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Requirements for High Temperature Materials for Space Vehicles

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Abstract

High temperature materials are required in space vehicles for components of propulsion devices and electric power generation systems. Many of these devices require these materials, not because of their strength at high temperatures, but rather because of unique characteristics such as their electronic work functions, thermoelectric properties, or resistance to corrosion by alkali metals. The devices and their high temperature materials requirements are described.

Introduction

Flight in space does not, in itself, impose very high temperatures upon the space vehicle; however, some of the devices that are required for propulsion and for electric power generation operate at high temperatures, and it is for certain components of these devices that high temperature materials are required.

Propulsion

First consider propulsion devices. Table I summarizes the several types applicable to space vehicles. In general, thrust is realized by acceleration of some kind of matter through a nozzle. The magnitude of the thrust realized is a function of rate of mass flow and the exhaust velocity. There are many ways of providing the required high-velocity exhausting material. The chemical rocket achieves a high-velocity exhaust mass by combustion of solids or liquids causing high temperatures with the resultant expansion and high velocity of the combusted gases and solids. For all devices used in space, weight is a basic parameter because everything must be lifted into space.

TABLE I

Thrust Devices[a]

Rocket type	Thrust achieved by	Specific impulse, lb/lb/sec[b]	Thrust per unit of engine wt, lb/lb	Use
Chemical	Combustion	To 450	To 100	Launch and some space missions
Thermal nuclear	Gas expanded by nuclear heat	To 1,000	To 30	Launch and space missions
Electro-thermal	Gas expanded by electric heat	To 1,000	10^{-3}	Space missions
Plasma	Plasma accelerated electromagnetically	1,200–5,000	10^{-3}	Space missions
Ion	Ions accelerated electrostatically	5,000–17,000	10^{-4}	Space missions

[a]Thrust = (mass flow rate) (exhaust velocity).
[b]Probable ranges of interest.

Weight minimization becomes all important to minimize launching vehicle cost and size. Propellants and rocket engine types are compared on the basis of pounds of thrust per pound of propellant per second. This term is known as specific impulse. For chemical rockets maximum specific impulses expected are of the order of 450 lb of thrust per pound of propellant per second. As is shown in Table I, other rocket types achieve higher specific impulses.

The thermal rockets function differently. They use a single propellant that is expanded by some auxiliary heating method such as passing the propellant through a nuclear reactor or passing the fluid across electrically heated elements. The first case is the nuclear rocket, the second, the electrothermal rocket. Because exhaust velocity, and therefore thrust, increases as the molecular weight of the propellant decreases, hydrogen is the most attractive propellant for these devices. With hydrogen at a temperature of 4700° F a specific impulse of 1000 lb/lb/sec is possible. An important distinction between these two engine types is that the electrothermal rocket requires a system to generate the required electrical energy for the heaters, a system that is far heavier than the nuclear reactor that provides the heat for the nuclear rocket. Rockets for launch vehicles must, of course, produce thrust greater than their weight (to achieve liftoff). Rockets for space propulsion are required merely to accelerate the vehicle, and thrusts as small at 30 to 100 lb are considered for acceleration of vehicles weighing 300,000 lb. Because the weight of the electric power generation system for the electrothermal rocket is great, the application of this rocket is limited to space propulsion, whereas the nuclear rocket may be considered for either launch or space missions. This is indicated by the thrust-to-weight ratios shown in Table I.

Another method of achieving thrust for space missions is to ionize a gas to create a plasma. This plasma is a mixture of electrons and ions. The plasma may then (because of its charge) be accelerated by an electromagnetic field. This device is known as the plasma rocket or electromagnetic rocket. These devices, because of the need for great amounts of electrical energy, are heavy, low thrust devices, but promise high specific thrust. Although much higher specific thrusts than the 5000 sec shown may be achieved with the plasma rocket, present information suggests that they will not be competitive on an efficiency basis with the ion rocket at higher specific impulses.[1] They may bridge the gap between the thermal rockets and the ion rockets.

Ion rockets, as their name indicates, achieve thrust by ionizing a vapor of a metal such as cesium, rubidium, or mercury and then accelerating these positive ions by an electrostatic field. Extremely high specific impulses appear possible, and good efficiencies have been demonstrated in the range 5000 to 17,000 lb of thrust per pound of propellant per second. Again, electric power is required in quantity.

Thermal Rockets

Nuclear Rockets

In reviewing the requirements for high temperature materials in these various propulsion devices, the chemical rockets will not be described, because they have been discussed in detail by another paper in this volume. The thermal rockets have some unique materials problems. A schematic drawing of the nuclear rocket is shown in Figure 1. A general discussion of the nuclear rocket by several prominent authors was recently presented.[2] As mentioned previously, this rocket is similar to the liquid-chemical rocket except that, instead of a fuel and an oxidant, a single working fluid is used; this fluid is heated, not by combustion, but by a nuclear reactor. A low molecular weight fluid is desired, and hydrogen (carried in the liquid state) is most commonly mentioned.

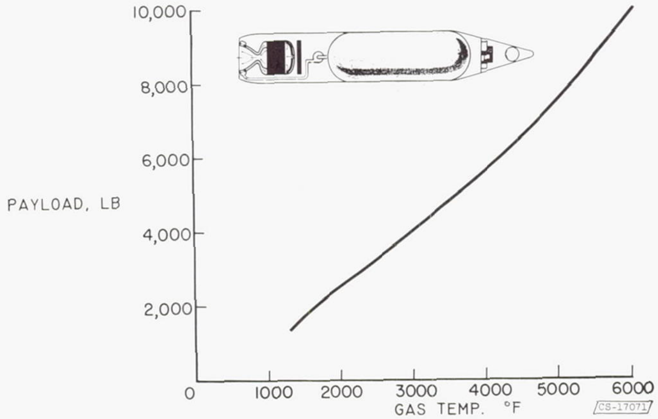


Fig. 1. Influence of temperature on payload capacity of a nuclear rocket for a Mars probe.

The nuclear rocket is generally being considered for either the upper stage of a booster rocket or for a space vehicle to provide space propulsion after being put into orbit by a chemical booster. The curve of Figure 1 shows the payload capabilities of such a rocket as a function of the propellant temperature. This curve is for a particular mission, a nuclear rocket having a gross weight of 25,000 lb and starting on a trip to Mars from a 300-mile earth orbit. Increasing the gas temperature from 3000–5000° F means the payload may be doubled from 4000 to nearly 8000 lb. High operating temperatures, say, about 3500° F and probably about 4000° F, must be achieved to make the nuclear rocket clearly an advantage to the chemical rocket for most missions studied. The propulsion gas is heated by the reactor fuel elements, and they must thus be at a temperature 200 or 300° F higher than the gas, perhaps at 4300° F. Fortunately, the required lifetimes of 10 min to about 1 hr are short, even for space missions.

The most difficult materials problems that are unique to the nuclear rocket are those associated with the fuel elements for the nuclear reactor, and until this materials problem is solved, the nuclear rocket will not be achieved. One possibility for the fuel element is plates in which the high melting uranium compound (e.g., UO_2) has been dispersed in a matrix of a suitable high temperature material. Some of the problems and promise of finding suitable materials have been described by MacMillan,[3] Probst,[4] and Deutsch.[5]

Requirements for such fuel plates are that the uranium compound should not react with the matrix material, that they should not be attacked or eroded rapidly by the flowing hydrogen, that they should have adequate strength and resistance to failure by repeated thermal cycling, that fission damage be minimized, and that they can be reliably fabricated into required shapes.

Preliminary screening studies have been conducted to find high melting point materials that may be compatible (nonreactive) with the two more interesting high melting point compounds of uranium, UO_2 and UC.[6-8] If reactions do not occur, it may then be feasible to form dispersion-type fuel materials by dispersing the uranium compound within the refractory material. It was found that, of 30 refractory materials studied for reaction with UO_2, 15 were nonreactive at 4300° F, and 4 were nonreactive to the melting point of UO_2 (about 5000° F). The duration of these tests was from 10–30 min at temperature and the reactions were investigated between bulk solid specimens, but not with the more critical condition of intimate contact between fine dispersions.

When the same materials were evaluated with UC, a lesser number of interesting combinations were found. Very few were nonreactive above 4000° F.

Many of these same materials have been investigated for compatibility with static hydrogen up to 5000° F.[9,10]

Several of the materials have been further investigated for suitability as a fuel material for the nuclear rocket. Considerable attention has been given to graphite, and the Los Alamos laboratory, which is responsible for the development of the reactor for the nuclear rocket, has actually operated a test reactor using this material in the fuel elements.[11] Graphite has the advantages of very high melting point and excellent thermal-shock resistance and is easily fabricated. It reacts with hydrogen, however, and must be coated or clad. The high melting point compounds (carbides, nitrides, etc.) have received less attention because they are difficult to fabricate and have poor shock resistance. Laboratory studies of the more ductile refractory metals have been conducted, and they are of considerable interest.[5]

Another difficult problem in the nuclear rocket is the nozzle. This nozzle will experience heat fluxes 50 to 100% higher than the heat fluxes in chemical rocket engines.[12] Liquid hydrogen is available to regeneratively cool the nozzle and, in this case, the nozzle would be fabricated from nickel or another superalloy. Current studies suggest that regenerative cooling may not be successful. One alternative would be to fabricate a nozzle from tungsten and permit the outer surface to radiate heat to space to provide some cooling. A second alternative is to fabricate the nozzle again from tungsten but to back it with a supporting structure, perhaps of graphite, as is done in current advanced solid-propellant nozzles. This latter design would operate hotter than the unsupported structure, but less strength would be required of the tungsten because the support structure would carry some of the load. Although one of these design concepts will undoubtedly solve the problem, they do introduce new requirements for high temperature materials.

Electrothermal Rocket

The second type of thermal rocket mentioned was the electrothermal rocket, which is similar to the nuclear rocket except that the propellant is heated by electrical heat rather than by nuclear fission. One scheme would be to heat tungsten plates by their own resistance and then to pass the propellant across the tungsten surfaces. Requirements are indicated for refractory materials in the heater and again in the nozzle. The heater problems are much simpler from a materials viewpoint than in the nuclear rocket; the nozzle problems are identical. For the electrothermal rocket difficult problems are presented by the electrical power generation system to be described later.

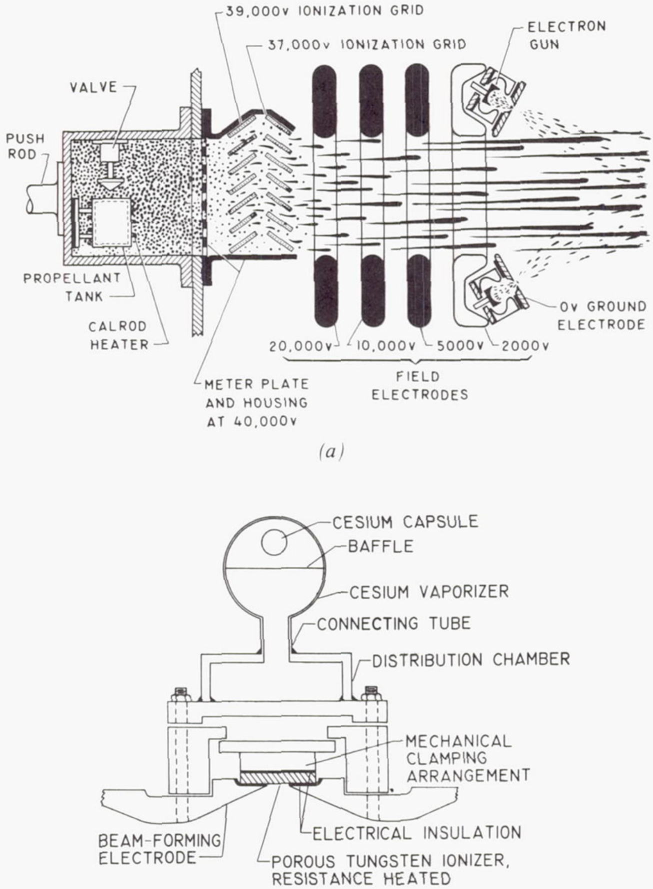
Plasma and Ion Rockets

As mentioned earlier, the other types of electric rockets, the plasma and ion rockets, are of considerable interest for propulsion in space.

There are several methods of achieving each of these devices, and it is not practical to describe each in detail in this paper. A summary is given by Mickelsen.[1] Although each design will have a requirement for high temperature materials, no one will use large amounts. Rather each device has a need for high temperature materials for a unique application, not just because of the obvious characteristic property of these materials of high structural strength at high temperatures. It was thought desirable for this paper to describe only one of these devices, one that is somewhat farther along in development, the contact ionization ion rocket engine.

A schematic drawing of one of these engines is shown in Figure 2*a*. The propellant is cesium, probably carried as a liquid (melting point, 83° F). The liquid is vaporized and then ionized by being passed over suitably heated ionizers. Thrust is achieved by accelerating the positive cesium ions by a very strong electrostatic field. Cesium is most frequently mentioned as the propellant because of its ease of ionization. It also has other desirable properties: low melting point, low heats of fusion and vaporization, and low specific heat. Ionization of the cesium atoms can be accomplished by having the cesium vapor come into contact with a metal surface having a higher electron work function than the cesium ionization potential. Ideally, one of the outer shell electrons of each cesium atom is captured by the ionizer and "pumped" away by the generator. The positively charged cesium ion leaves the surface and can be accelerated by an electrostatic field.

Tantalum and tungsten are among the materials usually considered for the ionizing grids because their electron work functions are above the ionization potential of cesium and because they are stable in the presence of cesium vapors at the ionization temperatures. For good performance it is essential that almost every atom of cesium contact the metal surface and be ionized before escape. Thus, although filaments and strips of tantalum and tungsten have been used for the ionizers of research engines, ultimately one would like to develop porous metal plates having extremely fine and very uniformly distributed interconnecting pores; for example, pores of 1 μ diam spaced 1 μ apart are suggested by Reynolds and Kreps.[13] By passing the cesium through these porous plates (as in Fig. 2*b*) intimate contact could be assured, and this should result in highly efficient ionization. The surface of these plates should be at about 2000 to 2500° F for



(a)

(b)

Fig. 2. Typical components of an ion propulsion engine. *(a)* Diagram of dc ion jet; *(b)* cross section of a porous tungsten ionizer.

efficient ionization of cesium, and the pore geometry must be maintained for perhaps many hundreds of hours. At these temperatures such fine particles tend to continue the sintering or densification process during operation and thus plug the passages. Compromises will undoubtedly be sought. Also it has always been difficult to produce porous bodies that have uniform and consistently controlled porosity.

A preliminary study conducted to produce porous tungsten plates of interest for this application described by Saunders[14] involved the sintering of 1 μ tungsten powder for 20 hr at 2750° F in a hydrogen atmosphere. These plates were used successfully (Cybulski and Lockwood[15]) to achieve high ionization efficiencies in an ion engine and demonstrated the merits of porous ionization plates. They were not of sufficiently fine geometry to permit the ultimate ionization efficiencies desired, however.

Several other problem areas with the ion rocket can be mentioned. One is the development of metal-to-ceramic seals. Because of the high electrical voltage levels used in these engines, ceramic electrical insulators are required. In some cases these must be sealed to metals and be impervious to alkali metal vapors. The highest operating temperatures in the ion engine are in the area around the ionizing plates, thus generally less than 2500° F. The ceramics and seals must, at their operating temperature, be stable for long times in very high vacuums and resistant to alkali metal vapors.

Also the high-energy charged particles of plasma and ion rockets damage surfaces they strike by sputtering; that is, the exchange of momentum from the charged particle to the struck surface eventually overcomes the atomic bonding of surface atoms and results in loss of these atoms and surface erosion. Tantalum and molybdenum are the best metals to resist sputtering, but they are not good enough. Theoretical analysis indicates irregular atomic structure should best resist sputtering; therefore ceramic films on surfaces may be required.

These few problems illustrate ways in which special properties of the refractory materials will require their use in critical components of space propulsion devices. The quantities used will be very small, however. Other similar applications could be cited.

ELECTRIC POWER GENERATION

In addition to the needs for electric power for propulsion illustrated by the electric rockets just described, electric power is required in space for communications and scientific equipment and for life support. Some rough generalizations of needs for electric power in space as a function of time are illustrated in Figure 3 (from Slone and Lieblein[16]). This figure indicates that our needs are continually increasing. Actually it should be stated that, if a great deal more

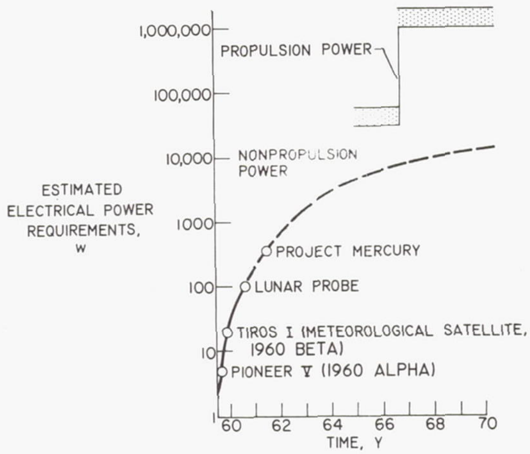


Fig. 3. Space power requirements.

power were now available from lightweight power sources, uses would quickly be found for it, and this curve does not truly plot our need but rather our progress. Another example of the need is that it would require about 1 Mw of power to televise a picture from Mars. Certainly we will want to accomplish such objectives before long. Propulsive power requires large power supplies, and this chart suggests that before 1970 we may want 1 Mw of power available for electric propulsion.

Currently our space vehicles get their power from chemical or solar batteries. These devices are used because they are available. They are not cheap and, more important, they are not light. As mentioned earlier, a basic parameter for evaluation of any object to be used in space is its weight because of the great cost and difficulty of launching payloads into space. Every pound in orbit requires at least 20 lb of launching vehicle on the ground. Figure 4 (from Slone and Lieblein[16]) illustrates the specific weight in pounds per kilowatt of various power generation systems as a function of power output in kilowatts, the objective, of course, being to achieve the lightest power plant possible. Many types are compared in this figure, including the currently popular solar cells, the thermoelectric devices, the thermionic devices, and the turbine generator systems. For the latter three types requiring heat input, both solar and nuclear reactor heating sources are considered. Systems under actual development today are indicated by squares and circles. The plotted curves are engineering estimates of what may be achieved in various systems. The estimates are based on analytical studies and systems designs available in the literature.

This curve would indicate that, if we are to achieve minimum weight power plants having the 10-kw or more power required in the next 6 to 10 years, we should concentrate attention on reactor thermionic or reactor turbine generator systems. The open circles show that turbine-generator systems of about 30 kw are already under development. Because the turbine-generator and thermionic systems apparently are of greater interest and are needed in the very near future, they will be emphasized in this discussion. A summary of the status of materials developments for thermoelectricity is regularly reported by the Naval Research Laboratory. A report by Davisson and Pasternak[17] is one of this series.

Turbine Generator Systems

A schematic drawing of a nuclear turbine-generator system is shown in Figure 5. This system is analogous to the common steam plant used to generate electric power for most of our cities. The coal or natural gas heat source has been replaced in the illustration by a compact nuclear reactor in which heat is generated by the fission process (at low power levels a solar heat source could be used).

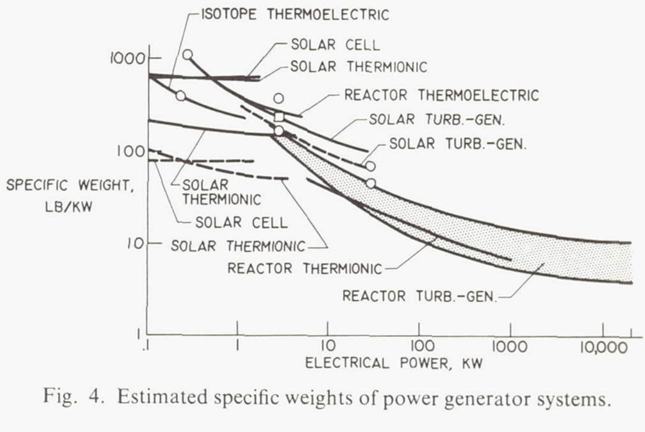


Fig. 4. Estimated specific weights of power generator systems.

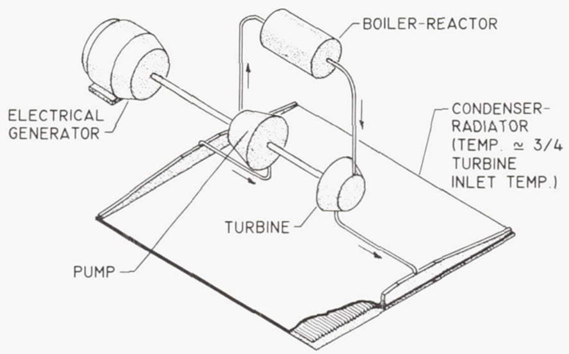


Fig. 5. Nuclear reactor turbo electric system. Single loop.

Instead of water, a more efficient liquid metal is used as the cycle working fluid. The liquid metal is converted into a vapor in the boiler-reactor and the vapor drives a turbine, condenses to a liquid in the condenser-radiator, and is pumped back to the reactor. The turbine drives a generator to produce the electrical power required for the propulsion device. Because in space cycle waste heat must be rejected by radiation, a radiator is shown for the condenser.

System studies have shown that, to minimize weight, there is an optimum relation of radiator temperature to turbine inlet temperature, absolute radiator temperature being about three-fourths of the absolute turbine inlet temperature. Reactor material temperature may be 200° F higher than turbine inlet temperature. The radiator makes up as much as 40 to 60% of the total weight. Because the size (and weight) of the radiator varies inversely as the fourth power of the radiator temperature, small gains in temperature produce large weight reductions. Considerable effort will be directed toward raising operating temperatures. Operating temperatures of devices under development have been chosen on material considerations. These devices require extreme reliability because they must operate continuously and unattended for 10,000 hr or more than 1 year. The highest stresses in the system are in the rotating turbine bucket; the highest material temperatures are in the reactor fuel elements. Choice of system materials and operating conditions, however, are made primarily from consideration of the problem of corrosion of container materials by the working fluids.

Table II shows typical operating conditions for some space turbine-generator systems. The SNAP 2 and SNAP 8 systems are under development now and will produce 3 and 30 kw of power, respectively. Both of these use mercury as the working fluid. SNAP 2 will probably have a turbine inlet temperature of 1150° F, the vapor having been superheated from a boiling temperature of about 950° F. The radiator temperature will be about 600° F. The vapor pressure of the working fluid at the boiling temperature chosen for the cycle determines the maximum pressure in the system and this value is about 115 psi for SNAP 2 and about 300 psi for SNAP 8. SNAP 2 will be built using a cobalt-base superalloy for the major piping and precipitation-hardened stainless steels for the turbine buckets. It is hoped that for SNAP 8, with temperature only slightly higher than SNAP 2, a cobalt-base alloy may again be suitable.

TABLE II

Typical Operating Conditions for Space Turbine-Generator Systems

		Temperature, °F				
System	Power, kw	Turbine inlet	Radiator condenser	Pressure psia, turbine inlet	Working fluid	Suggested boiler material
SNAP 2	3	1,150	600	115	Hg	Co alloys
SNAP 8	30	1,200	700	300	Hg	Co alloys
Future[a]	1,000	1,900	1,300	65	Na	Cb alloys

[a]For this 1,000 kw system, typical estimated requirements are: for boiler = 3,300 ft of $\frac{1}{4}$ in. tubing, 0.060 in. wall; for radiator = 54,800 ft of $\frac{1}{4}$ in. tubing, 0.025 in. wall.

Given in Table II are conditions that may be of interest for some future 1000 kw systems. If greater powers are to be realized from these devices, operating temperatures must be raised to reduce specific weights. With this higher turbine inlet temperature of 1900° F, sodium has been proposed as the working fluid and maximum pressures would be about 65 psi. Mercury could not be used because when boiling at 1900° F its vapor pressure is about 5500 psi and system weights would go up because the piping would have a very heavy wall.

This is the reason, of course, that different fluids are of interest for different temperature levels. (For example, from consideration of vapor pressure, rubidium is of interest at about 1450° F, potassium at about 1750° F, and sodium at about 2000° F.) For a 1000 kw system the refractory metals will be required. Presently available data indicate that the superalloys would be severely corroded by the working fluids at this temperature.

An important point made by Table II is that the high-temperature cobalt-base alloys and refractory metal alloys, because of unique corrosion resistance to molten alkali metals, will find application in these boiling-metal systems at temperatures appreciably below what is considered their normal use temperature in conventional high-temperature structural applications. The quantities of materials used can also become appreciable as illustrated in the lower part of this table. For the 1000 kw system, the boiler may be made of $\frac{1}{4}$ in. diam tubing and about 3,300 ft would be required. The radiator, also of $\frac{1}{4}$ in. diam tubing, would require about 55,000 ft. If $\frac{1}{2}$ in. diam tubing were used instead, about one-half the amount would be required. In addition, relatively small quantities of interconnecting tubing and pipe of perhaps 2 and 20 in. diam would be required. Assuming that perhaps 25 of any one of these systems may be built, the total quantities required become appreciable. A schematic drawing of a manned vehicle of this general type, but with a 10,000 kw system, is shown in Figure 6. The components are arranged logically. Length (600 ft) is used to separate the crew from the radiation of the nuclear reactor.

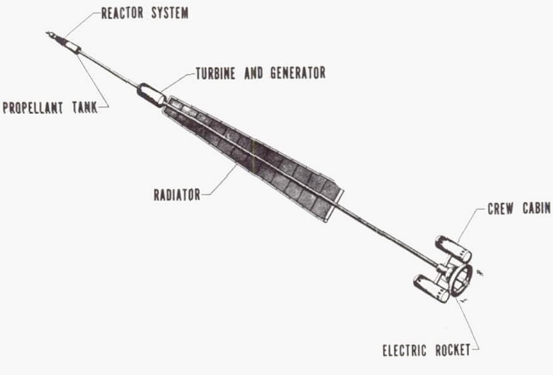


Fig. 6. Electric space vehicle.

Corrosion

The two primary unknowns that may prohibit development of the advanced high temperature systems are the corrosion problem and the meteoroid damage problem. Research has been conducted with boiling mercury up to about 1100° F, but almost negligible research has been conducted at higher temperatures with mercury, potassium, or sodium. In boiling systems the corrosion may be more severe than in all liquid systems. Figure 7 illustrates the nature of the problem by showing schematically a simple corrosion loop that attempts to

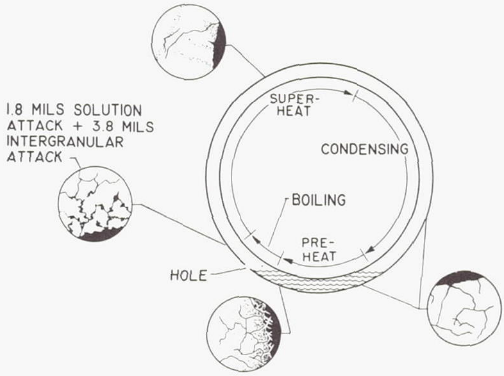


Fig. 7. Microstructures for Inconel from potassium boiling-condensing corrosion loop. Material: Inconel tubing, 0.250 diam by 0.014 wall. Duration of test: 490 hr. Mean temperature at boiling interface: 1650° F.

duplicate the problems of these systems. By using different heating rates around a tube partially filled with liquid, all working fluid states can be achieved, namely, boiling, superheat, condensing, and flowing liquid. (The exact cycle conditions of a pumped system are not duplicated, however. For this simple convection system, boiling and condensing are essentially at the same temperature, and fluid velocities and heat fluxes are relatively low.) Sketches are shown of the damage suffered by Inconel after containing boiling potassium for 490 hr at a boiling interface temperature of 1650° F. Boiling systems appear to cause especially severe corrosion problems partly because at the boiling interface the liquid is distilled to a vapor leaving behind impurities that may plug or attack the container. The high purity vapor is then ready to redissolve material in the condensing zone to repeat the cycle. In this case a hole corroded through at the boiling interface, and severe attack occurred as indicated by the schematic photomicrograph. Crystals, that in time may plug small diameter tubing, were deposited in the liquid zone. Figure 7 represents only preliminary data and is intended primarily to illustrate the problem. Based on some data with all liquid corrosion, it is thought that columbium or perhaps other refractory metals may be suitable container materials for the alkali metals at the high temperatures of interest but, although research is now under way, essentially no data are available at this date.

Evaporation

One of the serious shortcomings of refractory metals, namely, poor oxidation resistance, is of no concern in space because, of course, air is not present. Instead, space is an almost perfect vacuum. Such extremely low pressures raise the new problem of evaporation, however. At high temperatures atoms are lost from the surface of solids, and in high vacuums these atoms are not reflected back to the surface and thus are lost forever. Discussion relating to this phenomenon is reported by Lad.[18] The maximum rate of loss can be calculated from the Langmuir equation and is a function of the vapor pressure of the metal, its molecular weight, and its temperature. The temperature at which 0.010 in. is lost in 1 year from the surface of various metals is shown in Figure 8. In general these data indicate that the base metals of interest at high temperatures are suitable at temperatures where we may use them for space power systems. This includes cobalt, nickel, columbium, tantalum, molybdenum, and tungsten. Some of the elements commonly used for alloying are lost rapidly at temperatures of interest, however; an example shown here is chromium. Fortunately, the rate of loss of an element from an alloy is less than when the element is in its pure form. Assuming Raoult's law to hold, the rate of loss of an alloying element is the loss rate of the pure element times the mole fraction of the element in the alloy. Deviations either to higher or lower rates may be expected, but no detailed data are yet available. Selective evaporation of elements can present a problem as indicated by the photomicrograph for a nickel-chrome alloy in Figure 9. Here chromium has been evaporated leaving a porous alloy behind. Of course, this is an extreme

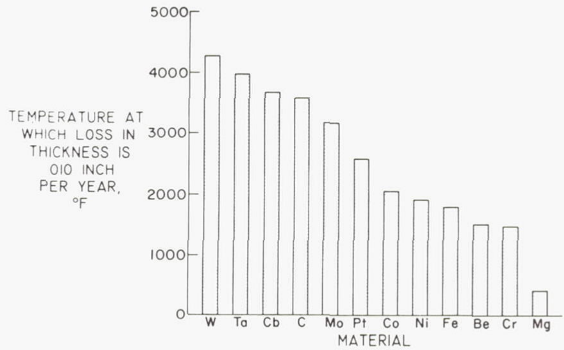


Fig. 8. Loss of material by evaporation in the vacuum of space.

example because of chromium's very high vapor pressure and its rapid rate of diffusion in nickel at this temperature. Chromium can be avoided in alloys for space systems because it is usually added to iron-, nickel-, and cobalt-base alloys almost solely to provide oxidation resistance and such resistance is not required in space. In sum-

Fig. 9. Selective evaporation of chromium from Nichrome heater wire. 1500° F, 250 hr, 10^{-5} mm Hg. 125×.

mary it appears that evaporation will not eliminate interesting base materials but is a matter for consideration in selecting alloying additions.

Strength

It is also of interest to examine strength requirements for these space power systems. The stress for rupture in 10,000 hr for several high temperature materials as a function of temperature is shown in Figure 10. Also shown are the hoop stresses for two sizes of tubing at various temperature levels for various boiling metals. The boiling temperature determines the pressure inside the pipe as mentioned earlier. Stress increases with tubing diameter and decreases with tubing wall thickness. Any material above the horizontal line labeled by temperature, fluid, and tubing size would be strong enough to avoid fracture in 10,000 hr. The sizes used here are some of those mentioned in design analyses and thus give a reasonable picture. The primary point made by the figure is that hoop stresses are very low and many materials undoubtedly have sufficient strength.

Although encouragement may be gained from Figure 10, considerable evaluation, development, and research will be required. The data shown are extrapolated data for 10,000 hr life, extrapolated for refractory metals from data that did not extend much beyond 300 hr. Long time data must be obtained, and designs will undoubtedly be based upon allowable creep, not rupture. The proper approach would be to obtain corrosion data seeking an alloy that appears compatible with the boiling liquid metal at temperatures of interest for modest times. This alloy must be capable of fabrication into high quality tubing. It must be capable of being welded or brazed. If the alloy is one of those now known, long time strength and corrosion data must be obtained. If corrosion-resistant alloys are not found from among those known, development of new alloys must be initiated seeking the unique combination of properties desired. The corrosion screening studies should by then have indicated alloying additions that must be avoided.

Before leaving the subject of strength requirements in turbine-generator systems, it should again be stated that the highest stresses will be in the rotating turbine bucket. One turbine was designed (in an analytical study by English et al.[19]) with stresses of about 7000 psi. It would be desirable to permit stresses higher than this. Figure 10 indicates that several materials may even meet this requirement. Blade alloys need not be as easily fabricated as tubing alloys and need not be weldable. The corrosion requirement may be less because the bucket could perhaps be exposed to vapor only. Droplets, if present, may cause erosion. The evaporation problem will not be important because the buckets are exposed to a high pressure vapor instead of the vacuum of space.

Meteoroids

A serious materials environment problem of space is meteroids. Meteoroids are particles traveling in space at speeds from 25,000 to 165,000 mph and ranging in size from a few molecules upward. Most of the particles are believed to be a very light stony sort of material, but some can be as heavy as iron.

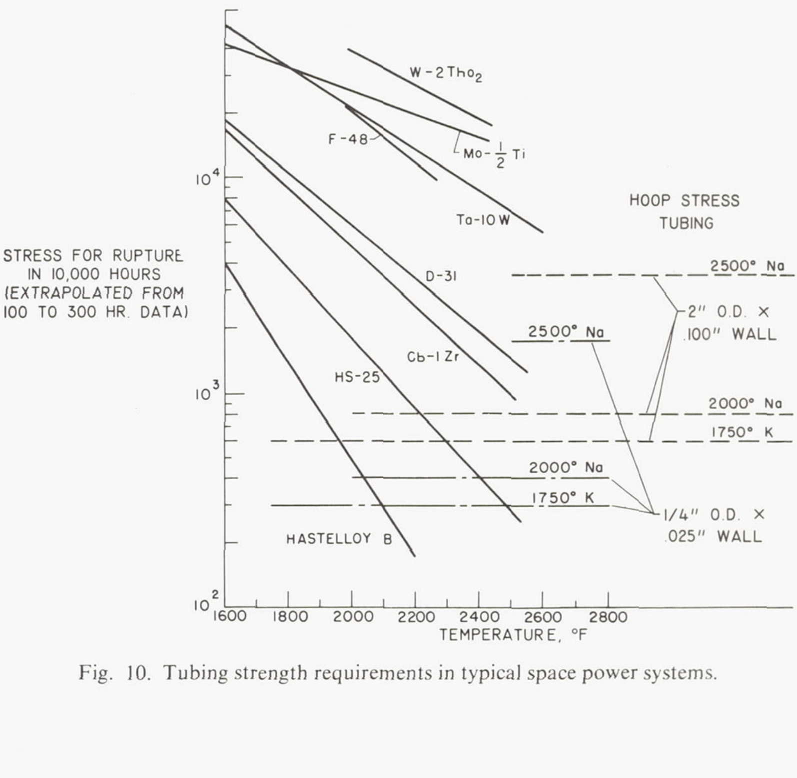


Fig. 10. Tubing strength requirements in typical space power systems.

We urgently need to know what will happen when a spacecraft collides with these meteoroids and how the vehicle may be protected. Fortunately, most of the particles are very small, much like dust, and will cause only a scrubbing of the surface. This can be serious, however, since radiators may be coated to achieve high emissivity surfaces, and this erosion will in time destroy the surface and lessen the radiator efficiency.

Larger particles will act as high velocity projectiles. Studies are under way at the laboratories of NASA as well as other laboratories to obtain an understanding of the phenomenon of very high velocity impact. A physical picture of the effect of velocity on damage by impact can be obtained from Figure 11. Shown by a scale drawing is a projectile $\frac{1}{8}$ in. in diameter. On the left is the hole it made at a relatively low velocity of about 1,800 mph. At the right is shown the damage resulting when an identical projectile hit the target at a high velocity of about 14,000 mph.

It is apparent that with an increase in velocity the phenomenon changes. Instead of driving farther through the target, the great energy of the projectile is apparently converted to heat, and the target acts almost as a liquid—the target appears to have splashed. The projectile disintegrates and coats the inside of the hole. The damaged area is many times the size of the projectile.

Figure 12 (Charters[20]) shows a photograph of aluminum and granite targets struck by a nylon ball of the size indicated at a speed of 13,000 mph, far below the speeds of meteoroids in space. The severity of damage is apparent. One can imagine the damage that may occur to a radiator fabricated from thin-walled tubing. Far more information must be obtained on the probability of being struck and on methods of defense against meteoroids if high reliability in such devices is to be achieved. Present data would suggest that considerable weight must be added to these vehicles to protect against meteoroid damage. For example, tubing wall thickness may be heavy not because of corrosion or stress considerations but because of necessity to withstand meteoroids.

Thermionic Conversion*

In a thermionic converter a metal is heated to the point where it boils off electrons, and the electrons are collected at a cooler anode.

*Discussion in this section is taken largely from refs. 4 and 16.

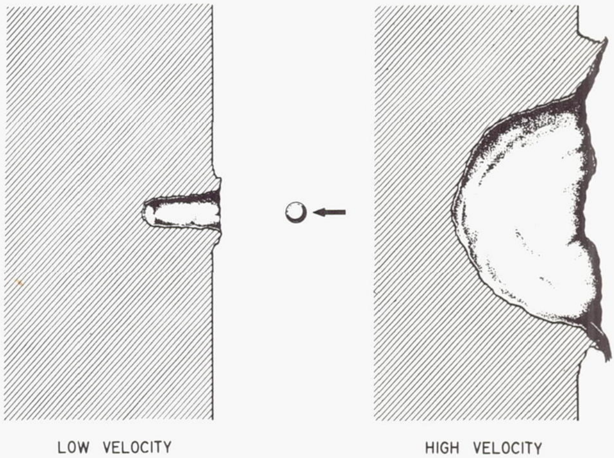
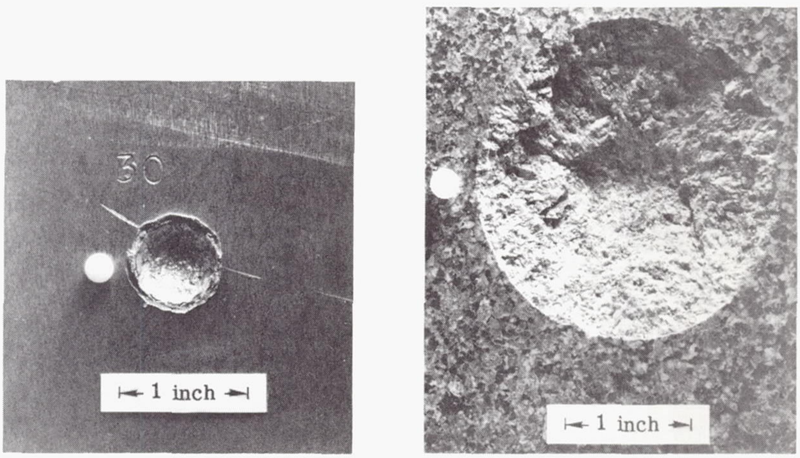


Fig. 11. Effect of velocity on type of impact damage. Projectile, tungsten carbide, $\frac{1}{8}$ in. diam; target, copper.

Such a system is shown schematically in Figure 13 (Slone and Lieblein[16]). Heat may be supplied by a solar or nuclear reactor. The cathode material should be one of low electron work function. The work function is the difference in energy levels between a free



(a) *(b)*

Fig. 12. Damage caused by $\frac{1}{8}$ in. diam nylon sphere at high velocity, 13,000 mph. *(a)* Aluminum target, *(b)* granite target.

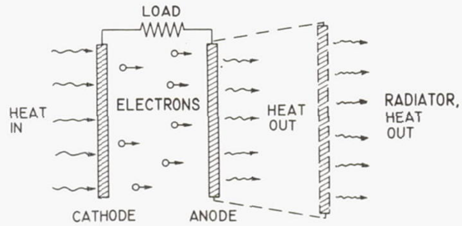


Fig. 13. Schematic of thermionic converter.

electron and the Fermi energy in the material; thus, the lower the work function, the easier it is to boil off electrons. Electrons that are boiled off travel from cathode to anode by virtue of their kinetic energy and are collected at the cooler anode and returned to the cathode through an external load (e.g., an electric propulsion device).

The power output of a thermionic converter is highly dependent on the cathode operating temperature. Increasing the cathode temperature from 3000–5000° F increases the power output nearly fivefold. This alone is evidence of the need for high temperature materials. Tungsten is presently being considered as a cathode material. Although tungsten has a rather high work function ($\approx$4.5 ev), it is nevertheless of interest because of its high melting point and overall refractory properties. Other high temperature materials are also being studied.

For the simplest type of thermionic converter, a vacuum is, of course, required between cathode and anode. In order to minimize the space-charge effect (i.e., an additional energy barrier due to the mutual repulsion between free electrons), a very close spacing of the order of 0.0005 in. must be maintained between cathode and anode. In such a diode the cathode temperature must be greater than about 1900° F.[16] For applications in space the vacuum may be supplied by space; that is, no enclosing envelope would be required. Maintaining a constant spacing of 0.0005 in. at the operating temperature may present a manufacturing problem.

The cathode-to-anode spacing may be increased to about 0.050 in. if provisions are made for neutralizing the resulting space charge. This may be done by introducing positive cesium ions in the volume between cathode and anode. Cesium may also be introduced at higher pressures in order to provide a coating on the cathode. When a coating a few atoms thick is reached, the work function of the cathode becomes that of the coating. Cesium is desirable because it has a low work function ($\approx$2.6 ev). Whether cesium is used to neutralize the space charge or to obtain a lower work function, such a gas diode introduces more materials problems. The minimum cathode temperature is about 2600° F.[16] The diode space must be enclosed in order to contain the cesium vapor, and at some point in this envelope there must be an electrically insulating material. This introduces problems of metal-to-metal and metal-to-ceramic seals to withstand the high temperatures involved similar to those previously described for the ion rocket. The corrosion of both metals and ceramics by cesium vapor is another area that must be investigated along with the corrosive effects of cesium on any braze material used in sealing.

An advantage of the thermionic converter is the possibility of radiating waste heat directly from the anode. In order to minimize the radiating surface, it must again be at a temperature equal to about 75% of the absolute cathode temperature. This would mean a minimum anode temperature for a gas diode of about 1830° F,[16] but the system must operate at even higher temperatures if the low specific weights are to be achieved. These anode temperatures quickly get into the range where, as with the cathode, refractory metals are the most feasible materials.

If radiation directly from the anode becomes impossible, some sort of liquid-metal cooling loop will be required to extract heat from the anode and carry it to a radiator. Then liquid-metal corrosion problems, discussed for turbine-generator systems, will plague thermionic converters. As indicated, for comparable power outputs the thermionic systems must operate at higher temperatures than the turbine-generator systems and may be limited by material corrosion.

Again in thermionic systems large quantities of high temperature materials are not required even in large power systems unless a liquid-metal cooling system is required. High temperature materials are required having unique properties for the emitter.

CONCLUDING REMARKS

High temperature materials are required in space vehicles for components of propulsion devices and electric power generation systems. Many of these devices require these materials, not because of their strength at high temperature, but because of unique characteristics such as their electronic work functions or thermoelectric properties. Uses of major quantities would be expected in liquid-metal and boiling-metal heat transfer and Rankine cycle systems where corrosion resistance of materials would make them suitable as container materials. Considerable research and development may be required to develop high temperature materials having the unique combination of corrosion resistance, strength, and ease of fabrication and joining required for these latter applications.

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