported through an ionized interelectrode vapor, and collected at the cold surface. By proper selection of materials and geometry and control of temperatures, a potential of about 1 volt is produced, which enables the electrons to do work in an external circuit.

Coupling of thermionic converters with a fission reactor heat source may be accomplished by placing the thermionic converters within, or external to, the reactor. Conceptual "out-of-pile" thermionic systems incorporate converters in the heat exchanger, or radiator. In these systems the emitter temperatures correspond to liquid-metal reactor coolant temperatures. Conceptual "in-pile" systems incorporate converters in the reactor fuel element where emitter temperatures correspond to fuel temperatures. Thermionic systems for electric propulsion application must have emitter temperatures of about 3000° F or higher. Because the in-pile concept requires a 3000° F or higher fuel material without the need for a 3000° F or higher liquid-metal containment material, only the in-pile system is currently of interest for electric propulsion application.

Powerplant description. - A schematic of an in-pile thermionic powerplant that has the potential of producing multi-megawatts of power for the missions of interest is presented in figure 8. The thermionic converters, which are an integral part of the reactor fuel elements, are heated directly by the fuel and cooled by the liquid metal circulated through the reactor.

The electric energy output of the converters is conducted from the thermionic reactor through bus bars to the power-conditioning equipment that tailors the reactor output to thrustor needs. At the multi-megawatt level, hundreds of these thermionic fuel elements must be contained within the reactor, and each fuel element may contain from 10 to 20 converters. The converters are connected in series and series-parallel networks to provide a reasonable voltage output and a measure of redundancy.

The liquid-metal coolant from the reactor is circulated by a pump to heat exchangers that are connected in parallel. Liquid-metal coolant transfers the heat from each heat exchanger to the main radiator, which is segmented. For the powerplant schematic shown, there is one radiator segment for each heat exchanger. Auxiliary cooling systems are used to maintain the temperatures of the cesium reservoir and the power-conditioning equipment at tolerable levels. In addition, a cooling system may be required for the reactor shield.

To achieve attractive efficiencies and system weights, the operating range for emitter surface temperatures must be 2800° to 3500° F, with collector temperatures of 1250° to 1900° F.

The thermionic reactor constructed by assembling arrays of thermionic fuel elements has a fast neutron energy spectrum for compactness and reduction of the shielding weight. Because the output of thermionic converters is very sensitive to temperature, nearly flat axial and radial power distributions are desired throughout the life of the reactor. Studies indicate that peak to minimum power distribution values of about 1.4 are needed for reasonable efficiencies. Small reactors can be controlled by varying neutron leakage with reflectors. However, for the large cores of interest, the control perturbations at the center of the core caused by the reflectors may be ineffective, and other schemes for control may have to be provided.

The power-conditioning equipment required for a thermionic powerplant must include inverters to convert the direct-current output of the thermionic converters to alternating current, in addition to transformers and rectifiers similar to those required for a Rankine cycle powerplant.

Development status and problems. - The technology required to design thermionic powerplant hardware is in the early phases of being developed. There is little experience in the design and construction of thermionic fuel elements, and development programs comparable to the SNAP-2, -8, and -50 are nonexistent for thermionic powerplants. The thermionic powerplant technology program is concerned with providing new materials and device configurations capable of performing reliably in highly stressed environments (temperatures up to 4100° F in the event of a converter open-circuit failure, high radiation fluxes, and corrosive active metal atmospheres) for long times.

Results from the current development program for advanced systems are applicable to the pump, heat exchanger, and radiator components of both the Rankine cycle and thermionic powerplant. The program includes a study of electromagnetic pump concepts and investigations of lightweight, high-temperature radiator materials and configurations. Components unique to the thermionic powerplant pose problems that create "make or break" areas of concern. These problems and the status of activities to solve them are discussed in the following paragraphs for the thermionic fuel element, thermionic reactor, and d-c to a-c inverter components, respectively.

Thermionic fuel element: The fuel-emitter combination or "fuel form," the insulators, and the metal-ceramic seal present the most challenging materials problems. Representative converter configurations, both single- and multi-cell modules, will have to be operated successfully in the laboratory and reactor environments. Activities to demonstrate the feasibility of a full-scale thermionic fuel element can then begin.

Fuel form: For the fuel form, handling of the gaseous fission products and compatibility of the fuel with good thermionic emitter materials are major requirements. Ideally, the fuel form should contain the fission product gases without swelling and also provide a suitable electron-emitting surface. To approach this condition, there is strong incentive to develop refractory metal-clad fuel forms having refractory metal matrices to strengthen the fuel-form structure.

In-pile screening tests of clad and bare fuel forms are currently being performed under AEC and NASA sponsorship to determine fission product containment and fuel-emitter compatibility characteristics in the radiation environment. If containment is not feasible, the products will have to be vented directly to space, vented via the interelectrode gap by flushing intermittently or continuously to space, or both. The effect of fission gases within the interelectrode space on thermionic performance is being investigated by NASA, AEC, Air Force, and Navy contractors.

The compatibility of fuel and emitter materials is also currently being investigated by several Government contractors. Tungsten, the highest melting temperature refractory metal, has been the most compatible emitter material with the candidate fuels, UO_2 and UC near a temperature of interest (3272° F) during 1000-hour furnace tests. Other advanced material combinations are promising and are being developed. Another aspect of compatibility is the diffusion of fuel constituents to the emitting surface. This phenomenon and its influence on thermionic performance are being studied under existing NASA and Air Force contracts.

The containment, compatibility, and emission-diffusion behavior of the best candidate materials in simulated operating environments for much longer times must be investigated to designate a fuel form for the thermionic fuel element feasibility demonstration. Fuel-form activity is pacing the progress of the thermionic powerplant materials technology program.

Insulators: Two different insulators are required. The thin, low-temperature insulator located between the collector and the outer clad of the thermionic fuel element must have high dielectric strength properties and be impervious to the interelectrode vapor. This insulator electrically isolates the thermionic converters from the reactor liquid-metal coolant and allows the converters to be connected in series and achieve higher voltages and lower current outputs to the power-conditioning equipment. Tests are being conducted under AEC contract to fabricate sandwiched structures and to evaluate the effects of alkali-metal attack and radiation on insulator properties.

The second insulator, a high-temperature insulator, is required to support one end of the emitter and must withstand voltages corresponding to the output of a single converter (less than 1 v). The properties of bulk insulator materials in cesium and radiation environments at temperatures of interest (up to 2910° F) are being investigated by contractors for the Navy, the AEC, and NASA. The failure of a high-temperature insulator could mean the loss of output from a single converter, whereas breakdown of the low-temperature insulator could lead to a major degradation in output power.

Metal-ceramic seals: Metal-to-ceramic joining capability is required at many different locations throughout the thermionic fuel element structure. Good bonding for low thermal resistance is required for the low-temperature insulator sandwich, leaktight metal-to-ceramic joints may be required between adjacent emitters if the fission gases are vented directly to space, and a metal-to-ceramic seal is required to contain the interelectrode vapor. The Navy's Bureau of Ships is currently sponsoring a program to develop high-temperature metal-ceramic seals. Activities for improved seals are necessarily a part of all thermionic converter programs and, also, other programs within industry to develop products (i.e., lamps, electronic tubes, etc.) for the space, military, and commercial markets.

Converter modules: The materials technology is incorporated into operating devices by constructing and testing single- and multi-cell converter modules. In the multi-cell modules, the cells have a common envelope and interelectrode vapor reservoir. With each additional cell, a new set of material and geometry problems is encountered.

Fuel forms and interelectrode vapors and geometries are being investigated in single cells. Individual cells are being connected in series-parallel arrays to investigate the character of electrical interplay between cells. End supports, intercell connections, and intercell venting structures (where thought necessary) are being investigated in dual-cell modules. After successful tri-cell module in-pile tests, thermionic fuel element mockups and demonstration units can be constructed.

For successful operation, the single- and multi-cell module structures must demonstrate that they possess the power output and life capabilities required for application. When the structures have been developed for steady-state and transient operation in simulated environments for short durations, long-time degradation effects and failure mechanisms must be eliminated or controlled.

One of the most serious failure modes is expected to be the occurrence of an open-circuit failure. Because the cells within the thermionic fuel element are connected in series, a mechanical failure, or zero load condition, which interrupts the current flow, would eliminate the electron cooling paths of all the emitters in the particular series circuit. It is estimated that 50 to 60 percent of the heat energy generated by fission is removed from the fuel forms through these paths. As a result, fuel-form temperatures would rise 800° to 900° F above the normal operating temperatures, as high as 4100° F. Mechanisms for correcting or tolerating the overtemperature conditions must be thoroughly investigated.

To date, a single-cell module has produced power for more than 8500 hours without degradation. The results demonstrate that the same thermionic electrodes and cesium plasma are capable of operating for long times in a nonnuclear environment. This module was constructed and operated by the General Electric Research Laboratory. Thirteen single-cell modules that typify thermionic fuel element structure will be constructed and life-tested under an existing NASA contract.

The performance of dual-cell modules out-of-pile and in-pile is currently being investigated under AEC contract. Several dual-cell modules simulating fueled emitters are being studied in the laboratory under Air Force contracts.

The Air Force is also sponsoring an out-of-pile investigation of nine converters in series with a common interelectrode vapor reservoir. Multi-cell modules have been operated in-pile by the AEC at Los Alamos Scientific Laboratory, but the tests were short lived, and performance degradation effects were inseparable.

An investigation of thermionic converters for nuclear marine application, being sponsored by the Navy's Bureau of Ships, is one of the largest thermionic programs in existence. NASA's solar thermionic programs to develop converter modules for space application are providing a useful background of experience.

Thermionic reactor: In addition to containing the thermionic converters, fast neutrons sustain the chain reaction within the thermionic reactor. The uniqueness of the thermionic reactor requires that methods be developed for flattening power distributions and achieving control capability. Low-power critical experiments can be performed to determine flux distributions and criticality requirements for such a reactor. However, until reactor systems similar to the one of interest have been operated, it will be difficult to accurately predict the temperature coefficients that correspond to certain changes within the reactor.

Because the economy of fast neutrons is poor, large amounts of fissionable material are required in the thermionic reactor. For the multi-megawatt power levels, core sizes are limited by thermionic emitter area requirements. Therefore, the fuel materials are heavily diluted, and additional uranium 235 is required for criticality. The increased fuel loading reduces the percentage of total uranium atom burnup required, and the diluent may improve burnup capability. Fuel volume fractions of about 0.2 to 0.4 result after the coolant and thermionic requirements have been considered. The resulting structure must provide for a suitable combination of nuclear, thermionic, and heat-transfer characteristics to achieve acceptable performance.

Problems related to the energy-conversion cycle are the design of electrical connections between fuel elements and the load, and the design of interelectrode vapor supply and regulating systems. The possible effects of electric oscillations, stray currents, or magnetic fields within the reactor must be investigated, and the ability to tolerate open-circuit failures within the thermionic fuel element must be developed.

Los Alamos is currently constructing a critical facility to mock up a thermionic powerplant. Parametric and preliminary design studies are being performed by NASA contractors to investigate thermionic powerplant designs with emphasis on the thermionic reactor. Effects that may degrade thermionic performance, dissipate available electrical energy uselessly, or create failure mechanisms are being investigated to reduce uncertainty and define development requirements.

Direct-current to alternating-current: For the thermionic powerplant, the low-voltage, direct-current output must be converted to a nearly square alternating-current waveform, transformed to the high voltage, and then rectified to the specified direct-current voltage. At present, all the electrical components are low-temperature devices that will necessitate large cooling loops unless major advancements are made in electric power-conditioning component technology.

A rough estimate made under a current NASA contract of the power-conditioning specific weight for a 1-megawatt-electric powerplant using Apollo technology (which is about 2 yr away) was 16 pounds per kilowatt. This weight does not include the weight of the auxiliary radiator or electrical bus bar required, and a 125° F coolant temperature and silicon-controlled rectifiers were assumed. About 85 percent of this weight is in the inverter stages and is due to the switching capacitors required to control the silicon-controlled rectifier devices and the support structure for these capacitors. To achieve overall powerplant weights less than 20 pounds per kilowatt, power-conditioning weights of 3 to 5 pounds per kilowatt will be required.

Available current-carrying devices for inverters are of the solid-state variety, either germanium transistors or silicon-controlled rectifiers. Although the transistors have lower power capacity, they do not require the continued application of gating signals to be maintained in an off condition, as do the silicon-controlled rectifiers. The capacitor penalty necessary to keep the silicon-controlled rectifiers in an off condition may offset their greater energy throughput capability. A study to evaluate the trade-offs involved is being made under an existing NASA contract.

Because the greatest weight penalty is imposed by the switching capacitors and the solid-state devices, NASA contracts to develop high-temperature - high power switchgear (for use as high as 1000° F) and high-temperature power tubes (for use at temperatures ranging from 930° to 1470° F) are being initiated. Solid-state devices for operation at 930° F are being studied under a current Air Force contract. The gas-filled power tubes (thyratrons) can be used in the rectifier as well as in the inverter stages. The thyratrons are of metal-ceramic construction similar to thermionic converters and should adapt to the highly stressed environments as well.

To design power-conditioning components for such an advanced power system, it is necessary to know the properties of materials for high-frequency and -temperature conditions and in vacuum and alkali metal environments. A NASA contract is being initiated to investigate magnetic materials, electrical conductors, and electrical insulators at such conditions. Thus, activity for the material and device improvements required is being sponsored under several NASA and Air Force contracts.

Powerplant Performance Potential

The performance or competitiveness of an electric engine depends primarily upon the specific weight and the attainable life of the power supply. From the present state of knowledge it is impossible to quantitatively estimate the life potential of an advanced power system, but weight estimates can be provided.

Pratt & Whitney under contract NASw-360 has prepared conceptual designs and parametric data for 1-megawatt Rankine cycle and thermionic powerplants. The program began in July 1962 and has reported primarily parametric design data (refs. 1 to 3). From personal contacts with Pratt & Whitney, additional data that include preliminary weight estimates for the early conceptual designs were obtained. These estimates were used as the basis for preparing the weights in this section. As the design work at Pratt & Whitney progresses, some changes in the weights will undoubtedly occur.

Rankine cycle powerplant assumptions. - The Pratt & Whitney 1-megawatt Rankine cycle system consists of a single reactor connected to four 250-kilowatt power-conversion loops operating in parallel. Each power-conversion loop contains a single boiler; a turbine directly coupled to an alternator; power conditioning; controls; a condensate pump for recirculating the flow from the condenser to the boiler; and 10 lithium-cooled condensers, each with its own pump and independent radiator. Schematically the powerplant is identical to that shown in figure 6. Potassium is used as the turbine fluid, and lithium is the coolant throughout. Cycle conditions, operating temperatures, component efficiencies, and component ratings are summarized in table III.

It was necessary for Pratt & Whitney to make a number of assumptions in preparing the designs. These cannot, of course, be justified because of the lack of experimental data. However, the assumptions are fairly conservative.

Pratt & Whitney used the meteorite-protection criteria recommended in reference 4 with 1956 meteoroid flux estimates (ref. 5) but neglected the spalling and thin-plate correction factors recommended by these investigations. Beryllium was assumed to be a suitable radiator material. The radiator was designed for a 90-percent probability that 75 percent of the radiator surface would be effective at the end of 16,000 hours. Recent data have indicated that the penetration criteria (ref. 4) and the flux estimates (ref. 5) are very conservative. Neglecting the spalling and thin-plate corrections and using a 90-percent probability, Pratt & Whitney is optimistic. Thus, there is a tendency for these two effects to cancel each other, although calculations confirming this have not been conducted by the investigators. The radiator design is admittedly crude. However, at this time it is not felt that more detailed or more refined calculations of meteorite protection requirements are indicated, as the uncertainties still remaining in the meteorite area are too large to warrant further refinement.

Shield design for the megawatt systems assumes that a 20-foot-diameter payload is located 50 feet from the reactor and receives neutron and gamma doses of 10^{13} nvt and 10^7 rads, respectively. This integrated dose of 10^7 rem is obviously too high for manned spacecraft, but a new shield has not been calculated as its design depends to a very large extent upon the spacecraft configuration and the shield provided for the space environment. Very preliminary estimates indicate that the shield required to limit the dose to 10 rem for a 250-foot separation distance from the powerplant weighs approximately 1 to 2 pounds per kilowatt (paper by Karp). If this is correct, the error in using Pratt & Whitney's shield design is $\frac{1}{2}$ to $1\frac{1}{2}$ pounds per kilowatt.

Rankine cycle powerplant weight estimates. - As stated before, the Pratt & Whitney design assumptions have been fairly conservative. However, there are a few additional areas the authors have taken the liberty of modifying to provide better estimates. These include the following:

(1) Boiling and condensing average heat fluxes were based on the present state of the art - heat fluxes in the 20,000 to 30,000 Btu/(hr)(sq ft) range in

contrast to Pratt & Whitney's assumption of fluxes in the 100,000 to 250,000 range.

(2) Turbine and alternator efficiencies were reduced from 83 and 95 percent to 77 and 90 percent, respectively.

(3) The Pratt & Whitney radiator incorporates segmenting in the design, but does not provide redundancy, as they assume that the mission can be accomplished if 75 percent of the radiator area required for full power remains at the end of 16,000 hours. The authors have added 33 percent additional radiator area to compensate for this loss of area so that full power is available at the end of 16,000 hours.

(4) The authors feel that the reactor design is too optimistic. Consequently, the weight of the reactor has been increased significantly to allow for the use of more conservative fuels at lower fuel burnup rates.

Weight breakdowns for the 1-megawatt Rankine cycle system, together with the numbers of each component and their duty, are presented in table IV.

The Pratt & Whitney 1-megawatt powerplant weights have been extrapolated to the 5-megawatt level by assuming that all weights scale linearly except the reactor, shield, piping, controls, and startup components. The weights of these components were estimated. The weight breakdown for a 5-megawatt system together with the component ratings and the number of components is shown in table V. Note that the weight breakdown includes all anticipated items, including power conditioning and controls. It should also be noted that, although a single 30-megawatt-thermal reactor and shield is included, all other components include a 25-percent allowance for redundancy. Thus, although four boilers, turboalternators and power-conditioning units are sufficient to provide 5 megawatts electric, five of these are provided; likewise, where 80 condensers and radiator segments are sufficient, 100 are provided. Despite this conservatism, the weight of the powerplant without shielding for manned missions is 20 pounds per kilowatt - a weight that appears to be just barely competitive with nuclear rockets for some of the more ambitious manned missions.

There is hope, however, that these weights can be improved. If just a little less conservatism is allowed in estimating the temperature and efficiency potentials of an advanced Rankine system, a considerable reduction can be obtained in weight. This is shown in table VI, where the weight savings is indicated that would result with certain components improvements. As an example, a turbine-inlet temperature of 1850° F was assumed. If this can be increased to 2100° F and the condensing temperature increased to 1400° F (14 lb/sq in. abs), the weight of the powerplant is reduced 2.4 pounds per kilowatt. Also, turbine and alternator efficiencies of 77 and 90 percent were assumed. There is some hope that these efficiencies could be raised to 85 and 95 percent, respectively. If the larger values are obtained, the weight of the powerplant is reduced another 1.4 pounds per kilowatt. Similarly with the temperature of the electrical components, it was assumed that rectifiers using semiconductors operate at temperatures of 140° F and that the alternator and transformer operate at 500° F. If these temperatures can be raised to 500° and 800° F, respectively, a weight savings of 1.9 pounds per kilowatt results. If the reactor burnup can be improved or if the boiling and condensing heat-transfer coefficients can be improved, there is another possibility of saving 1.6 pounds per kilowatt. The accumulative savings approaches 8 pounds per kilowatt. While it is unlikely that all of these improvements can be achieved, there is potential for accomplishing some and partially fulfilling others. Consequently, it is likely that a Rankine cycle powerplant weighing considerably less than 20 pounds per kilowatt at 5 megawatts is achievable.

Thermionic powerplant. - The Pratt & Whitney thermionic powerplant design is an in-pile thermionic system similar to that shown in figure 8. The collector is cooled by lithium, which is the coolant used in the radiator segments and other cooling loops. Thermionic converter performance is based on an empirical correlation of available thermionic test data (ref. 2). Power conditioning presents a rather large unknown in the design, as the only available inverter data use semiconductors. The inverter alone could weigh as much as 14 pounds per kilowatt while operating at 140° F. So in the design it was necessary to assume that higher capacity tubes or semiconductors would be developed to achieve lower power-conditioning weights. Pratt & Whitney's assumptions and the authors' corrections in the areas of meteorite protection and shielding are consistent with those used in the Rankine analysis, although there does appear to be some advantage to using niobium in the radiators and operating the main radiators at higher temperatures to provide lower radiator areas.

The design conditions for the thermionic system are summarized in table VII, and a weight breakdown for the 1-megawatt system with corrections similar to those used for the Rankine system is provided in table VIII. An extrapolation technique similar to that used for the Rankine system provides the 5-megawatt thermionic system weight breakdown, also shown in table VIII.

Comparison of Rankine and thermionic powerplants. - The specific weights of Rankine and thermionic powerplants are compared in figure 9, where the specific weights are plotted as a function of radiator inlet temperature. The thermionic systems are also shown parametrically as a function of emitter temperature. The specific weights presented for both systems do not include the redundancy that was included in the detailed weight breakdowns presented in the previous tables. The specific radiator areas for four powerplants are also shown; however, these areas do not include provisions for component cooling.

The Rankine powerplants are shown for two cases: one with a beryllium radiator, the other with niobium. Presently, only beryllium, niobium, and molybdenum appear to have the properties desired for high-temperature radiator materials (ref. 6). In estimating weights it was assumed that beryllium is resistant to meteoroid impact, even though there are some indications that it may be too brittle. The use of higher density niobium will impose a severe weight penalty on the Rankine powerplant because the powerplant cannot readily utilize the high-temperature potential of niobium unless very high liquid-metal temperatures (2500° F) can be tolerated in the reactor.

The specific weights for the thermionic powerplants are shown for both niobium and beryllium radiators. Beryllium appears to be limited to temperatures less than 1400° F by strength and sublimation. The thermionic powerplant weight is a minimum at the highest temperature at which beryllium can be used (about 1350° F), and another minimum occurs at about 1900° F with niobium radiators.

The Rankine cycle powerplant using beryllium appears to offer a slight weight advantage over a 3200° F thermionic powerplant. While the niobium Rankine powerplant is heavier than the thermionic, the differences in specific weight are not large. In any case, in considering the assumption and unknowns inherent in the analysis, there is no reason to select one power system over the other at this time.

If radiator surface is the most important selection criterion, the higher temperature thermionic system offers advantages. The primary radiator area is about 800 square foot per megawatt as compared with 3700 square foot per megawatt for the Rankine cycle. As these areas do not include secondary cooling, this 4-to-1 area advantage may not be maintained when cooling requirements for power conditioning are included, unless higher temperature (500° F) d-c - d-c converters are developed.

In summary, neither thermionics nor Rankine power systems possess any inherent advantages that would allow the selection of one over the other for intensive development at this time. Instead, each has certain advantages and disadvantages, which include the following:

(1) Thermionic powerplants may not require rotating equipment.

(2) The nuclear and power-conversion problems are separated in a Rankine powerplant.

(3) The Rankine powerplant appears to be lighter.

(4) The thermionic powerplant requires less radiator area.

(5) The thermionic powerplant can operate with lower liquid-metal temperatures.

(6) A Rankine powerplant has less complex power-conditioning problems.

CONCLUSIONS

Electric propulsion appears to be competitive with chemical and nuclear propulsion providing lightweight, long-lived engines are developed. High-specific-impulse thrustors that promise to satisfy advanced electric engine requirements are nearing engineering phases of development. Presently, small thrustors are being ground-tested, and it is expected that the electrostatic devices will soon be flight-tested. The development of 30-kilowatt thrustors has been initiated, and, if they have sufficient life, they could serve as thrustor modules along with the megawatt powerplants.

Technology programs for high-temperature, lightweight power-conditioning equipment are now getting under way. High-temperature materials and devices are being studied, but it will be many years before useful hardware is available.

At present, the equipment that can be built is much too heavy, presents cooling problems, and introduces radiation-shielding complexities.

The nuclear-electric power supply poses the most difficult problems. The research and development program is still in the early technology phase with NASA and other Government agencies and is concerned, primarily, with investigating materials, securing engineering design data, establishing component performance capabilities, determining meteoroid effects, and so forth. It is felt that this technology phase will have to continue for a number of years before meaningful hardware designs can be initiated and feasibility demonstrated.

For the two powerplants currently of interest, the advanced Rankine cycle technology is more advanced and has a broader technology base. In contrast, thermionic technology is in an earlier technology phase, and predictions of its potential are less reliable. At present there appears to be no incentive to select either a Rankine or thermionic powerplant for intensive development, as either powerplant has good potential.

It appears that lightweight, high-efficiency electric engines competitive with other propulsion schemes can be developed. It is not apparent, however, that long life can be obtained unless extensive redundancy and/or in-flight repair capability are provided. The advanced electric engines will require a long and expensive development program, especially for the electric powerplant. The program will probably last 10 to 20 years and cost hundreds of millions of dollars, if the reliability required for manned flight is to be realized.

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TABLE I. - ELECTRIC ENGINE DESIGN OBJECTIVES

	Manned	Unmanned
Power level, Mw	5 - 40	0.4 - 5
Life, hr	10 - 15,000	10 - 30,000
Specific weight, lb/kw	10 - 20	10 - 30
Reliability, percent	99+	90
Radiator temperature, °F	1200 - 1800	1200 - 1800

TABLE II. - PRESENT STATUS OF THRUSTORS

Thrustor	Approximate power, kw	Specific impulse, sec	Power efficiency, percent	Specific area, sq ft/kw	Specific weight, lb/kw
Lewis Resisto jet	15.0	850	75	0.003	1.0
AVCO Arc jet	30.0	1050	45	.0004	.22
TAPCO Electron bombardment[1]	3.0	5000	75	.05	3.3
EOS Electron bombardment	1.0	5500	82	.34	4.0
EOS Electron bombardment[1]	2.3	7000	75	.10	1.3
Lewis Electron bombardment	.5	5000	70	.88	6.0
Lewis Electron bombardment	2.0	5900	75	.17	5.0
Hughes Contact ionization[1]	.5	4500	40	.54	4.1
Hughes Contact ionization[1]	2.5	7600	62	.08	4.8

[1]These performance figures have not been attained (4-63), but are believed to be realistic estimates of performance within 12 months.

TABLE III. - RANKINE CYCLE POWERPLANT

ASSUMED CYCLE CONDITIONS

Net power output high-voltage d.c., Mw Alternator outputs low-voltage a.c., Mw Reactor thermal output, Mw	5 5.9 30
Reactor-outlet temperature, $^{\circ}F$ Turbine-inlet temperature, $^{\circ}F$	2000 1850
Turbine-inlet pressure, lb/sq in. abs Turbine-exit pressure, lb/sq in. abs	89 4
Radiator-inlet temperature, $^{\circ}F$ Radiator-exit temperature, $^{\circ}F$	1150 1000
Turbine efficiency, percent Alternator efficiency, percent Power-conditioning efficiency, percent	77 90 97
Radiator material	Beryllium

TABLE IV. - WEIGHT BREAKDOWN OF 1-MEGAWATT RANKINE CYCLE POWERPLANT

Item	Number of units	Unit rating,* Mw	Weight, lb
Reactor	1	$^{t}6$	1500
Shield	1	-----	800
Boilers	5	$^{t}1.50$	1700
Primary loops and pumps	5	-----	1200
Turboalternators	5	$^{e}.30$	1750
Condensers	20	$^{t}.30$	1550
Primary radiators	20	$^{t}.30$	3000
Structure	--	-----	4600
Secondary radiators	5	$^{t}.25$	2800
Power conditioning	5	$^{e}.25$	2700
Secondary piping	5	-----	400
Startup loops	5	-----	600
Miscellaneous and contingencies	--	-----	1400
	Total weight, lb		24,000
	Specific weight, lb/kw		24

*t, megawatts thermal; e, megawatts electric.

TABLE V. - TYPICAL WEIGHT BREAKDOWN OF 5-MEGAWATT

RANKINE CYCLE POWER SUPPLY

Item	Number of units	Unit rating,* Mw	Weight, lb
Reactor	1	t30	3,000
Shield	1	------	1,500
Boilers	5	t7.5	6,500
Primary loops and pumps	5	------	5,400
Turboalternators	5	e1.48	7,500
Condensers	100	t.30	7,700
Primary radiators	100	t.30	15,000
Structure	---	------	17,000
Secondary radiators	25	t.05	13,500
Power conditioning	5	e1.25	12,700
Secondary piping	---	------	1,800
Startup loops	5	------	1,400
Miscellaneous and contingencies	---	------	7,000
	Total weight, lb		100,000
	Specific weight, lb/kw		20

*t, megawatts thermal; e, megawatts electric.

TABLE VI. - IMPROVEMENT POTENTIAL FOR 5-MEGAWATT

RANKINE CYCLE POWER SUPPLY

	Design value	Future value	Weight reduction, lb/kw
Turbine-inlet temperature, $^{\circ}F$	1850	2100	2.4
Turbine efficiency, percent	77	85	.9
Alternator efficiency, percent	90	95	.5
Electrical equipment temperature, $^{\circ}F$	140/500	500/800	1.9
Reactor burnup, percent	1	5	.4
Boiler average heat flux, Btu/(hr)(sq ft)	30,000	150,000	.6
Condenser average heat flux, Btu/(hr)(sq ft)	50,000	150,000	1.0
Accumulative improvement, lb/kw			+7.7

TABLE VII. - THERMIONIC POWERPLANT ASSUMED

OPERATING CONDITIONS

Emitter temperature (maximum), $^{\circ}F$	3200
Collector temperature (average), $^{\circ}F$	1800
Radiator-inlet temperature, $^{\circ}F$	1850
Radiator-outlet temperature, $^{\circ}F$	1580
Converter power output, low-voltage d.c., Mw	6.2
Net power output, high-voltage d.c., Mw	5
Theoretical converter efficiency, percent	16.7
Theoretical converter power density, w/sq cm	7.2
Average converter efficiency, percent	12.7
Average converter power density, w/sq cm	4.1
Power-conditioning efficiency, percent	93
Overall system efficiency, percent	11
Radiator material	Niobium

TABLE VIII. - WEIGHT ESTIMATES OF 1- AND

5-MEGAWATT THERMIONIC POWERPLANTS

Item	Weight, lb/kw	
	1-Mw system	5-Mw system
Reactor	4.9	3.3
Shield	1.5	.6
Primary heat exchangers	.2	.2
Pumps	.6	.6
Bus bar	.5	.5
Power conditioning	5.0	5.0
Structure	3.0	1.0
Main radiator	4.4	4.4
Secondary radiators	6.0	6.0
Total	26.1	21.6

SCHEMATIC OF ELECTRIC ENGINE

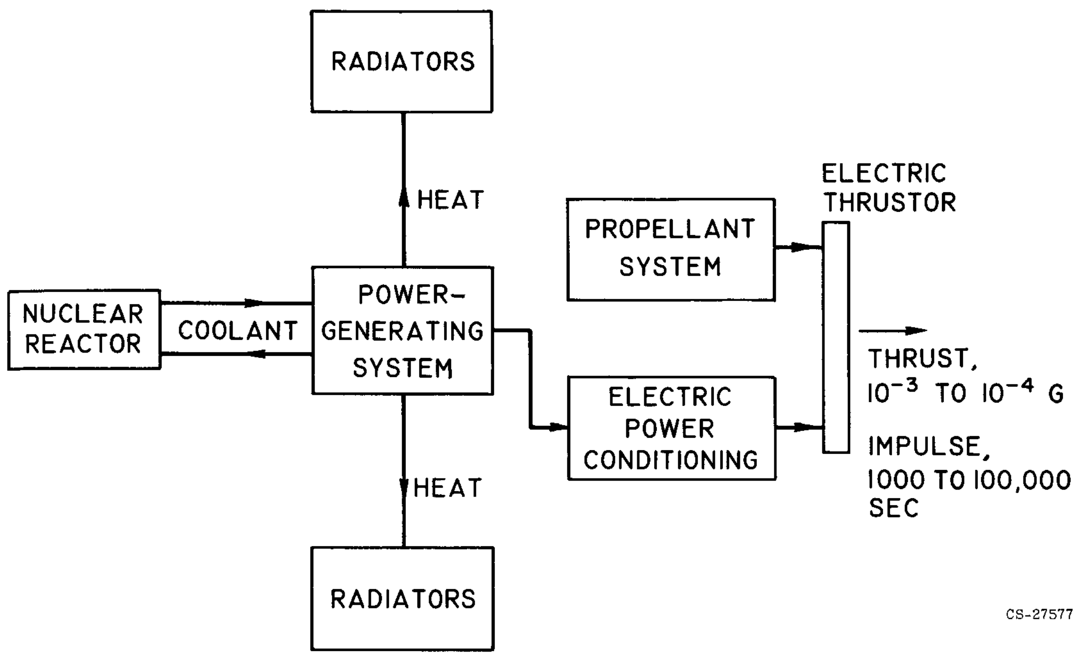

Figure 1

COMPARISON OF NUCLEAR ROCKET AND ELECTRIC ENGINE PERFORMANCE FOR MANNED MARS ROUND TRIP

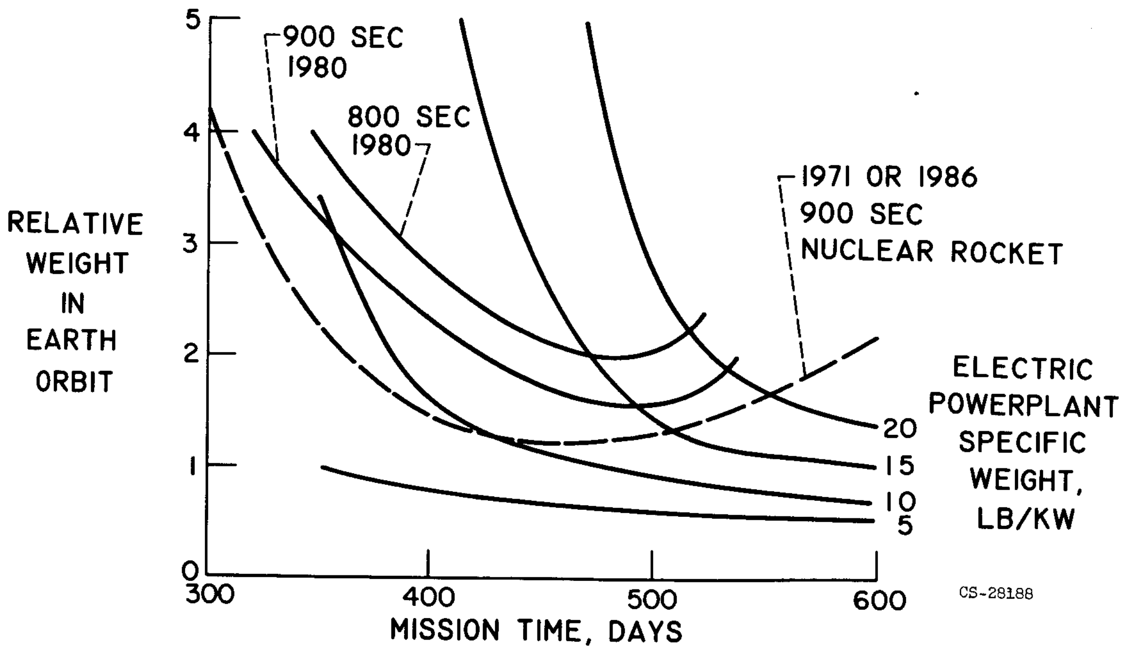

Figure 2

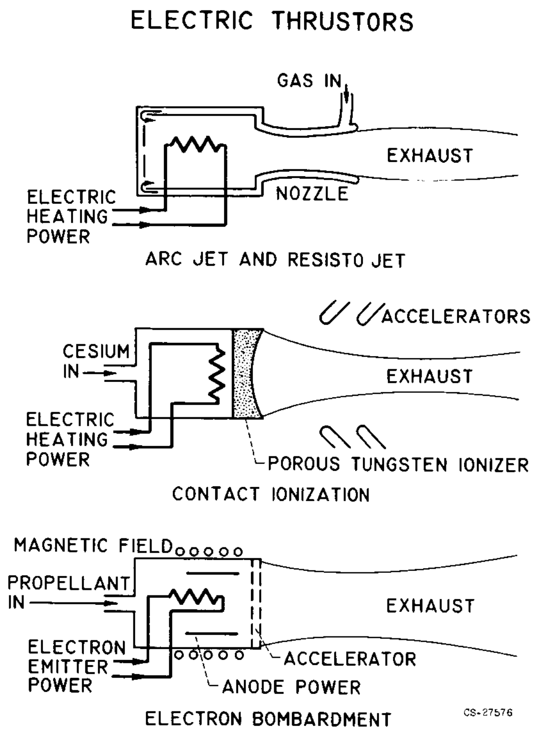

Figure 3

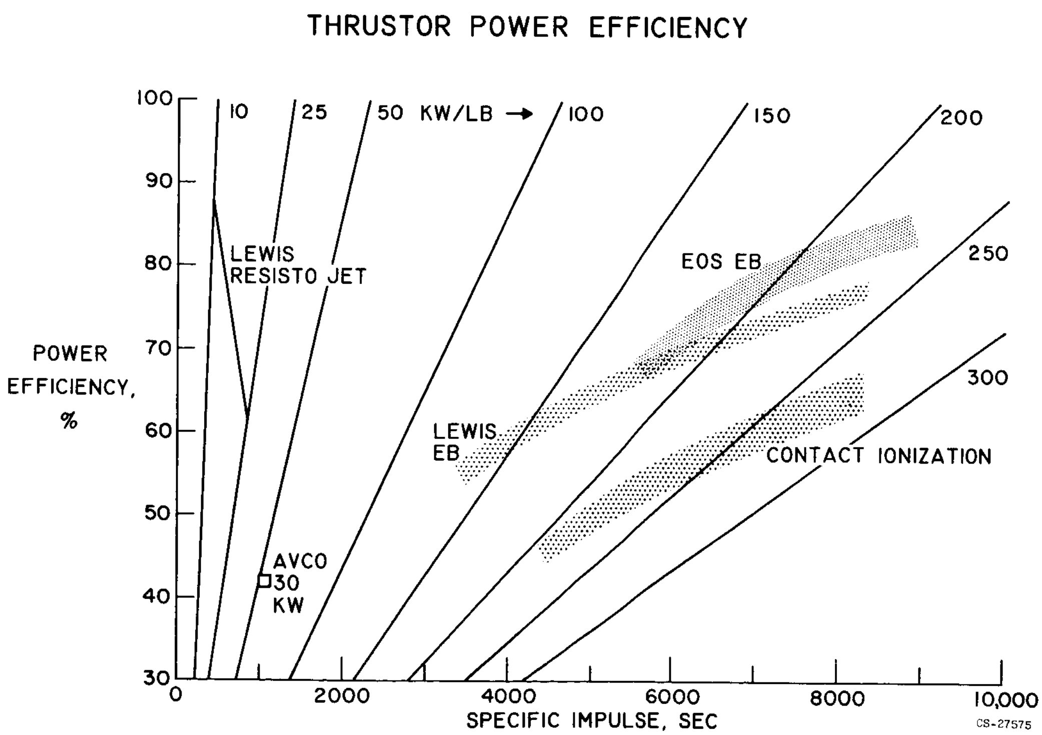

Figure 4

ESTIMATED SPECIFIC WEIGHTS OF NUCLEAR POWER SYSTEMS

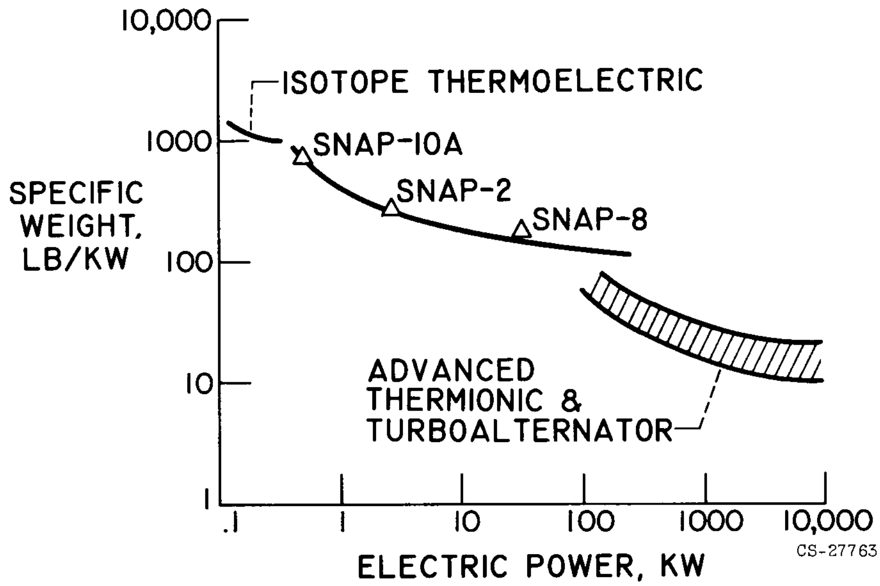

Figure 5

RANKINE CYCLE NUCLEAR-ELECTRIC SPACE POWERPLANT

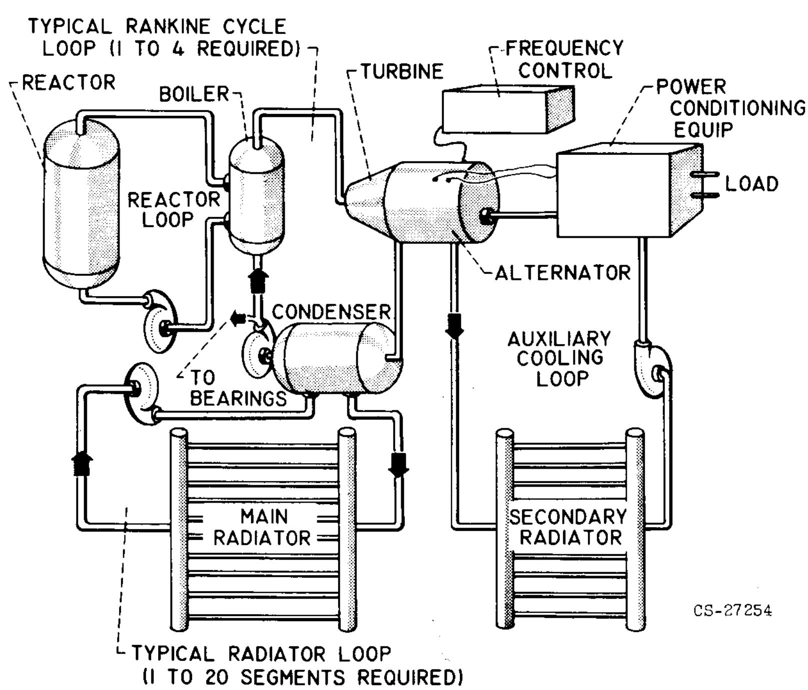

Figure 6

THERMIONIC CONVERTER

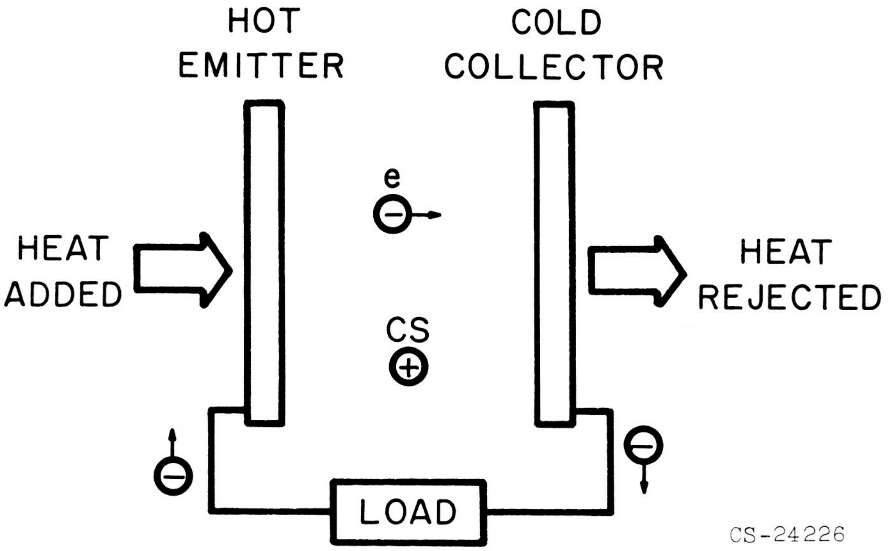

Figure 7

NUCLEAR THERMIONIC POWER SYSTEM

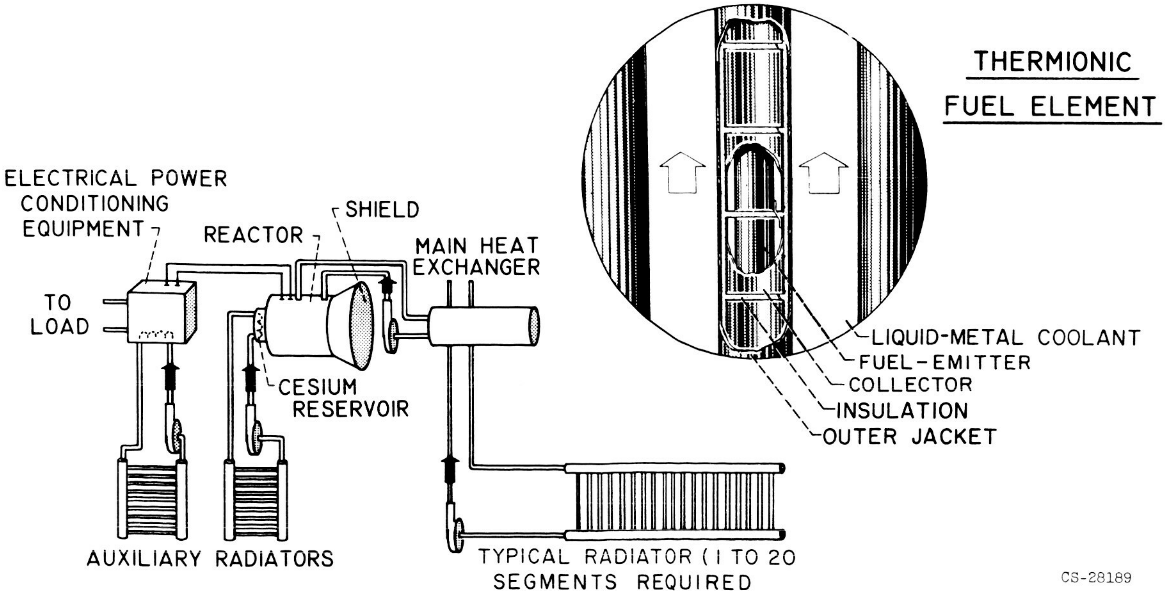

Figure 8

SYSTEM SPECIFIC WEIGHT PLOTTED AGAINST RADIATOR-INLET TEMPERATURE FOR RANKINE AND THERMIONIC POWERPLANTS

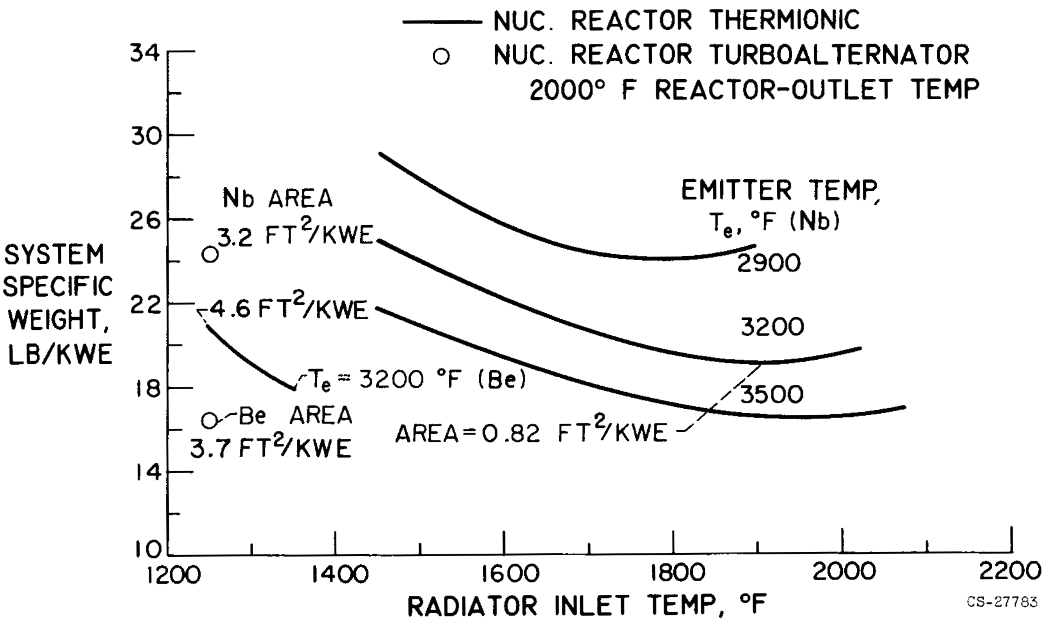

Figure 9