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SURVEY OF MATERIALS FOR THERMIONIC CONVERTERS

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16. Abstract

This is a literature survey of materials for gaseous thermionic conversion systems for use in space. It is intended for the use of people unfamiliar with the field. The effect of material selection and characteristics on the electrode properties is emphasized. The following areas are explored: (1) materials requirements, (2) identification of materials most likely to meet these requirements, (3) relevant physical and mechanical properties of these materials, and (4) proposals for modifying these materials for improved systems performances.

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SURVEY OF MATERIALS FOR THERMIONIC CONVERTERS

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SUMMARY

This report presents the results of a literature survey on materials for gaseous thermionic converters. It is intended for people unfamiliar with the field. Because of the high temperatures associated with thermionic converters, refractory metals are considered to be the prime candidates for electrode surfaces for these devices. By properly selecting electrode materials, improvement in converter performance can be obtained. The close-packed planes of high-work-function refractory metals (i.e., the (110) plane for tungsten and the (0001) plane for rhenium) in cesium vapor are known to produce high power densities.

Low-work-function collectors can improve converter performance by increasing the converter output voltage. However, the lower-work-function collectors require lower collector temperatures to minimize back emissions. One method of lowering collector work function is to introduce electronegative additives into a cesiated converter.

The physical and mechanical properties of some refractory materials are presented in tabular form. The original reference source for the data is cited. Improvement in fabrication techniques with the refractory metals is necessary if these materials are to be used extensively in the support structure and liquid-metal loops of thermionic converters. Joining techniques that are currently used consist of inert gas welding, electron beam welding, and some special brazing techniques.

The T-111, T-222, and FS-85 alloys displayed very good creep properties, corrosion resistance to liquid metals, and good weldability characteristics. These materials and some tungsten and molybdenum alloys are leading candidates for advanced space power systems application.

Considerable thermionic converter testing has been done by various organizations, and converter lifetime exceeding 1 year has been obtained in most cases with no appreciable degradation in performance.

INTRODUCTION

The large gains realized in the performance of thermionic converters in the past few years is the result of a better understanding and utilization of converter materials. Much of this understanding came from results obtained in programs designed to evaluate the performance of individual converters with various material combinations for electrode surfaces and support structures. This report presents the results of a literature survey of some of these programs, particularly those related to the electrode properties of thermionic conversion systems. It is intended for people unfamiliar with the field. The theory of operation of the thermionic converter is reviewed, followed by descriptions of various thermionic conversion systems. The electrical and mechanical properties of some promising electrode materials are presented, as well as the mechanical properties of some support structure materials.

THERMIONIC DIODE OPERATION

A thermionic converter is a heat-engine which uses thermionically emitted electrons as a working fluid in a cyclic process. The basic principle of thermionic conversion is illustrated in figure 1. It consists of a hot cathode (emitter) which thermionically emits electrons, a cooler anode (collector) which collects the emitted electrons, and a ceramic insulator which separates the cathode and the anode.

Cesium is introduced into the interelectrode gap of practically all operational converters in order to reduce electrode work functions and to provide positive ions needed for space charge neutralization. As a result, high power densities, high conversion efficiencies, and practical interelectrode spacing can be realized in thermionic converters (ref. 1).

The energy conversion process can be illustrated by the motive diagrams shown in figure 2. Heat from the thermal source (e.g., solar, nuclear) elevates more electrons to the higher energy levels so that greater numbers of electrons can surmount the potential barrier V_1. Some of these electrons migrate to the collector, fall through the potential barrier V_2, and deliver work to the electrical load as they return to the emitter through the external circuit. The idealized motive diagram present in figure 2(a) shows the energy required to enable the emitted electrons to hurdle the space charge potential barrier. This term is incorporated in the potential barrier term V_1. Practical thermionic converters are almost never as ideal as shown in figure 2(a). These converters, in general, have motive diagrams represented by figure 2(b).

Thermionic converters are usually operated with cesium in the ignited mode condition. This mode of operation permits the generation of cesium ions by volume ionization. As can be seen in figure 2(b) the emitted electrons are accelerated into the central part of the cesium plasma by the plasma potential drop. Plasma oscillations and plasma collisions tend to randomize the directed velocities and energies to these electrons. These electrons drift to the collector and fall down the potential barrier V_2. Energy (plasma voltage drop V_d) is expended by the electrons in the ignited mode operation in order to sustain the plasma, by replacing the energy removed in forming excited atoms, photons, ions, and hot electrons. This results in a reduction in the output voltage from the collector of the order V_d.

As purposely shown in the figure, the potential barrier V_2 (typically equal to 1.5 volts) at the collector is considerably smaller than the potential barrier V_1 (typically 3 volts) at the emitter. It is this potential energy difference minus the plasma voltage drop term that may be tapped for useful power output.

The thermionic converter being a heat-engine is limited to operating at Carnot efficiency or less. The converter efficiency is proportional to the ratio of power out to power in; consequently, the expression describing the efficiency for a practical converter is given by

$$\eta = \frac{J_{net}(V_1 - V_2 - \Delta V')}{J_1(V_1 + 2kT_1) - J_2(V_1 + 2kT_2) + Q} \leq \eta_{Carnot}$$

The output voltage is equal to $V_1 - V_2 - \Delta V'$, where $\Delta V'$ is a voltage loss which occurs external to the converter (i.e., lead losses and IR drops). The net current J_{net} equals the electron emission from the cathode J_1 minus that from the anode J_2. The numerator is simply the electrical power output term, which is the product of the net current times the difference in emitter and collector voltage barrier minus a voltage drop term.

The power input given by the denominator is more complex. The first term gives the energy involved in elevating electrons to higher energy levels so that the electrons can flow over the potential barrier. This term also contains the average kinetic energy of the emitted current at the top of the emission barrier $2kT$ (where k is the Boltzmann constant). The second term gives the energy returned to the emitter by electron flow from the collector. The third term Q represents radiation plasma transport losses such as gaseous conduction. The plasma transport expressions can include negative terms that reflect a return of energy from the plasma back to the emitter (ref. 2).

Practical thermionic converter output power densities (or alternately, converter efficiencies) are limited because of the numerous electrical and thermal losses encountered at operating temperatures. It is of interest to note the performance limitation of the present state of the art for practical systems. The typical output voltages from thermionic converters vary from 1/2 to 3/4 volt. The cesium plasma drop is approximately 1/2 volt. Power losses, due to thermal and electrical losses, can exceed 10 percent of the output power at converter operating temperatures. Cesiated collector work functions are typically $1\frac{1}{2}$ volts and, in some special cases, even lower. By utilizing these limitations it is possible to make an estimate of the operating capabilities of practical converters. For a converter operating with a collector work function of 1.3 volts, 5 watts per square centimeter of power should be developed at an emitter temperature of approximately 1500 K. If the converter's collector temperature and work function are 1060 K and 1.7 volts, respectively, 10 watts per square centimeter of power should be developed at an emitter temperature of approximately 2000 K. If the electrical and thermal losses increase above the assumed value, the emitter temperature must be increased to even higher values in order to obtain the same output power level. As a consequence, materials must be selected to facilitate the transfer of energy throughout the systems with minimum thermal losses and to provide maximum power densities for long periods of time. Some of the factors that may influence this choice are

(1) Emission properties of emitter materials
(2) Heat-transfer characteristics
(3) Ductility and creep properties at high temperature
(4) Thermal stability (resistance to evaporation of emitter material and corrosion)
(5) Chemical reactivity among the various metals, brazes, ceramics, fuel, and gaseous constituents at high temperature
(6) Weldability and ductility at room temperature

THERMIONIC CONVERSION SYSTEMS

Application of thermionics in space power systems requires the mating of a thermionic converter to an external heat source. The heat source may be solar or nuclear (refs. 3 to 8).

SOLAR THERMIONIC CONVERTER

Solar thermionic generators utilize a parabolic mirror to collect radiant energy from the sun and concentrate it into a small cavity ringed by a cluster of thermionic converters. The converter geometry usually employed in these systems in planar.

Solar thermionic converters have demonstrated good performance characteristics and good life capability. However, there are some problem areas that exist with this system (ref. 1). Problems include (1) high orientation accuracy required in order to aline the concentrators to the sun, (2) degradation of the concentrator surface in space by micrometeorite erosion or by impurities evaporating from the generator onto the mirror surface, (3) possibly critical flux control on orbits that move toward the sun, (4) ground testing problems because of reduced solar constants, and (5) a warmup problem with the cesium reservoir when the system emerges from the earth's shadow.

NUCLEAR THERMIONIC CONVERTER

For compact, self-contained, long-life, high-power space supplies (100 kW), the nuclear reactor is an attractive heat source. Nuclear reactors can develop the high operating temperatures thermionic converters require. Furthermore, typical collector temperatures and rejection temperatures are high enough to permit a substantial savings in radiator area. Thermionic converters can be incorporated into a nuclear reactor system either in core or out of core (refs. 4, 6, and 8).

In Core

For in-core use, the emitter can be fabricated either external to or internal to the fuel element. In the external concept, converter assemblies are designed in a cylindrical geometry so that the nuclear fuel surrounds the emitter. In the internal concept, the emitter surrounds the nuclear fuel. The concentric cylindrical collector, appropriately spaced from the emitter, is basically a trilayer tube constructed of a thin-film ceramic insulator material sandwiched between metallic layers (fig. 3). The trilayer tube, in addition to collecting electrons, serves generally as a current carrier and a heat-sink. Waste heat is removed by a liquid metal, which carries it to a radiator where it is radiated into space. The maximum temperature at which heat can be transferred to the radiator with confidence is dictated by the heat-transfer fluid used in the cooling loops. Assuming state-of-the-art advancement in liquid-metal technology, this fluid should be able to circulate at temperatures greater than 1500 K. This then determines the maximum collector temperatures for in-core thermionic systems.

Certainly there are other factors to be considered, such as the effect of rejection temperature on core size, conversion efficiency, and shielding weight. Intrinsic difficulties with this concept have been encountered with attempts to develop a practical in-core system. The requirements of high temperatures, long lifetimes, and high power densities to provide low specific mass present a difficult engineering problem. Some of the specific problems are fuel swelling, fission products, and electrical isolation. Some attempts to ameliorate these problems by unique design concepts exist but, in general, such attempts compromise performance levels and/or increase reactor size.

Out of Core

Heat-exchanger concept. - The out-of-core thermionic systems avoid some of the disadvantages, such as fuel swelling and radiation damage, of in-core systems. If the converter is external to the reactor (out of core), a high-temperature loop must be used to transfer heat from the reactor to the emitter.

Numerous out-of-core design concepts have been suggested for applying a thermionic converter external to the reactor core. In one proposed system the converter assemblies are designed in a cylindrical geometry such that the emitter surface surrounds the hot liquid metal. This tube is surrounded by a concentric cylindrical collector, appropriately spaced from the emitter by an ionized gas gap (fig. 4). A series of converters are formed by sectioning this tube. As shown in the figure, waste heat is removed by a secondary coolant loop (liquid metal) or by radiation into space. The maximum temperature of this device is dictated by the corrosion effects on refractory metals of the liquid metal, typically lithium. Electrodes of the series-connected converters must be electrically isolated from the liquid-metal coolant. This requires a material capable of good electrical isolation and thermal conduction at the liquid-metal temperature.

Another proposed out-of-core system would couple a simple reactor with modular thermionics. This design would expose the liquid-metal loop to the reactor fuel temperature. Here again, the system's maximum operating temperature will depend upon the corrosion limits of the liquid metal employed. However, liquid-metal technology is adequate if simple configurations are used, but the reliability of the complex systems required in actual practice makes this approach appear to be of marginal interest.

Heat-pipe concept. - Loewe (ref. 9) conducted a survey of conceptual out-of-core thermionic systems using heat pipes. Loewe states that the purpose of the survey was to identify critical technological areas, to investigate feasibility for space application, to locate parameter regimes of interest, and to estimate specific mass values. Loewe concludes that, in general, out-of-core thermionic systems with heat pipes appear to be attractive candidates for use in space over a broad range of electric power levels, meeting the requirement of both advanced auxiliary power and nuclear (electric) propulsion.

Heat pipes may be employed to deliver thermal energy to out-of-core thermionic converters (fig. 5). The operation of the heat pipe depends upon the evaporation of a liquid, the transport of the vapor through a duct, and the condensation back to the liquid phase. Capillary action is utilized by the heat pipe to recirculate the condensate to the evaporator. A typical heat-pipe design uses a cylindrical tube with a capillary or wick structure lining the inner wall. The wick may take one of many forms ranging from several layers of wire-mesh screen to rectangular grooves cut in the inner wall of the tube. This structure is saturated with the working fluid. When the working fluid delivers energy by condensing, the wick transports the liquid back to the hotter end of the heat pipe to revaporize. For continuous operation, the condensate must be returned to the evaporator.

The main problem confronting heat-pipe development is corrosion of the inner wall by the liquid metal used as the working fluid. Busse (ref. 10) suggests that encouraging progress has been made in understanding and solving some of the corrosion problems encountered in heat pipes operating at or near temperatures required for thermionic converter emitters. He concludes that there is a good chance that further work will lead to satisfactory solutions of the emitter heat-pipe problems. In the temperature range of operation for the collector (1000° C), the heat pipe to a large extent is ready for practical application.

ELECTRODES

Electrodes must be selected with care if the diode is to operate at maximum power. In addition to the performance requirement of these materials, ease of fabrication and compatability with the associated parts must be considered. This section will discuss some of the factors that should be considered in the selection of electrode materials.

EMITTER MATERIAL

The fuel element of a nuclear thermionic converter will be a metallic emitter in the form of a small cylinder. The high temperatures involved in thermionics require the use of refractory metals, especially for the emitter. These metals include tungsten, thoriated tungsten, rhenium, osmium (clad or plate), and molybdenum. In some cases, tantalum, iridium, and niobium or some alloy combinations of these materials are considered. Of course, the selection of emitter material will be dictated by the operational requirements of the particular thermionic system. Tungsten is usually preferred for the highest temperature operation because of its good thermal properties, high melting point, reasonable emission characteristics in the presence of cesium, compatibility with nuclear fuel, favorable thermal transport properties, and low vaporization rate. At room temperature, however, it is quite brittle, which makes it difficult to fabricate. Molybdenum is considered at lower temperatures because of its relative ease of fabricability and its emission current densities. Rhenium generally gives better performance characteristics than the other refractories, but it is expensive and difficult to fabricate.

Thermionic emitter materials should meet the following requirements:

(1) A cesiated electron work function in the operating temperature range such that useful output power and maximum efficiency of conversion can be attained

(2) High thermal and electrical conductivities to facilitate the transfer of heat generated in the bulk to the surface, and to reduce joule loss

(3) Chemical and mechanical stability over a temperature range of 1600 to 2000 K

(4) Stability under irradiation, so that no significant changes in dimension and physical properties occur

(5) Compatibility with cesium vapor between 1600 and 2000 K and, in some concepts, with nuclear fuel

(6) Impermeability (as great as possible) to cesium vapor and fission products, so as not to deplete or contaminate the plasma

COLLECTOR MATERIAL

In general, the collector should meet the same requirements outlined for the emitter. However, the collector temperature will rarely exceed 1000° C.

Several investigators have studied collector material for thermionic energy converters (refs. 11 to 14). The following materials were used or proposed for collectors: nickel, molybdenum, niobium, tungsten, rhenium, ruthenium, and the oxides of these metals. The minimum work function for cesium on these bare materials is also generally lower than the work function of bulk cesium. Maximum output power is obtained for practical converters when the collector work function is of the order of 1.6 volts over a collector temperature range of approximately 800 to 1050 K. The efficiency increases with a decrease in the collector work function, provided that the back emission from the collector is maintained below a minimum value. The collector work function varies with its temperature and the cesium pressure, and reaches a minimum for optimum cesium adsorption.

THERMIONIC EMISSION AND COLLECTION EXPRESSIONS

The thermionic work function is a complex and difficult phenomenon to study experimentally, because of nonuniformity of the metal surface. Consequently, three definitions are generally used to define the work function (ref. 15):

(1) True work function - The difference between the Fermi energy and the surface potential energy.

(2) Effective work function - The work function obtained by direct substitution of the temperature and emission current density into the Richardson-Dushman equation

$$J = AT_E^2 \exp\left(\frac{-\varphi_E e}{kT_E}\right)$$

where

J	current density, A/cm^2
A	thermionic constant, 120 A/(K^2)(cm^2)
T_E	emitter (cathode) temperature
φ_E	thermionic work function
e	electronic charge
k	Boltzmann constant

(3) Richardson work function - The function defined by the slope of the plot of log J/T_E^2 as a function of $1/T_E$, where A is determined experimentally by the intercept at $1/T_E = 0$. The Richardson work function is often used in expressing the vacuum work function.

Since partially cesiated surfaces are almost exclusively used to achieve the high emission currents required in thermionic conversion, the use of an A value other than 120 at present introduces arbitrariness. Thus, it is customary to express the emission current, the Richardson-Dushman equation, and the effective work function concurrently.

Read (ref. 16) gives a computer-calculated tabulation of the effective work function φ related to current density and electrode temperature. The assumption made in the compilation is that the current density is given by the Richardson-Dushman equation (i.e., negligible space-charge, magnetic-field, and transport effects). Data are presented for values of work function at 20 K intervals in the temperature range from 300 to 2800 K and at 50 equally spaced intervals in each order of magnitude in the current density range from 1.0×10^{-11} to 9.8×10^{2} amperes per square centimeter. The author also includes a brief tabulation of current density J as a function of T (300 to 3200 K in 100 K increments) and work function (0.5 to 6.0 V in 0.1-V increments). Smith and Breitwieser (ref. 17) present a nomograph (fig. 6) yielding emission current density from effective work function and electrode temperature.

THEORETICAL CONSIDERATION

Theoretical analyses relating to thermionic converters have been completed in the areas of surface physics and converter performance.

Smith (ref. 18) has calculated electron work functions, surface potentials, electron number density distribution, and electric fields in the surface region of 26 metals using the free electron model. The number of free electrons per atom was taken as the group number listed in the periodic table. Grain orientation effects were not included. With this simple model, reasonable results were obtained for electron work functions and surface potential characteristics for all metals studied. Levine and Gyftopolous (ref. 19) calculated surface equations of state and electronic emission curves for metallic surfaces immersed in monatomic metal vapors. The authors state that the results are shown to be in agreement with most of the available experimental results.

Theories based on simple models, as discussed above, do not appear adequate to the analysis of composite surfaces (e.g., Cs-O-W). Nevertheless, for practical purposes a simple correlation (Smith and Smith, ref. 20) gives emmission current density in terms of cesium atom arrival rate and surface temperature.

MONOCRYSTALLINE ELECTRODES

The best agreement between experiment and theory has been achieved with monocrystalline electrode surfaces.

Monocrystalline metals have been used as electrode materials in various experimental programs (refs. 21 to 26). The advantages of using oriented refractory electrodes in thermionic converters include selected work function, uniform emission, and grain stability at high temperatures. Results obtained in references 19 and 27 suggest that the lowest values of cesiated work functions are obtained with surfaces that have the highest initial bare work functions. The closest-packed planes of a refractory metal have a stronger affinity for cesium. This preferred orientation can be achieved by etching or by certain vapor-deposition processes. Houston (ref. 1) showed that power densities for converters using emitters with the preferred closest-packed orientation were typically 50 to 100 percent higher than those using polycrystalline emitters. These studies indicate that high bare work functions are desirable for use in practical thermionic converters. Tests indicate that the (110) crystal face of tungsten is stable in vacuum at temperatures needed for practical thermionic diodes (ref. 6). Stabilities of surfaces of monocrystal tantalum, molybdenum, and tungsten are reviewed in reference 6.

NONORIENTED ELECTRODES

Polycrystalline emitters have been considered for use in thermionic converters, and several investigators (refs. 28 to 34) have studies their performance characteristics in the presence of cesium vapor. However, quantitative agreement between investigators has not been attained.

One of the preconditions for high power output of a thermionic converter is a sufficiently homogeneous electron emission from all parts of the emitter. Surface areas of lower emission (higher work functions described in previous section) do not take part in power generation. These surfaces tend to reduce emission and lower conversion efficiency. Since the electron emission is dependent on the work function of the basic metal, it is useful to examine the work function distribution of different metals. Wilson (ref. 33) experimentally measured effective vacuum thermionic work function values for polycrystalline niobium, molybdenum, tantalum, tungsten, rhenium, osmium, and iridium. All the metal surfaces were thermally treated, which caused preferential orientation and crystal growth. Vacuum thermionic work functions are reported in reference 34 for these preferred orientations: 70 percent (100) + 20 percent (211) oriented niobium (4.19 eV), 70 percent (100) + 20 percent (211) oriented molybdenum (4.0 to 4.3 eV), 70 percent (211) oriented tantalum (4.25 eV), 96 percent (100) + 4 percent (111) oriented tungsten (4.51 eV), randomly oriented rhenium (4.96 eV), randomly oriented osmium (4.83 eV), 80 percent (111) + 15 percent (100) oriented iridium (5.27 eV).

Analysis of experimental data for a polycrystalline emitter is complex because of the various work function patch distributions that are not reproducible for different specimens of the same material (ref. 31).

ORIENTED VAPOR-DEPOSITED ELECTRODES

Significant progress has been made in the fabrication of oriented refractory metals by using the thermochemical or vapor-deposition process. Thus, the thermionic properties of oriented monocrystalline electrodes can be achieved in practical shapes. Cylindrical and planar surfaces of tungsten, rhenium, molybdenum, and tungsten and rhenium alloys have been prepared by hydrogen reduction of metal halides (refs. 6 and 35 to 38). The tungsten produced appears to have finer grain structure, to exhibit less grain growth, and to have a lower brittle-to-ductile transition temperature than that produced by other methods. Observations indicate that, if tungsten hexachloride is used, the bulk sample exhibits a strong (110) orientation parallel to the surface of the mandrel; alternatively, if tungsten hexafluoride is used, the bulk sample displayed a dominate (100) orientation (ref. 6). It was found (ref. 39) that, after a series of surface treatments (chemical etch and electrochemical etch), the surface work function changed from a (100) orientation to a surface with a predominately (110) orientation; but high-temperature thermal treatment generally resulted in relaxation to surfaces of lower work functions.

Performances of cylindrical thermionic converters using vapor-deposited emitter materials have been reported by several investigators (refs. 37 to 39). Holland and Kay (ref. 40) operate two out-of-core thermionic converters with vapor-deposited tungsten emitters, niobium collectors, and an interelectrode spacing of 10 mils. One emitter with a preferred (110) orientation exhibited a vacuum work function of 4.78 eV. A second emitter with a (100) preferred orientation had a 4.55-eV vacuum work function. The output and efficiency of both systems were stable within measurement errors over durations in excess of 3700 hours. Yang and Hudson (ref. 41) reported work function values of 5.0 and 4.5 eV for oriented vapor-deposited tungsten of (110) and (100), respectively. Campbell, Hamerdinger, and Worden (ref. 42) obtained effective Richardson work function values for a vapor-deposited rhenium emitter strongly textured with the (0001) planes parallel to the emitting surface. The data were obtained over the temperature range from 1800 to 2300 K. An average effective work function was computed by the direct substitution of the temperature and the emission current density into the Richardson-Dushman equation with the thermionic constant A taken to be 120 amperes per square centimater per K^2. Reference 42 presents an average work function, computed in this manner, of 5.28±0.05 eV, which compares to a value of 5.13±0.04 eV obtained from vacuum emission. More detailed discussion of vapor-deposited materials may be found in references 40 to 42. For highly oriented surfaces, the value presented for oriented monocrystalline electrodes in the tables in the subsequent section should apply.

WORK FUNCTION TABULATION

Tabulated work function values for various polycrystalline metals are reported by Carr (ref. 43) and Fomenko (ref. 44). Work function values and some typical properties of tungsten, tantalum, molybdenum, niobium, rhenium, and iridium are presented in table I. The source of the data is indicated in the table.

Table II shows the variations in work function with changes in crystal orientations. Data are shown for the various crystal faces of tungsten and molybdenum. Work function values of polycrystalline metals are largely determined by the statistical distributions of the crystal faces exposed on the various grains. Grain distribution is affected by processing procedures, thermal history, and physical and chemical environment of the metal.

A compilation of thermionic and (related) properties of elements and compounds obtained from the literature is presented in references 43 to 48. The quantitative data are summarized and cataloged according to substrate in reference 48. The experimental method used by each author is listed in the reference. Ehrlich and Kirk (ref. 48) present work function values obtained by several investigators for single-crystal planes of tungsten. They state that, for most of the planes of immediate interest, there is good agreement between values obtained in different studies. For the {110} planes, however, the work function is still in doubt. Two possible causes of difficulty suggested by the authors were field emission effects and differences in surface preparation by the several investigators. Lee and Blott (ref. 29) obtained contact potential difference measurements between polycrystalline tungsten surfaces in cesium vapors.

Fomenko (ref. 44) present the emission properties of some of the chemical elements and their compounds. Included in the reference are experimental emission properties of elements and compounds on various substrates; theoretically calculated values are also reported.

The influence of cesium vapor on the performance of the thermionic converter is discussed in the performance section of this report. Since the environment strongly affects the performance of cesiated converters, experimental data obtained from these systems are the most meaningful.

PROPERTIES OF THERMIONIC CONVERTER MATERIALS

METALLIC COMPONENTS

This section reviews some problems associated with certain materials and classes of materials proposed for utilization as components in gaseous thermionic converter systems. Emphasis is placed on identification of materials most likely to be used in space thermionic systems and pertinent properties (physical, mechanical, and electrical) of these materials.

Standard Physical Properties

The high-temperature requirements of thermionics restrict the selection of candidate material. Refractory metals are usually employed, especially for the emitter. Data of pertinence to the selection of suitable refractory metals (electrical resistivity, thermal expansion, and thermal conductivity) are presented in tables III (a) to (c). Most of the data were obtained from curves. (The precision of the data used to generate the curves is given in the references listed on the data tables.) Vapor pressure data for refractory materials are presented in table III(d). Additional thermionic data are presented in reference 46.

Creep Strength

Deformation of components due to creep characteristics of materials at high temperatures can be minimized by proper selection of materials. The interelectrode gap is typically of the order of 0.005 inch (0.127 mm). Variation in gap spacing can affect diode performance and, in the most extreme case, result in device failure. Consequently. the creep properties of component materials must be considered very carefully for high-temperature and long-life operation.

The creep rate behavior of emitter materials is dependent on a great number of parameters (e.g., temperature, atmosphere, grain size, impurity content, load, and preferred orientation (refs 49 to 56). To obtain consistent properties (or structures) from specimen to specimen of a given metal or alloy requires careful control during fabrication of composition and purity, consolidation procedures, mechanical processing conditions, vapor-deposition conditions, and associated thermal treatments. Well-documented creep data are sparse and are mostly available at temperature levels of 1600° C and above.

Data on polycrystalline refractory metals and their alloys are presented in tables IV and V. The original source of the data can be found from references given on the tables. Creep life data for various metals and metal alloys are presented in figure 7. The data are presented in terms of stress against the Larson-Miller parameter for 1 percent creep values. As can be seen in figure 7, the tantalum-base alloys have good creep life over the range investigated.

Conway and Flagella (ref. 54) present creep-rupture data for wrought, unalloyed tungsten and molybdenum obtained at temperatures from 1600° to 3000° C. These authors state that wrought material, fabricated by the powder metallurgy process, does not consistently exhibit the same rupture life, linear creep rate, and elongation at rupture. Chin, Weinberg, and Lindgren (ref. 59) report the results of a test on the creep behavior of a cylindrical specimen machined from a slab cut from the wall of a piece of thick-wall, vapor-deposited tungsten tubing. The test temperature and stress were 1760° C and 1000 psi. After 664 hours the strain was 0.715 percent, and after 2671 hours the strain was 1.57 percent. The authors state that these values were essentially identical to those for arc-cast tungsten presented by Schmidt and Ogden (ref. 58).

Ductility and Weldability

For converter construction materials, refractory metals must have satisfactory weldability and reasonable ductility from temperatures of -54° C to values considered for thermionic converter operation.

Of the refractory metals, tungsten has a high ductile-to-brittle transition temperature (DBTT). The DBTT of molybdenum is near room temperature for small grain size. But at the temperatures of interest for thermionic application, grain growth occurs and the DBTT is higher. The transition temperatures for tantalum and niobium are below room temperature even after grain growth has occurred.

If refractory metals are to be used extensively, there is the need for developing satisfactory joining methods, particularly welding and brazing. Reasonably good methods have been developed for columbium and tantalum alloys. Molybdenum alloy joining has proved practical when electron beam welding techniques are used, and this is also true with tungsten alloys. The usefulness of refractory metals for supporting structures has been greatly enhanced by the use of improved joining methods (i.e., electron beam welding, inert gas welding, and some brazing techniques). Successful brazing and welding practices with refractory metals must, of course, result in joints of reasonable ductility. Excessive embrittlement by braze alloys or loss of ductility due to recrystallization of material caused by heat of welding may not be acceptable, although the degree of ductility required is difficult to define.

Numerous studies have been directed toward evaluating the weldability and the ductile-brittle behavior of refractory metals and refractory-metal alloys (refs. 59 to 66). Lessman (ref. 62) presents results obtained from a program concerned with the weldability of refractory-metal alloys. Commercial and experimental alloys of interest in space power system applications were included in the program. Lessman states that "weldability was interpreted in the broadest sense, namely, in terms of its effect on mechanical and metallurgical characteristics rather than merely the ability and ease of joining. Both sheet and plate weld characteristics were determined using the applicable joining process." Lessman presented the following conclusions:

(1) Excellent weldability was demonstrated by the tantalum alloys, decreasing and variable weldability among the columbium alloys, and generally poor weldability with tungsten alloys.

(2) Alloys with large weld grains (solid-solution alloys), low recrystallization temperatures, and relatively weak grain boundaries (yttrium-modified alloys) had the least desirable tensile fracture characteristics.

(3) Porosity was not a problem in the least sensitive alloys, but special procedures were developed for the more sensitive alloys.

(4) A statistical sampling showed that the refractory-metal alloys can be welded without contamination.

Lessman and Gold (ref. 63) studied the thermal stability (particle stability) of Ta and Nb base refractory metal alloys which might be considered for application in high temperature space power systems. For the alloys with the highest creep strength (T-111, T-222, and FS-85) the instabilities were strikingly similar and were associated almost entirely with core weld. In the case of T-111 and T-222, bend test fracture occurred through ductile grain boundary tearing. The columbium alloys, however, displayed an abrupt change from ductile to brittle behavior at the weld transition. Based on the fabricability, the columbium alloys appear to have been alloyed to the maximum extent possible, whereas current tantalum alloys are more conservatively alloyed.

Lessman and Gold (ref. 66) also evaluated the weldability of unalloyed tungsten and two tungsten alloys (W-25Re and W-25Re-30Mo). These were evaluated as arc-cast material and, for the ternary alloy, also as a powder-metallurgy product. The powder-metallurgy W-25Re-30Mo alloy displayed excellent weldability, whereas the arc-cast material displayed extensive hot tearing, and hence poor weldability. The hot tearing behavior for this alloy was ascribed to a very high sensitivity to oxygen contamination.

Stoner (ref. 64) examines the effect of contamination level on the weldability of refractory-metal alloys. The alloys evaluated were FS-85, T-111, and T-222. These alloys were surface oxidized at low oxygen partial pressure followed by a vacuum anneal to diffuse the oxygen contamination throughout the material. Bend tensile and restrained weld tests were used to determine the effect of oxygen contamination. Stoner states that all three alloys exhibited a reasonable tolerance for contamination up to 100 to 200 ppm oxygen; above this value ductility impairment became excessive. Alloy T-111 proved to be the most tolerant of oxygen contamination. In addition, the thermal history influenced mechanical properties of T-111 more than the total oxygen content. Stoner reports that at 250° F (394 K) fully ductile 90° bends were obtained in T-111 contaminated with 800 ppm oxygen following 1000 hours at 2200° F (1478 K); however, before aging, bend ductility occurred above 1000° F (811 K). Weld metal mechanical properties were nearly equal to base material properties over the investigated oxygen contamination range.

Schmidt and Ogden (refs. 58 to 61) summarized data obtained from the literature on mechanical and metallurgical properties of refractory metals. Data are presented for columbium and columbium alloys, molybdenum and molybdenum alloys, tantalum and tantalum alloys, and tungsten and tungsten alloys. The data are presented in references 58 to 61 in tabular and graphical form.

Corrosion Resistance

Although the strength of materials and the development in fabrication and joining techniques suggest that satisfactory high-temperature operation required for thermionic conversion can be achieved, it should be emphasized that these properties were evaluated in a vacuum environment. In practical applications, many of the structural elements may be exposed to alkali-metal liquids and/or vapors. The effect of this exposure may result in subtle changes in the trace composition of the alloys and in some cases catastrophic failure by severe corrosion.

DeMastry and Griesenauer (ref. 67) investigated the corrosion characteristics of 11 refractory metals in lithium and cesium vapor. Exposure periods of 100 and 1000 hours were employed in static lithium (2500° to 3000° F; 1644 to 1922 K) and cesium vapor (2500° to 3400° F; 1644 to 2143 K). The following results were obtained for W; W-0.9Cb; W-15Mo; W-10Re; and W-25Re: lithium attacked none for 100 to 1000 hours at 2500° F (1644 K), attacked some during 1000 hours at 2800° F (1813 K), and attacked all in 1000 hours at 3000° F (1922 K). All these alloys exhibited surface dissolution in 3400° F (2143 K) cesium vapor. The W-25Re alloy was the most resistant to cesium attack.

In reference 68, it has been shown that high-purity niobium and tantalum refractory-metal alloys exhibit 2000 hours compatability with refluxed high-purity potassium to better than 1500 K with essentially no corrosive attack, while an ungettered alloy experiences corrosion after a 1000 hours exposure at approximately 1500 K. It is significant that the total oxygen available in the metal (i.e., the sum of the dissolved oxygen initially present and the oxygen which getters from the external environment) was suggested to be the fundamental life-limiting factor for liquid-metal corrosion. Hence, as better alloys are fabricated and low oxygen environments are established, long-life operation at high temperatures may be anticipated for nuclear thermionic converter systems.

INSULATING MATERIALS

Functional Requirements

Electrical insulators are needed in several locations in the various thermionic energy converter systems. The out-of-core system usually requires electrical isolation of the emitter from the energy source. Both in-core and out-of-core systems require some form of electrical isolation between the collector and the coolant. Electrical isolation between the emitter and the collector is also required. Although the insulators are used primarily for electrical isolation, they may differ in environmental location and functional requirements.

The insulator that isolates the heat source from the emitter in out-of-core thermionic energy conversion systems must be thin to reduce thermal impedance, must operate at or near the emitter temperature T, and must sustain high voltages (of the order of 20 to 50 V). Grossman (ref. 69) estimates, for a 0.020-inch (0.51-mm) tube wall, this places a maximum gradient of 1000 volts per inch (394 V/cm) across the insulator. This insulator is usually not in contact with corrosive material and is not exposed to neutron flux.

The insulators that provide electrical isolation between the emitter and collector also act as a structural member in ceramic-to-metal seals. The technique used in perfecting the seal is discussed in the next section. Most designs require that the insulator be in constant contact with the gaseous cesium environment. The insulator should maintain a potential drop of about 1 volt in the cesium atmosphere. It is desirable that the insulator seal should be leak-tight, light, and small, and be chemically and mechanically compatible with other converter components. This tube must have good heat conduction and must be chemically and mechanically compatible with the surrounding structures, as well as with the cesium vapor. The temperature requirement of this insulator will be dictated by the coolant in a practical converter system.

The insulator that isolates the coolant from the collector is usually of a trilayer configuration. This insulator operates at a lower temperature than that located at the emitter and must be able to conduct heat efficiently. In the in-core thermionic conversion system the insulator must be able to tolerate a significant fast neutron flux. The voltage gradient requirement is similar to that required for the emitter.

Metallic Oxides

The insulator materials used in the three localities are the oxide refractories (principally, Al_2O_3, BeO, Y_2O_3). These materials are usually considered as insulator materials because of their high melting points (over 2000° C) and their favorable decomposition pressures under 10^{-3} torr at 2000° C. Alumina appears to be the most widely used because of its advanced state of fabrication technology and its many desirable properties. Selected data for promising insulator materials considered for use in thermionic energy conversion devices are given in table VI. These data for the most part were obtained from references 69 to 71. As shown in table VI and indicated in reference 69, Al_2O_3 exhibits the most realistic compromise between the needed properties of all the candidate oxides. BeO is less desirable because of its toxicity and its well-known catastrophic disintegration in the presence of water vapor. Additional data on insulator materials are presented in references 70, 72, and 73.

Since cesium vapor pressure of the order of a few torr will be in contact with some of the insulators at or near the collector temperature, the interaction between cesium vapor and the insulator is important. Grossman (ref. 69) reports a study made on the compatibility of some insulators and cesium vapor with the following results: Dense oxide bodies made from high-purity ($\leq$1000 ppm total impurities) Al_2O_3, BeO, ThO_2, Y_2O_3, or ZrO_2 revealed no interaction when exposed to 4-torr cesium vapor for 300 hours at 1600° C. A 300-hour test at 1400° C of Al_2O_3 in Cs vapor which contained Na, K, Mg, Ca, and Si showed reaction between the Ca (100 ppm Ca in the cesium) and the Al_2O_3 to form $CaO \cdot 6Al_2O_3$. Static exposures of Al_2O_3, ThO_2, ZrO_2, CaO, MgO, HFO_2, and BN for short periods (10 min) were reported to produce no visible attack, from 866 to 1083 K at cesium pressures of 20 torr (ref. 70).

Ceramic-to-Metal Attachment

The insulator seal consists of a ceramic insulator bonded to two separate metal sections, one of which is joined to the emitter and the other to the collector. Most of the techniques involve establishing an initial bond to the ceramic by means of a metal or alloy chemically active enough to react with the ceramic. In some applications the brazing or filler alloy will establish the bond; in others a metallized layer is bonded initially and is brazed to the metal. Phillips (ref. 74) discusses joining techniques that have revolved as a result of continuing research and development in metal-to-ceramic seal technology.

Commercial seals consist mostly of Al_2O_3 brazed to Ni-Fe alloys with BT solder (silver-copper eutectic) and are usable to about 700° C (ref. 69). A special seal was fabricated and tested by DeMastry and Griesenauer (ref. 67). Yttria was successfully bonded to TZM, tungsten-rhenium, and W-10Re using 0.001- and 0.003-inch (0.025- and 0.076-mm) thick yttrium foil as an intermediator material. Bonds prepared by this method remained intact after five rapid thermal cycles between 400° and 2500° F (478 and 1644 K). Tungsten-yttria has been employed as a metallizing material in conjunction with palladium or copper as the braze material in the ceramic-to-metal seal process.

Several investigators (refs. 75 and 76) have recently studied the problem associated with fabrication and evaluation of graded-type ceramic-to-metal seals. Gibson (ref. 75) fabricated a seal by grading a metal-to-ceramic mixture between two metallic interfaces with isostatic gas pressure bonding. Densification was obtained at 1650 K under 10 000-psi (6.89×10^7-N/m^2) helium pressure. Gibson states that these seals have higher temperature capabilities due to the lack of high interface stresses and to the absence of brazing alloys which can diffuse into the matrix leaving the interface structure weak. The graded seal consisting of niobium and Lucalox is being tested and evaluated for thermal stability by General Atomics and NASA Lewis Research Center. General Atomics reported all seals were leak-tight after 1000 hours at 1200° C.

Kaufman, Tischler, and Breitwiesser (ref. 76) describe a cermet seal consisting of one or more layers of alumina-coated niobium particles sandwiched between thick niobium pieces and bonded by isostatic hot pressing. Simple compact cermet assembly configurations, planar and cylindrical, have been fabricated. Both are machinable and can be welded or brazed.

DIODE PERFORMANCE

EFFECT OF CESIUM

The electron emissions from the refractory metals are enhanced in the presence of cesium vapor. Cesium has the lowest known work function of all the chemical elements. Condensing cesium on the surface of refractory metals results in a reduction in work function and an increase in electron emission of these materials.

Figures 8(a) and (b) show the emission properties of molybdenum and tungsten in the presence of cesium vapor. The figures were obtained from reference 19. The electron emission from bare refractory materials increases exponentially with temperature, but in the presence of cesium vapor the emission current is represented by an S-shaped curve (ref. 19). At low values of emitter temperatures, cesium metal completely covers the surface of the substrate material, and the electron work function is that of the absorbed cesium. As the emitter temperature increases, electron emission increases until the absorbed cesium atoms begin to vaporize. Additional increases in emitter temperature reduce the cesium concentration on the substrate surface until a minimum work function is attained. As the emitter temperature is increased beyond the work function minimum, electron work function begins to increase and the emission current to decrease. At somewhat higher temperatures, most of the cesium atoms are removed from the surface. The emission current is now controlled predominately by the work function of the metal and increases exponentially with temperature.

EFFECT OF ELECTRONEGATIVE ADDITIVES (AND CONTAMINANTS)

For most applications of oxide insulators and spacers, the oxide and refractory metal are joined along an interface which provides a tortuous path for the escape of volatile species. The principal diffusing species in volatile-product, metal-oxide reaction is probably oxygen (ref. 69). Inevitably, for long-life operations, contamination is present.

It is well-established that, in the presence of cesium, electronegative contaminants lower the work function of refractory-metal substrates. Several investigators have shown that oxidizing or fluoridizing the surface of refractory-metal substrates results in an increase in work function which enhances cesium adsorption characteristics (refs. 77 to 79). A qualitative correlation between the work function and the particular gaseous environment at the emitting surface is difficult to obtain because the additives become soluble in the cesium liquid and form gaseous molecular compounds to an unknown extent. It has not been ascertained whether the additive is present as an oscillating dipole or whether it lies flat on the surface (ref. 80). Additional detailed experiments are required in order to clarify the mechanism and to obtain reproducible data.

Levine and Gelhaus (ref. 77) diffused pure oxygen into the interelectrode space of several operating thermionic converters by using a semipermeable membrane. Their results indicated that the work functions of both the collector and the emitter were lowered, that postdose power densities for times exceeding 200 hours were enhanced, and that an increase in the maximum power density to a value twice that of cesium-only operation was observed. Becker (ref. 8) reviews some oxygen introduction schemes employed to increase the affinity of thermionic converter electrodes for Cs. He discusses a development effort (ref. 78) concerned with O_2 addition in a thermionic converter. The converter had a W emitter and a Mo collector. A Cu_2O reservoir was used to maintain oxygen pressure. The optimized power density of the converter was nearly doubled by the O_2 addition for an emitter temperature of 1850 K and an interelectrode spacing of 10 mils (0.25 mm). The additive may be fabricated in the electrode or metered by way of an external source to maintain a partial pressure in the interelectrode space. Becker suggests that fabricating the additive in the electrode may suffer because of diffusion losses of the additive, whereas the other method provides a self-healing electrode.

Langpape and Minor (ref. 79) studied the effect of cesium fluoride additive on the performance of a thermionic converter. Diode performance was evaluated with Nb, Ta, Mo, W, and Re as emitter materials and Ni as the collector material. This test indicated that CsF additive effects a reduction of the optimum cesium pressure by raising the emitter substrate work function. However, tests described in reference 78 suggest that O_2 impurity in the CsF-Cs system produced the performance gains observed and that pure CsF has been shown to be much less effective than O_2 in altering the work function of tungsten. The additive program has not demonstrated the ultimate material nor has it demonstrated the best method of distribution at this time. Also it has not been demonstrated that potential performance gains expected are great enough to compensate for the added engineering complexity required in incorporating electronegative additives into practical converters.

EFFECT OF ELECTROPOSITIVE ADDITIVES

Several investigators have studied the performance characteristics of thermionic converters with barium present in the interelectrode plasma. The barium is expected to increase the electron transport effect by reducing electron scattering and inelastic collisions, thus making it practical to operate the converter at larger interelectrode spacings.

Kennedy and Shefsiek (ref. 81) investigated the performance of a barium-vapor-filled thermionic converter. Barium has a high ionization potential of 5.19 eV as compared to 3.89 eV for cesium. Consequently, emitter temperatures of 2000 K or higher are generally necessary in order to obtain significant output power densities (W/cm^2). The authors observe that some experimental evidence indicates that good performance at lower temperatures is obtainable for the niobium emitter. Results obtained suggest that niobium is a poor emitter in a cesium vapor device because its adsorption properties are such that a very high cesium pressure is required for acceptable work function reduction. The adsorption properties of Ba are such that the lower-work-function region of substrate material continued to have the lower work function after Ba adsorption. The investigation utilized a molybdenum emitter and collector with an interelectrode gap of 0.02 inch (0.51 mm) and a series of flat-plate variable spacing devices having tungsten emitters and niobium collectors. Kennedy and Shefsik obtained 1 to 10 amperes per square centimeter in the temperature range 1800 to 2000 K for Ba vapor pressures less than 0.1 torr. Performance showed little dependence on interelectrode spacing between 0.005 and 0.02 inch (0.13 and 0.51 mm). Output power densities maximized at collector temperatures in excess of 1200 K. The potential advantages of using Ba instead of Cs in those thermionic converter devices requiring high collector temperatures have been demonstrated. With close attention to the development of high-temperature seals and containment materials for Ba vaporization temperature requirements, Kennedy and Shefsiek suggest that Ba might be an attractive additive for certain power applications.

Psarouthakis (ref. 82) utilized a low-pressure combination of barium and cesium vapor for the reduction of transport losses in thermionic energy converter studies. The barium vapor was introduced to modify the emitter work function, and the cesium was added to generate ions at the emitter surface for space-charge neutralization. The optimum characteristic showed output densities up to 14 watts per square centimeter at emitter and collector temperatures of 2050 and 1275 K, respectively - essentially independent of interelectrode spacing variations up to the tested spacing of 0.040 inch (1.02 mm) at an output voltage of 1.0 V and an estimated converter efficiency of 21.4 percent. Psarouthakis states that the analysis and projection of the data show that 20 watts per square centimeter at an estimated converter efficiency of 25 percent could be obtained with this approach if the collector work function can be reduced from the presently attained 2.1 eV down to 1.76 eV.

CONVERTER LIFE TESTS

The results of (electrically heated) thermionic converter life tests performed by various organizations have been summarized by Prosser (ref. 83), Breitwieser and Schwartz (ref. 6), and Becker (ref. 8). The authors of reference 84 recorded the lifetime and electrical performance of eight converters with various emitter and collector material combinations. One converter was still running after 8500 hours. Post-test examinations of the converters showed that performance instability and abnormal behavior of high-efficiency converters, together with reduced lifetime, may be related to gaseous contaminants. Ernst (ref. 85) conducted life tests on four cylindrical diodes to investigate the thermionic stability of emitter surfaces prepared on chemical vapor-deposited fluoride tungsten. The measured performance of the four diodes over a period of 23 925 hours indicate that minimal surface change occurred during the duration of the test. Tests were terminated upon completion of the program.

Stapfer (ref. 86) describes the thermionic life test program presently being conducted that includes a total of 10 thermionic converters. During a 2-year period, a total of 68 316 hours of combined converter operation were recorded. One converter that achieved more than 20 000 hours of operation continues to operate at an average power density of 25 watts per square centimeter at 0.7 volt, according to Stapfer. Of the original 10 converters tested, two failed. Failure was attributed to the loss of interelectrode cesium. These studies indicate that considerable life testing has been done and that converter lifetimes exceeding 1 year have been obtained in most cases with no appreciable degradation in performance.

CONCLUDING REMARKS

Although many of the following comments are self evident and have been discussed earlier, it is pertinent to emphasize again the directions for additional thermonics materials activity:

1. Work is being continued to obtain uniform emitters having surfaces consisting of the close-packed planes of high-work-function refractory metals in cesium vapor.

2. The effort to achieve low-work-function collectors is also being continued. The use of lower work function values improves the output voltage from the converters and thus reflects directly in improvements in output power. The use of lower-work-function collectors requires lower collector temperatures. The concept will be limited to systems where radiator weight is not critical.

3. Improvements in fabrication techniques with the refractory metals are desirable if these materials are to be used extensively in the support structure and liquid-metal loops of thermionic diodes. And efforts are being made to develop ductile materials with improved creep strength.

4. A continued study of insulators should allow development of improved materials.

5. Although electronegative additive addition to the thermionic diode has been demonstrated to improve the output power of these devices, additional effort is required to ascertain whether these performance gains are great enough to compensate for the added engineering complexity required in incorporating these additives into practical converters.

6. Thermionic converter life test programs indicate that converter lifetimes exceeding 1 year have been obtained in many cases with no appreciable degradation in performance.

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TABLE I. - WORK FUNCTION VALUES AND SOME TYPICAL PROPERTIES OF REFRACTORY METALS

Material	Work function (ref. 44)	Ionization potential (ref. 43), eV	Melting point (ref. 45), K	Spectral emissivity ($\lambda = 0.65$) (ref. 45)
Tungsten	4.5	7.98	3650	>0.44(1000 to 2000 K)
Rhenium	5.0	7.87	3453	.41
Molybdenum	4.59	7.10	2895	>.38(2000 K)
Tantalum	4.12	7.88	3269	.46(1700 to 2800 K)
Iridium	5.3	9.00	2727	.30(ref. 12)
Niobium	3.99	6.88	2740	.49(ref. 12)

TABLE II. - WORK FUNCTION IN CERTAIN CRYSTALLOGRAPHIC DIRECTIONS

(a) Tungsten

Crystallographic direction	Work function	Type of emission[a]	Reference
411	4.40	FE	48
310	4.30	PE	44
	4.31	FE	46
	4.35	FE	46
100	4.52	TE	43, 44
	4.56	TE	↓
	4.59	TE	
	4.6	TE	
	4.72	FE	43
	4.97	TE, FE	43, 44
110	4.58	TE	43
	4.60	FE	44
	4.66	TE	↓
	4.68	FE	
	4.9	FE	
	5.0	FE	
	5.11	TE	48
	5.1	TE	29
	5.14	TE	29
	5.29	TE	48
	5.3	TE	44
	5.33	TE	44
	5.4	TE	48
	5.5	FE	44
	5.6	FE	44
	5.7	FE	43
	5.99	FE	44
	6.0	FE	44
111	3.9	FE	43
	4.2	FE	43
	4.29	FE	44
	4.3	FE	43
	4.38	TE	43, 44
	4.39	TE, FE, PE	43, 44
	4.40	TE, FE	43, 44
	4.42	TE	44
	4.43	TE, FE	43, 44
	4.45	Condenser	44
	4.64	FE	43, 44
112	4.50	PE	44
	4.65	TE, FE	↓
	4.69	TE	
	4.74	TE	
	4.76	PE	
	4.8	TE, FE	
	4.87	FE	48
	4.88	FE	44
	4.9	FE	44
	4.93	FE	43
	4.96	FE	48
116	4.2	FE	44
	4.29	TE	↓
	4.30	TE, FE	
	4.39	TE	
	4.49	FE	

[a] Type of emission: FE, field emission; PE, photoelectric emission; TE, thermionic emission.

TABLE II. - Concluded. WORK FUNCTION IN CERTAIN CRYSTALLOGRAPHIC DIRECTIONS

(b) Molybdenum (ref. 43)

Crystallographic direction	Coombes and Boeck	Coombes (Gardner)
	Work function (where A is the thermionic constant)	
110	5.4±0.2 (A = 2500±1500)	4.83 4.81
112	4.5±0.1 (A = 85±35)	4.69 4.72
001	4.5±0.1 (A = 118±30)	4.57
111	4.3±0.1 (A = 25±10)	4.40 4.42
116	4.2±0.1 (A = 17±8)	4.31 4.33

TABLE III. - PHYSICAL AND ELECTRICAL PROPERTIES OF SOME REFRACTORY METALS (REF. 45)

(a) Electrical resistivity

Material	Temperature, K				
	500	1000	1500	2000	2500
	Electrical resistivity, ρ, Ω-cm				
Tungsten	9×10^{-6}	2.4×10^{-5}	4×10^{-5}	5.7×10^{-5}	7.3×10^{-5}
Rhenium	3.4×10^{-5}	6.4	8.5	9.9	10.8
Molybdenum	9.5×10^{-6}	2.0	3.1	4.1	5.0
Tantalum	2.2×10^{-5}	4.1	5.8	7.6	9.0
Iridium	1.0	2.1	3.4	--------	---------
Niobium	2.4	4.4	5.9	--------	---------

(b) Thermal expansion

Material	Temperature, K				
	500	1000	1500	2000	2500
	Thermal expansion, percent increase				
Tungsten	0.008	0.11	0.56	0.86	1.23
Rhenium	.12	.47	[a].81	----	-----
Molybdenum	.10	.38	.72	1.16	1.67
Tantalum	.13	.47	.85	1.26	1.68
Iridium	-----	----	----	----	-----
Niobium	.13	.50	.96	1.52	[a]2.2

[a] Extrapolation.

TABLE III. - Concluded. PHYSICAL AND ELECTRICAL PROPERTIES OF SOME REFRACTORY METALS (REF. 45)

(c) Thermal conductivity

Material	Temperature, K				
	500	1000	1500	2000	2500
	Thermal conductivity, cal/(sec)(cm)(K)				
Tungsten	0.36	0.29	0.26	0.24	0.227
Rhenium	.107	.099	-----	-----	-----
Molybdenum	.310	.267	.234	.214	.204
Tantalum	.163	.151	.147	.146	.146
Iridium	.336	-----	-----	-----	-----
Niobium	.115	.130	.148	[a].170	-----

(d) Vapor pressure

Material	Vapor pressure, torr					
	10^{-10}	10^{-8}	10^{-6}	10^{-4}	10^{-2}	10^{0}
	Temperature, K					
Tungsten	2150	2390	2680	3030	3500	4180
Rhenium	1995	2220	2490	2860	3340	4080
Molybdenum	1690	1865	2095	2390	2800	3390
Tantalum	2020	2230	2510	2860	3330	3980
Iridium	1665	1850	2080	2380	2270	3360
Niobium	1845	2035	2260	2550	2930	3450

TABLE IV. - CREEP PROPERTIES OF TUNGSTEN, TUNGSTEN-RHENIUM, AND MOLYBDENUM

(a) Electron-beam-melted tungsten-rhenium alloys (ref. 51)

Alloy	Analyzed rhenium content, wt % (a)	Test temperature (b)		Stress		Steady creep rate, sec^{-1}	Stress factor, n
		°F	K	psi	N/m^2		
EB-160A	1.9	3500	2198	2380	1640×10^{4}	0.10×10^{6}	5.1
				2860	1971	.28	
				3460	2385	.76	
				4170	2874	1.6	
EB-127	2.5	3000	1922	9030	6220×10^{4}	5.2×10^{6}	----
		3000	1922	9760	6725	6.4	----
		3500	2198	3000	2069×10^{4}	0.44×10^{6}	5.0
				3350	2310	1.1	
				4070	2801	2.4	
				4910	3385	6.6	
				5990	4130	16	
EB-156	2.8 (0.03-in. sheet	3000 (as rolled)	1922	8790	6055×10^{4}	1.8×10^{6}	5.6
		3500 (as rolled)	2198	2750	1895	.067	
				3670	2530	.45	
				4580	3090	1.6	
				5500	3800	4.4	
				6410	4415	9,8	
		3500	2198	3490	2405×10^{4}	0.51×10^{6}	5.7
				4180	2880	1.2	
				4880	3363	3.5	
				5930	4080	9.1	
EB-159A	3.6	3500	2198	3050	2101×10^{4}	0.29×10^{6}	4.4
				3690	2542	.78	
				4450	3065	1.9	
				5340	3680	3.4	
EB-139	4.5	3000	1922	4470	3080×10^{4}	0.073×10^{6}	4.5
				5340	3680	.11	
				6450	4444	.26	
				7700	5310	.58	
				9180	6325	1.4	
		3500	2198	2130	1468×10^{4}	0.078×10^{6}	4.7
				2510	1730	.12	
				2880	1985	.17	
				3380	2333	.33	
				4000	2758	.84	
				4760	3280	1.8	
				5510	3798	3.3	
EB-176	4.7	3500	2198	3540	2440×10^{4}	0.50×10^{6}	5.3
				4190	2888	1.3	
				4830	3330	2.7	
				5470	3770	5.8	
				6110	4210	9.1	
EB-126	6.5	3500	2198	2620	1806×10^{4}	0.19×10^{6}	4.4
				3810	2627	1.8	
				4400	3070	1.9	
				5000	3449	3.3	
				5950	4100	7.4	
		[c]3500	2198	2610	1800×10^{4}	0.15×10^{6}	4.4
				3560	2455	.71	
				4510	3110	2.3	
				5220	3600	3.8	
				6170	4254	7.4	
				7120	4910	12	
EB-179	9.1	3500	2198	2660	1834×10^{4}	0.10×10^{6}	5.3
				3320	2289	.33	
				3980	2745	.80	
				4650	3208	2.0	
				5310	3670	3.8	
				6640	4580	11	
EB-181	24	3500	2198	2970	2048×10^{4}	1.5×10^{6}	4.0
				3720	2565	3.5	
				4460	3075	7.7	
				5200	3585	14	

[a] Rod specimens with 0.16-in. (0.41-cm) diam reduced section employed except where sheet is indicated.

[b] Specimens annealed in vacuum for 1 hr at 3600° F (2256 K) except where indicated.

[c] Duplicate test.

TABLE IV. - Continued. CREEP PROPERTIES OF TUNGSTEN,

TUNGSTEN-RHENIUM, AND MOLYBDENUM

(b) Arc-melted tungsten at 3000° to 4000° F (1922 to 2478 K) (ref. 52)

Lot	Annealing condition			Stress		Steady creep rate, sec^{-1}	Total elongation, percent	Total reduction in area, percent	Average grain diameter, L, cm
	Temperature		Time, t, hr	psi	$\mathrm{N/m^2}$				
	°F	K							
Test temperature, 3000° F (1922 K)									
F	4000	2478	1	7 980	5500×10^{4}	26.3×10^{-6}	-----	-----	----------
				8 970	6180	40	-----	-----	----------
				10 080	7450	84	-----	-----	----------
				10 980	7570	210	[d]36.5	[d]20.4	32.2×10^{-3}
G	4200	2583	1	7 480	5155	43.4×10^{-6}	-----	-----	----------
	4200	2583	1	8 470	5835	81.3	-----	-----	----------
	4200	2583	1	9 500	6550	200	[d]37.8	[d]17.2	114×10^{-3}
Test temperature, 3500° F (2198 K)									
D	3600	2256	1	5 020	3461×10^{4}	15.7×10^{-6}	-----	-----	----------
				5 480	3778	19.7	-----	-----	----------
				5 990	4180	30	-----	-----	----------
				6 540	4510	52.6	-----	-----	----------
				6 970	4805	96.6	[d]23.4	[d]15.6	7.21×10^{-3}
	3800	2365	1	4 490	3095×10^{4}	10.7×10^{-6}	-----	-----	----------
				5 030	3555	15.3	-----	-----	----------
				5 490	4785	21.4	-----	-----	----------
				5 970	4115	30.7	-----	-----	----------
				6 490	4475	55	-----	-----	----------
				6 990	4820	110	[d]22.6	[d]12.5	10.45×10^{-3}
F	4000	2478	1	4 720	3253×10^{4}	19.5×10^{-6}	-----	-----	----------
				5 530	3810	36.2	-----	-----	----------
				6 220	4289	68.8	-----	-----	----------
				6 940	4785	171	72.0	>98	38.3×10^{-3}
				5 030	3465	25	-----	-----	----------
				5 530	3813	35	-----	-----	----------
				6 000	4135	60	-----	-----	----------
				6 480	4467	115	69.0	>98	32.6×10^{-3}
Test temperature, 4000° F (2478 K)									
F	4000	2478	1	2 600	1794×10^{4}	18.3×10^{-6}	-----	-----	----------
				2 890	1890	26.7	-----	-----	----------
				3 180	2191	41.2	-----	-----	----------
				3 490	2407	73.4	[d]18.4	[d]9.8	29.7×10^{-3}
G	4200	2583	1	2 310	1593×10^{4}	21.7×10^{-6}	-----	-----	---------
				2 590	1786	30	-----	-----	---------
				2 880	1985	50.3	-----	-----	---------
				3 180	2192	93.3	[d]26.1	[d]16.3	97.6×10^{-3}

[d] Test discontinued.

TABLE IV. - Continued. CREEP PROPERTIES OF TUNGSTEN, TUNGSTEN-RHENIUM, AND MOLYBDENUM

(c) Creep data for electron-beam-melted tungsten (ref. 53)

Lot	Annealing condition			Temperature		Stress, S		Transient creep constant, β, $sec^{-1/3}$	Steady creep rate, $\dot{e}$, sec^{-1}	Average grain diameter, L, cm
	Time, hr	Temperature		°F	K	psi	N/m^2			
		°F	K							
EB-43	1	3600	2256	3500	2198	2130	4680×10^{4}	0.877×10^{-3}	0.373×10^{-6}	------
	1	3600	2256	3500	2198	4760	3281	12.9×10^{-3}	80.0×10^{-6}	0.42
EB-100	0.5	3000	1922	2500	1655	4660	3211×10^{4}	0.438×10^{-3}	-----------	0.038
	.5	3000	1922	2500	1655	5760	3970	1.13	-----------	
	.5	3000	1922	2500	1655	6870	4735	1.71	-----------	
	As swaged			3000	1922	4010	2765×10^{4}	(e)	-----------	0.088
	↓			3000	1922	4860	3350		4.68×10^{-6}	
	↓			3500	2198	2430	1614×10^{4}	1.46×10^{-3}	0.675×10^{-6}	0.223
	↓			↓	↓	2820	1944	-----------	1.83	
	↓			↓	↓	3185	2195	-----------	3.89	
	↓			↓	↓	3675	2533	-----------	9.79	
	↓			↓	↓	4165	2871	-----------	21.0	
	1	3600	2256	2250	1511	6200	4275×10^{4}	0.786×10^{-3}	-----------	0.203
	↓	↓	↓	2500	1655	6200		2.56	-----------	
	↓	↓	↓	2750	1783	6200		4.48	-----------	
	↓	↓	↓	2750	1783	4200	2910×10^{4}	1.47×10^{-3}	-----------	0.176
	↓	↓	↓	2875	1853	↓	↓	2.42	0.808×10^{-6}	
	↓	↓	↓	3000	1922	↓	↓	-----------	1.70	
	↓	↓	↓	3125	1995	↓	↓	-----------	3.50	
	↓	↓	↓	3250	2062	↓	↓	-----------	9.81	
	↓	↓	↓	3525	2218	3200	2205×10^{4}	4.36×10^{-3}	5.43×10^{-6}	0.181
	↓	↓	↓	3630	2273	↓	↓	-----------	1.81	
	↓	↓	↓	3355	2121	↓	↓	-----------	1.65	
	↓	↓	↓	3495	2198	↓	↓	-----------	5.51	

[e] Abnormal behavior.

TABLE IV. - Continued. CREEP PROPERTIES OF TUNGSTEN, TUNGSTEN-RHENIUM, AND MOLYBDENUM

(d) Wrought, arc-cast unalloyed molybdenum sheet[f, g] tested in hydrogen (ref. 54)

Specimen[h]	Test conditions		Strain, percent							Rupture		Linear creep rate, min^{-1}
	Temperature, °C	Stress, kg/mm^2	0.2	0.5	1	2	3	5	10	Time, hr	Elongation, percent	
			Time to indicated strain, hr									
M(6)4												
4	1600	2.11	-----	------	0.03	0.13	0.28	0.60	1.4	2.5	30	9.8×10^{-4}
5		1.76	-----	0.05	.18	.53	.98	1.9	4.2	6.9	30	3.6
6		1.41	0.06	.20	.58	1.5	2.5	4.7	9.8	25.1	55	1.6
7		1.05	.26	.99	2.6	6.5	10.4	18.8	38.7	99.6	64	2.9×10^{-5}
16		.84	9.7	3.1	7.4	17.8	29.6	51.2	100	247	47	1.4
3		.70	3.8	12.0	24.2	48.5	73.0	122	234	554	45	6.8×10^{-6}
12		.56	8.5	26.5	57.5	124	198	345	------	[i]452	[i]6.4	2.3
15		.35	90.5	255	-----	------	------	------	------	[i]348	[i].68	2.9×10^{-7}
8	2200	.56	-----	------	-----	------	------	.02	.09	0.22	40	--------
9		.35	-----	------	0.03	.12	.24	.53	1.2	2.88	53	1.1×10^{-3}
10		.21	.10	.40	.97	2.0	3.0	5.1	10.1	23.8	49	1.6×10^{-4}
11		.14	1.8	5.5	11.5	21.9	29.8	43.3	67.0	123	52	1.3×10^{-5}
17T		.10	10.0	28.0	55.0	95.0	126	169	232	[i]244	[i]11.0	2.7×10^{-6}
M(9)4												
40	1200	7.03	-----	------	-----	0.01	0.04	0.12	0.35	1.06	70	3.6×10^{-3}
41		5.62	-----	------	0.04	.20	.42	.96	2.63	9.70	78	4.8×10^{-4}
42		4.22	-----	0.07	.34	1.15	2.25	4.93	12.4	33.2	72	1.1
44		3.37	0.12	.42	1.13	3.05	6.00	13.6	34.2	98.2	84	4.0×10^{-5}
36		2.81	.76	1.93	4.62	13.2	24.8	50.4	112	214	44	1.3
43		2.11	5.20	14.6	37.5	94.0	159	278	611	1742	52	2.4×10^{-6}
11	1600	1.41	.01	.08	.33	1.03	1.88	3.71	8.33	17.5	34	1.8×10^{-4}
9		1.05	.65	1.35	2.67	5.30	8.60	14.8	29.7	59.3	57	5.0×10^{-5}
29		1.05	.26	.82	2.09	5.50	9.00	16.0	33.0	81.7	51	4.8
30		.844	1.20	2.80	6.00	14.0	23.4	42.2	87.2	241	52	1.8
0		.703	2.80	7.15	15.8	37.2	61.0	110	228	488	35	6.8×10^{-6}
12	2200	.352	-----	.01	.04	.15	.27	.55	1.25	3.40	78	1.2×10^{-3}
13		.281	-----	.03	.15	.48	.87	1.71	3.72	9.92	52	4.0×10^{-4}
26		.211	.11	.58	1.35	2.90	4.45	7.45	13.6	32.1	73	1.1
27		.176	.54	1.76	3.82	7.93	11.9	19.5	35.0	89.0	82	4.1×10^{-5}
28		.141	5.45	14.5	27.0	49.0	68.5	99.4	145	247	50	7.2×10^{-6}
14		.141	5.00	11.1	20.3	37.2	53.3	77.3	108	[i]200	38	8.5
49T	2400	.211	-----	.02	.04	.12	.20	.36	.76	1.88	48	2.0×10^{-3}
60		.190	.02	.06	.14	.30	.56	.78	1.52	3.89	52	1.0
48T		.176	-----	.02	.07	.19	.32	.59	1.13	2.80	54	1.2
23		.141	.12	.48	1.10	2.36	3.44	5.18	8.37	17.0	63	1.4×10^{-4}
53T		.120	.63	1.90	3.81	6.86	9.25	13.0	19.2	28.3	46	4.4×10^{-5}
47T		.105	2.05	4.90	8.52	14.3	19.0	25.9	35.3	48.5	38	--------
54		.084	15.1	31.0	47.2	58.9	66.1	76.9	88.7	101	32	2.6×10^{-6}

[f] Annealed at test temperature for 2 hr in hydrogen before testing.

[g] 0.05-cm-thick sheet 0.64-cm by 2.54-cm gage section.

[h] T denotes specimen transverse to rolling direction, all others parallel to rolling direction.

[i] Power failure at 88 hr caused increased strain rate.

TABLE IV. - Concluded. CREEP PROPERTIES OF TUNGSTEN, TUNGSTEN-RHENIUM, AND MOLYBDENUM

(e) Wrought arc-cast unalloyed molybdenum rod,[j,k] M(8)1, tested in hydrogen (ref. 54)

Specimen	Test condition		Strain, percent							Rupture		Linear creep rate, min^{-1}
	Temperature, °C	Stress, kg/mm^2	0.2	0.5	1	2	3	5	10	Time, hr	Elongation, percent	
			Time to indicated strain, hr									
9	1600	1.76	----	0.02	0.12	0.44	0.82	1.60	3.30	5.18	64	4.5×10^{-4}
10		1.41	0.01	.14	.49	1.40	2.37	4.35	7.47	11.7	72	1.7
11		1.05	.11	.74	2.30	5.60	8.92	13.4	23.3	58.2	53	5.0×10^{-5}
13		.844	1.88	3.48	7.40	16.7	26.7	48.7	105.	222.	82	1.4
12		.703	5.20	17.0	26.5	45.0	68.5	120.	244.	[l]357.	15	7.0×10^{-6}
3	2200	.316	----	.02	.07	.24	.44	.82	1.60	2.66	86	8.9×10^{-4}
5		.246	.02	.09	.17	.76	1.33	2.52	5.20	9.60	78	2.8
2		.197	.26	.79	1.67	3.43	5.19	8.70	11.6	17.0	44	9.3×10^{-5}
4		.162	1.05	3.32	6.11	11.56	17.0	26.2	31.5	50.0	38	3.1
1		.141	2.66	6.00	10.6	19.2	27.8	48.5	77.5	145.	64	1.9

[j] Annealed at test temperature for 2 hr in hydrogen before testing.

[k] 0.41-cm-diam by 2.54-cm-long gage section.

[l] Test terminated, no rupture.

TABLE V. - STRESS TO CAUSE RUPTURE AT TIMES INDICATED FOR VARIOUS REFRACTORY METALS AND ALLOYS (REF. 54)

Material[a]	Temperature, °C							
	1600				2200			
	Stress,[b] kg/mm^2, at hours indicated							
	1	10	100	1000	1	10	100	1000
Tungsten:								
AC	7.7*	5.2	3.6	2.5	2.0	1.3	0.88	0.49
PM	.84	5.5	3.5	-----	2.3	1.6	1.1	------
Molybdenum:								
AC	2.5	1.5	.98	.62	.46	.28	.17	.098*
PM	-----	----	1.3	-----	.70	.59	.38*	------
Rhenium:								
PM 1	-----	5.6	3.1	-----	3.5	2.2	1.2	------
PM 2	-----	7.4	4.8	3.2*	4.2*	2.8	1.7	------
Niobium (AC)	.63	.39	----	-----	-----	-----	-----	------
W-25Re (wt %):								
AC	15.*	8.8	4.9	2.8	2.5	1.3	.70	.38
PM	15.*	7.9	4.1	-----	1.9	1.1	.44*	------
Mo-30W (wt %)(AC)	5.2*	3.0	1.8	1.0	1.0*	.57	.32	.17
Mo-50Re (wt %):								
PM 1	4.3	2.7	1.7	1.1*	.81	.35	.15	.063*
PM 2	4.3	2.4	1.3	.75*	.81	.35	.15	.063*
W-30Re-30Mo (at %)(AC)	-----	5.9*	2.8*	-----	-----	.70*	.42	.25*
		4.2	2.2	-----	-----	.74*	.32	------
Mo-5W (at %)(PM)	4.7*	2.5	1.3	-----	.75*	.48	.31	------
Mo-5Re (at %)(PM)	4.7*	2.5	1.3	-----	.69*	.46	.31	------
Re-100s (at %)(PM)	-----	6.7	4.5	-----	-----	2.7	1.1	------
Ta-10W (wt %)(AC)	-----	7.7	4.9*	-----	2.1*	1.2*	-----	------
Mo-TZM (AC)	-----	----	----	-----	.48	.28	-----	------
Tantalum:								
AC	1.4	----	----	-----	.34*	-----	-----	------
PM	-----	----	----	-----	-----	-----	-----	------
Cb-753[c] (AC)	-----	----	.84	-----	-----	-----	-----	------

[a] Wrought sheet material, AC = arc-cast, PM = powder metallurgy.

[b] Values with asterisk are based on extrapolations.

[c] Nb-5V-1.25Zr (wt %).

TABLE VI. - PHYSICAL AND ELECTRICAL PROPERTIES OF SOME REFRACTORY METAL OXIDES

(a) Electrical resistivity (ref. 45)

Material	Temperature, K			
	500	1000	1500	2000
	Resistivity, ρ, Ω-cm			
Al_2O_3	$>10^{13}$	3.5×10^{9}	1.4×10^{6}	7×10^{3}
BeO	$\sim3\times10^{10}$	1.7×10^{8}	9.6×10^{5}	1.2×10^{4}
ThO_2	$\sim2.4\times10^{9}$	6.4×10^{4}	2.3×10^{2}	3.9
Y_2O_3	----------	-------	-------	--------
ZrO_2 (ref. 12)	[a]$\sim10^{8}$	[a]$\sim5\times10^{5}$	2×10^{3}	[a]<10

(b) Vapor pressure (ref. 76)

Material	Temperature, K		
	1500	2000	2500
	Vapor pressure, mm Hg		
Al_2O_3	6×10^{-8}	1×10^{-5}	10^{-1}
BeO	7×10^{-10}	2×10^{-8}	10^{-2}
ThO_2	8×10^{-8}	3×10^{-6}	5×10^{-3}
Y_2O_3	-----------	-----------	----------
ZrO_2	[a]10^{-12}	[a]10^{-9}	6×10^{-7}

[a] Extrapolation.

TABLE VI. - Continued. PHYSICAL AND ELECTRICAL PROPERTIES OF SOME REFRACTORY METAL OXIDES

(c) Thermal expansion, (ref. 45)

Material	Temperature, K			
	500	1000	1500	2000
	Thermal expansion, percent expansion from 298 K to T(C)			
Al_2O_3	0.14	0.59	1.15	[a]1.7
BeO	.12	.55	1.16	[a]1.60
ThO_2	.18	.67	1.17	[a]1.70
Y_2O_3	.14	.57	1.02	[a]~1.55
ZrO_2	.17	.62	1.2	1.25

(d) Thermal conductivity (ref. 45)

Material	Temperature, K			
	500	1000	1500	2000
	Thermal conductivity, cal/(sec)(cm)(K)			
Al_2O_3	0.043	0.020	0.020	-----
BeO	------	.120	.054	0.038
ThO_2	[a]1.96	.90	.68	[a].63
Y_2O_3	2.25	.80	.60	.75
ZrO_2	.41	.48	.56	.65

[a] Extrapolation.

TABLE VI. - Concluded. PHYSICAL AND ELECTRICAL PROPERTIES OF SOME REFRACTORY METAL OXIDES

(e) Free energy of formation (ref. 54)

Material	Temperature, K			
	500	1000	1500	2000
	Free energy of formation, kcal/g-atom			
Al_2O_3	-119	-108	-97	-82
BeO	-132	-119.5	-108	-97
ThO_2	-145	-134	-112	-102
Y_2O_3 (ref. 75)	-418	-382	-346	-309
ZrO_2	-119	-108	-97	-86

(f) Melting temperature (ref. 45)

Material	Melting temperature, K
Al_2O_3	2316
BeO	2843
ThO_2	3540
Y_2O_3 (ref. 70)	2683
ZrO_2	2983

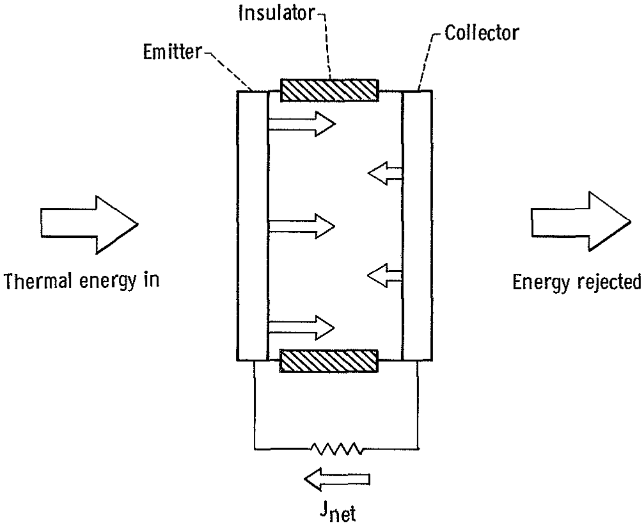
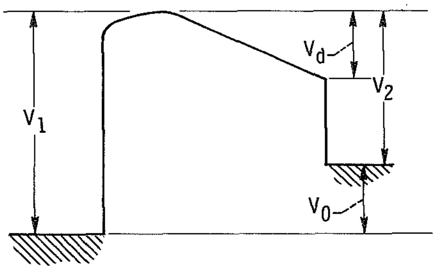
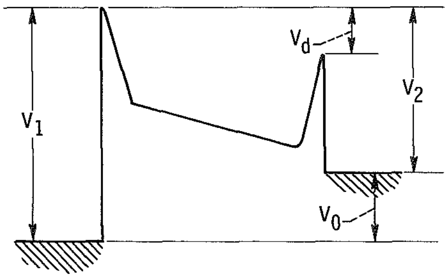


Figure 1. - Schematic of a basic thermionic converter.



(a) Electron-rich emitter sheath.



(b) Ion-rich emitter sheath.

Figure 2. - Potential energy diagram for thermionic converter.

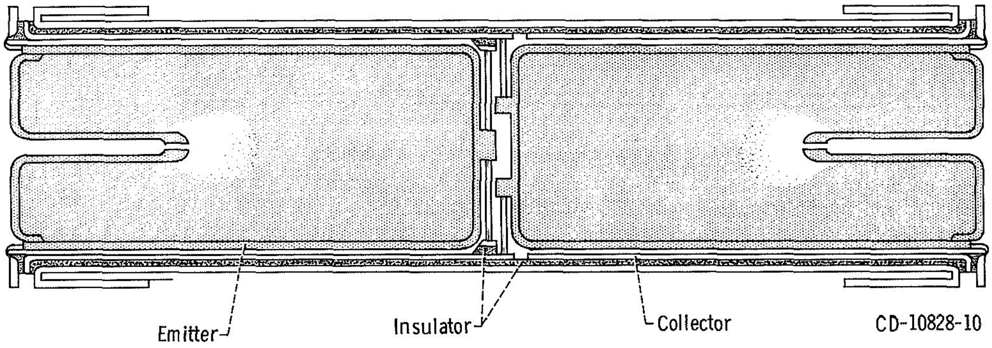


Figure 3. - In-core thermionic unit cell.

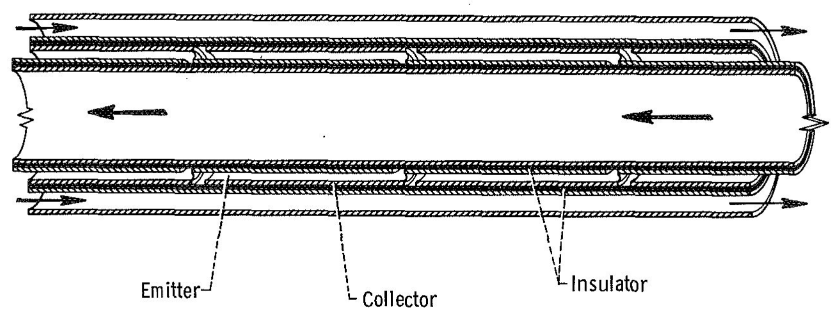


Figure 4. - Out-of-core thermionic converter.

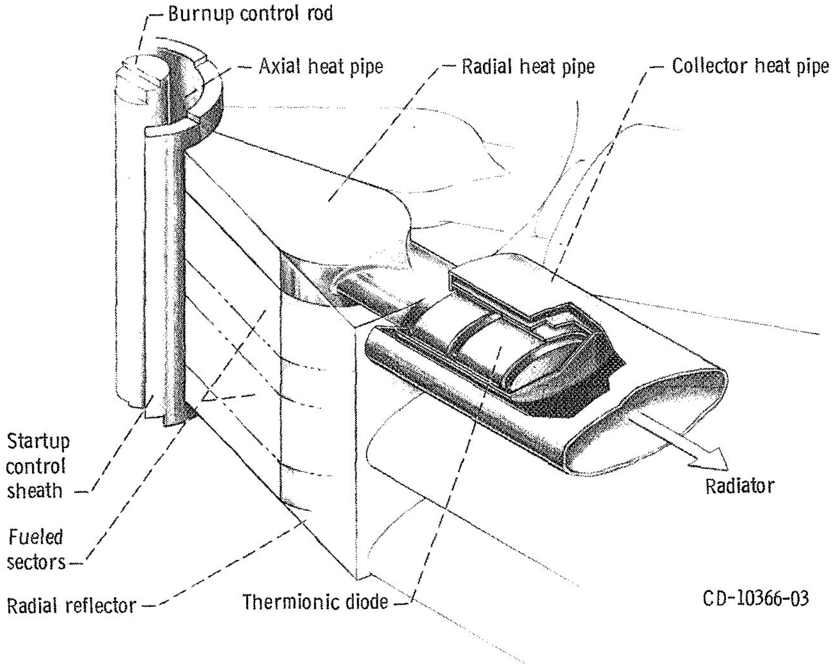


Figure 5. - Cutaway of thermionic space power system using heat pipes.

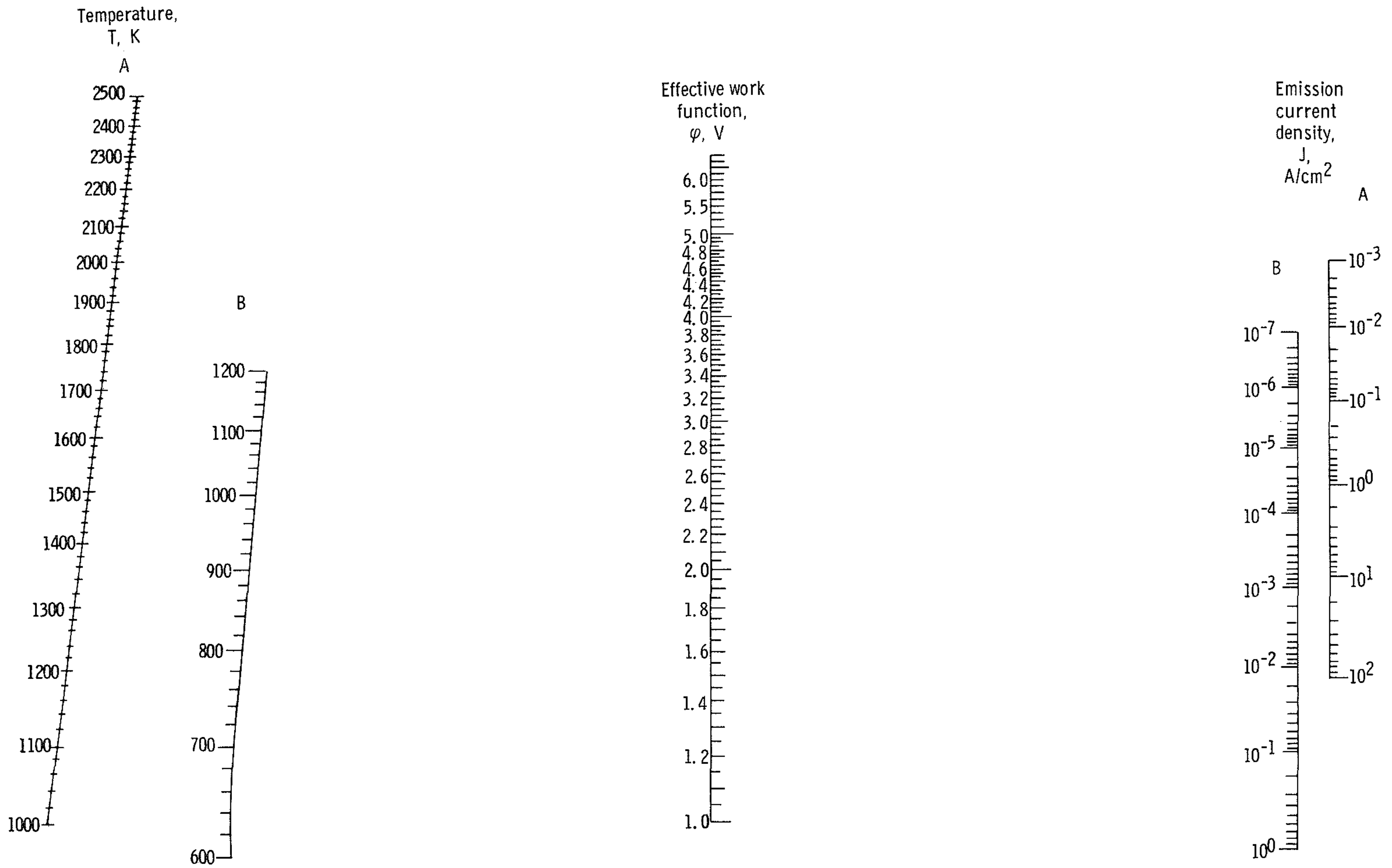


Figure 6. - Emission current density based on the solution of the Richardson-Dushman equation for various effective work functions and electrode temperatures.

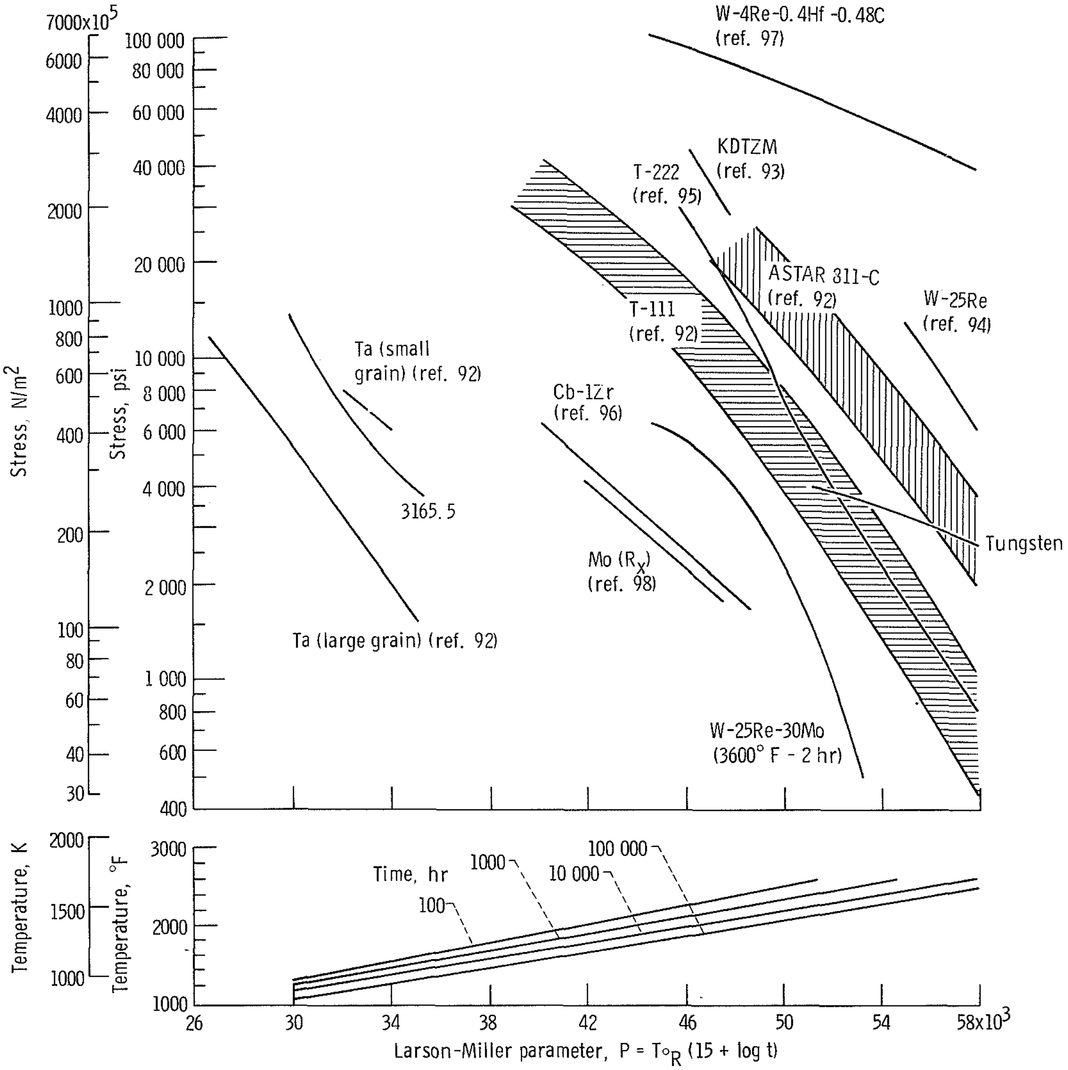
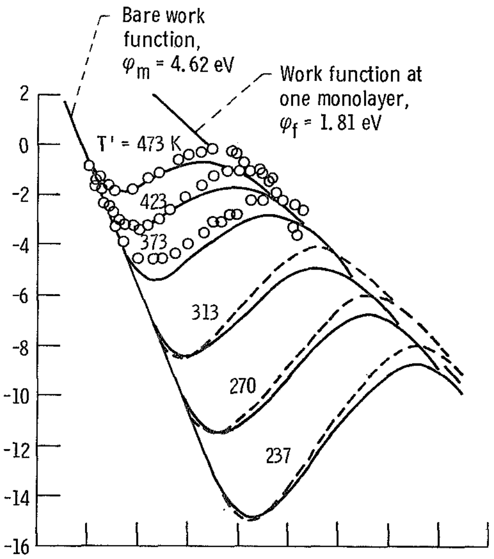
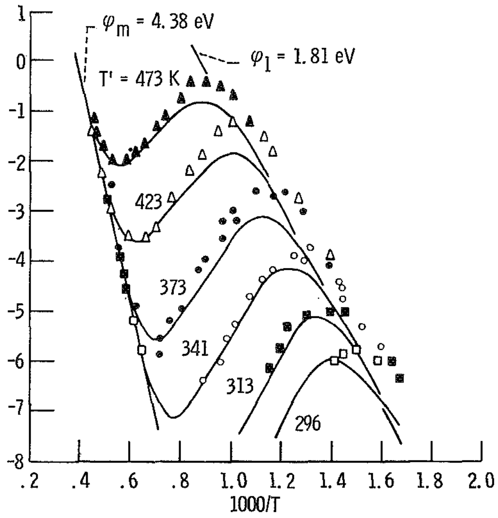


Figure 7. - Larson-Miller plot of 1 percent creep life data for various metals and metal alloys.



(a) Comparison of theoretical S-curves (solid lines) with experimental results of Taylor and Langmuir (dashed lines) and Houston (circles) for the system cesium-tungsten.



(b) Comparison of theoretical S-curves (solid lines) with experimental results of Houston (triangles) and Aamodt et al (circles and squares) for the system cesium-molybdenum.

Figure 8. - Comparison of theoretical S-curves with experimental results. (Data from ref. 19.)

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