PROBLEMS ASSOCIATED WITH THE DEVELOPMENT OF A THERMIONIC CONVERSION REACTOR*

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Abstract

Thermionic conversion of nuclear reactor power is particularly attractive for space applications because of the potentially high conversion efficiencies obtainable, and high heat rejection temperatures. This results in attractive low specific weight electrical generating systems. This paper describes a conceptual design of a 300 kwe thermionic space power reactor with a subsequent discussion of associated development requirements.

I. 300 kwe Conceptual Design

A. The Thermionic Fuel Element

One method of employing the thermionic converter is to integrate it in a nuclear reactor core in such a manner that the fuel material also serves as the cathode of the converter. A typical thermionic conversion fuel element is illustrated in Fig. 1, where a number of thermionic converter cells are shown connected in series. Since each cell is capable of producing a potential of approximately one volt, many cells must be connected in series to produce useful high voltage. Each cell consists of a cathode, an anode, an interelectrode space containing cesium vapor, insulation to provide the proper electrical configuration, and an outer sleeve to isolate the entire element from its external surroundings and provide the structural integrity for the assembly.

The cathodes are solid cylinders of fuel material which are held in place by the insulation separators and the electrical leads in the manner of a filament in a light bulb. Nuclear

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*Presented at the Space Power Systems Conference, Santa Monica, California, September 27-30, 1960. Work done under AEC Contract: AT(11-1)-GEN-8

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heat supplies the thermal energy to 'lift' free electrons at the cathode surface to an energy level at which they are emitted into the interelectrode space. This electron removal of heat from the cathode is accompanied by other cooling processes including radiation to the anode, and conduction of heat through the electrical leads connecting the anodes to the cathodes. These latter two processes are heat losses and must be accounted for in cell optimizations. It may be that the cathodes will have to be clad to prevent deleterious effects caused by the release of the fission products from the fuel. For this conceptual design, however, cladding is not considered.

The anode is a thin cylindrical shell of metallic conductor surrounding the cathode. The electrons which travel to the anode from the cathode are absorbed with the conversion of their kinetic energy into sensible heat. This heat must be removed from the anode to maintain the electrode temperature difference. For good heat transfer the anode must be in thermal contact with the outer metallic sleeve, which is cooled by a liquid metal as is discussed later. In order that the anode of the adjacent cells are not electrically shorted, a layer of electrical insulation must be interposed.

The annular space between the electrodes contains cesium vapor which is ionized by the high temperature environment and serves to neutralize the space charge which is produced by the high electron flux in the interelectrode space.

B. Thermionic Reactor

The thermionic fuel elements are assembled into a close spaced hexagonal lattice to form a 9 inch diameter by 10 inch long cylindrical reactor core. Figure 2 presents the entire reactor assembly which consists of the core composed of converter fuel elements located by an upper and a lower grid plate, a reflector with movable sections for nuclear control, electrical terminals for power output, and a cesium circulation system.

There are two electrical series of the conversion fuel elements in the core; one for the main power output and a series of special elements for supplying the power required by an electromagnetic pump used to circulate a coolant between the reactor and waste heat radiator. There are two cesium reservoirs to serve the two sets of converter fuel elements. These reservoirs are externally located to the reactor so their temperature can be more easily controlled. The reservoirs are connected to one end of each series of elements and the other end is a bleed-off nozzle which is used to continuously release a small amount of the vapor in order to minimize the concentrations of gaseous fission products.

The reflector completely surrounds the core, and can be used for nuclear control because of the high neutron leakage associated with a small fast core. Reflector control is especially useful since this type of control causes only small power perturbations within the core. The reflector consists of three parts: control drums which rotate away from the core to provide continuous control; three safety shutdown slabs which are spring loaded to fall away from the core sides; and a stationary portion which constitutes the end reflectors.

The reactor coolant is the liquid metal, NaK eutectic which is selected because of its good heat transfer properties, high temperature capabilities, and the ability to employ an electromagnetic pump. The use of an EM pump provides operation of a completely sealed system. The reaction vessel has plenum chambers at both ends of the core for proper flow distribution through the channels formed by the converter fuel elements.

C. Auxiliary Equipment

The auxiliary equipment to complete and integrate the system includes the waste heat radiator, pump, control system, payload shielding (if required), and structure as shown schematically in Fig. 3. The NaK pump is of the direct current conduction variety. It was selected because of the convenient source of low voltage high current electrical power is easily supplied by thermionic converters. This pump is used to circulate the NaK through the reactor and out to the radiator where the cycle waste heat is radiated to space.

D. Assumptions for the Conceptual Design

Assumptions of the converter performance are based on a reasonable extrapolation of current experimental data. Table I compares the experimental data with the assumed performance.

In the light of the recent research accomplishments in approaching the emission limited diode performance, the assumed performance values do not appear to be unreasonable. Work at Atomics International has resulted in achieving power densities as high as 18.5 watts/cm^2 at a cathode temperature of 1800°C when the spacing of molybdenum electrodes is 0.005 inch.

Table I

Converter Performance

	Current Experimental Data	Assumed Performance
Efficiency	15%	20%
Power flux	10 watt/cm^2	20 watt/cm^2
Cathode temperature	1700°C (unfueled)	2000°C
Anode temperature	600-700°C	800-850°C
Cesium temperature	275°C	300°C
Gap	0.030 inch	0.020 inch

The reactor criticality calculations are based on a fast one group criticality equation and reflector worths and extrapolation lengths are based on the Los Alamos Godiva and Topsy experiments.

II. Development Requirements

The development of a thermionic reactor is complicated by extremely high operating temperatures and a need to satisfy both the nuclear and electrical requirements. There are a number of very severe problems in the technology which will require significant advances, but none appear to require a major break-through. The scope of this discussion is limited to the thermionic reactor.

A. Materials and Fabrication Requirements

Several requirements exist which apply to all of the materials within the thermionic cells. These are high temperature capability (see temperatures in Table I), physical and chemical compatibility, fabricability and joinability, and ability to withstand thermal cycling and a high radiation environment. Several intercompatibility problems will exist and are due to the extremely high temperatures where vapor pressures of ordinary solids become appreciable and reaction rates between the cell materials may be unusually rapid. Also since insulating materials are involved, which are usually oxides, the problem of disassociation may prove quite important in the presence of cesium. Some of the requirements for each material are enumerated below.

1. Cathode-Fuel Material

The fuel must have a high uranium density in order to result in a compact fast reactor. This is required because of the unusually large amounts of non-fissionable materials in the core required for proper electrical configuration. Long term endurance is usually a specification for space power, so high burnups will be required on the order of 1 to 2 metal atom percent. The dimensions of the fuel cylinders must remain practically time invariant because of the rather high tolerance required on the dimensions of the interelectrode space. Should fuel swelling occur short circuits would result. In order for the cathode not to crack as a result of thermal stresses, the fuel should have a high thermal conductivity and have good strength characteristics at operating temperatures.

A desirable property of the fuel is that it have an optimum work function or a surface capable of being coated with a material with an optimum work function. A particularly interesting fuel material which may fill many of the specifications is UC-ZrC. The addition of zirconium carbide to UC is found to add strength and thus reduce the swelling problem, and to increase the melting point of the fuel.

2. Anode

The anode material should have a high thermal conductivity, low surface emissivity, and a low electrical resistivity. The latter property is important to system weight if there is a high current power output requirement. Anode temperatures in the order of 800°C must be endured for extended periods of time. Nickel plated copper may be able to fulfill the anode requirement.

3. Electrical Connections Between Adjoining Anodes and Cathodes

In addition to conducting the electrical current, the connections support the cathodes. The material must have strength and low electrical resistivity at elevated temperatures. Likely candidates for the connectors are molybdenum, tantalum, tungsten, and possibly rhenium. Connection to the anode will be far less difficult due to the probable metallic nature of the anode and much lower temperatures involved.

4. Electrical Insulation

The insulation between the anode and the cladding must satisfy the operating requirements of: good thermal conductivity; high dielectric strength; fabricability in thin layers; ability to contact anode and cladding surfaces without high thermal resistance; and have a compatible thermal coefficient of expansion with the contacting materials.

Possible candidates for this insulation include aluminum oxide, beryllium oxide, and boron nitride. Probably none of these materials possess all the desired characteristics, so that some compromise must be made in producing a device which has the required lifetime and performance. It appears that one of the most difficult problems lies in the fabrication of the anode-insulation-cladding sandwich since electrical shorts are intolerable and thermal contact resistances must not vary with time. If separations occur between the layers, melting of the anode could occur.

Insulation between the adjacent cells must have high temperature strength since it must directly face the cathodes. Dielectric strength is much less significant for this application since the potential between adjacent cells is of the order of one volt.

5. Cladding Materials

The cladding must have high strength and chemical resistance to both the internal and external environment, in order to maintain structural integrity and isolate the cells from the liquid metal coolant. Fabrication of the cladding in the end areas where the electrical leads and the cesium ducts emerge will undoubtedly be a difficult task.

B. Design Requirements

The specific reactor problem of power flattening is unique to this type of reactor. In a small reactor with a fast spectrum the peak to average power can be as high as 1.8. A series of uniformly fueled thermionic converters in such a flux field would produce electrical power at significantly less than maximum efficiency. Several methods can be employed to remedy this. Electrical power production can be flattened by nuclear means or certain converter characteristics can be altered to improve overall performances. The significant characteristic of nuclear power flattening is to increase core volume and weight. For this reason, its use must be minimized in thermionic reactors which are criticality limited.

The techniques of increasing core performance by thermionic converter techniques are as follows:

1) Converter length can be varied so that each cell can produce total line current at the optimum conditions corresponding to its integrated thermal power input.

2) Heat shielding techniques can be utilized not only to increase equivalent surface emission but to decrease internal cathode temperature differences.

The performance gains resulting from cathode length variations can be easily determined once the characteristics of a converter have been established. The gains resulting from heat shielding will be considerably more difficult to evaluate because the problem depends on such variables as electrode spacing variations, groove geometry, and temperature distribution.

Because minimum weight is the ultimate goal, thermionic space reactors will probably utilize both converter and nuclear methods of power flattening. In higher power systems critical volume will no longer be a limiting factor, and nuclear power flattening will be less costly from a weight standpoint.

III. Growth Potential

Thermionic conversion systems have excellent growth potential, and achievable upper limits on efficiency and specific power are much higher than have been presently demonstrated. Improvements in converter performance will decrease core, pump, and radiator size requirements and permit lighter weight power plants. The reactor specific weight for various size power plants has been estimated and is shown in Fig. 4. Thermionic conversion reactors are estimated to weigh less than one pound per kilowatt for state-of-the-art specific powers of 10 watts/cm^2 and for powers greater than 800 kwe.

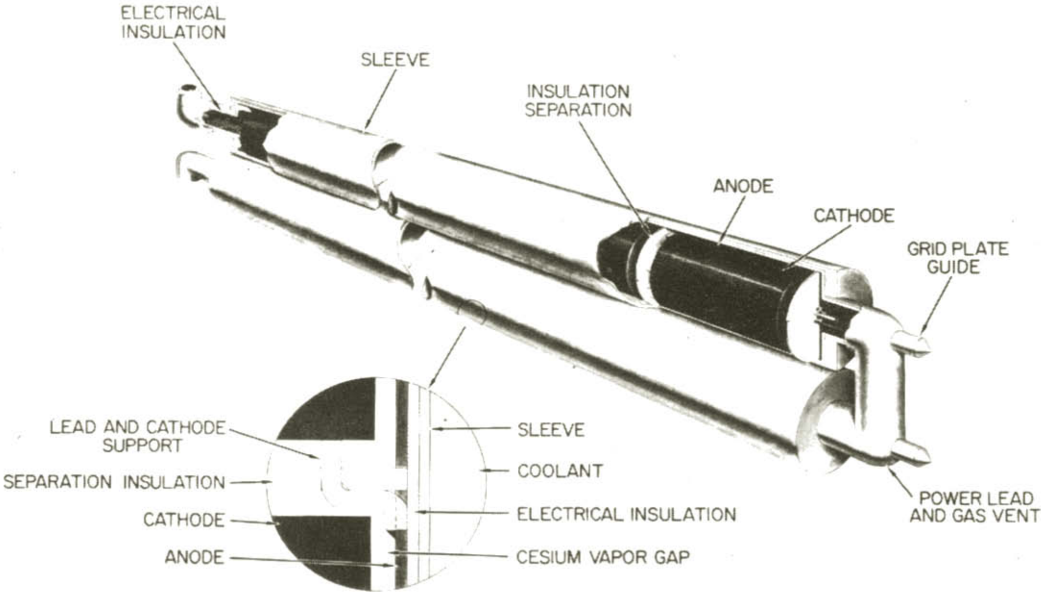

Fig. 1. Thermionic Conversion Fuel Element

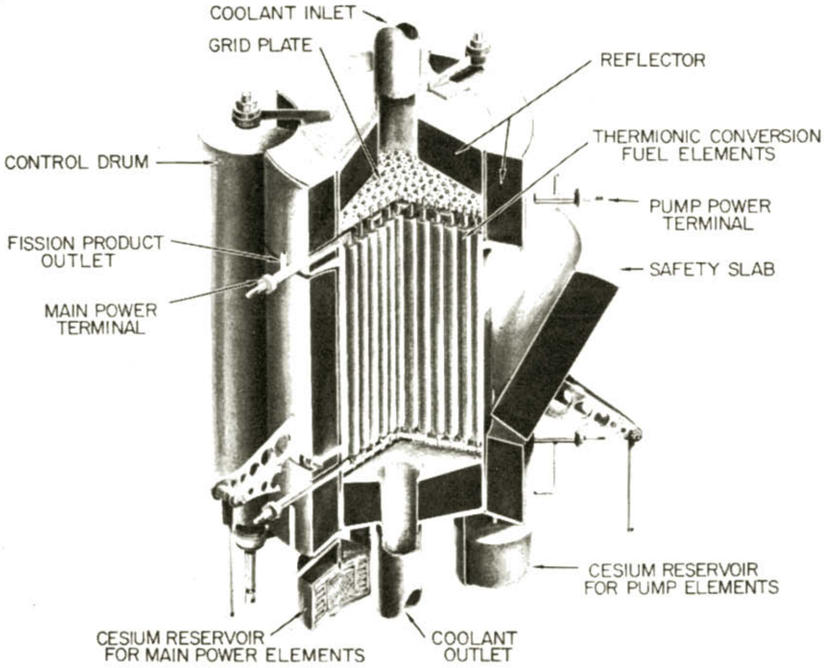

Fig. 2. Thermionic Reactor

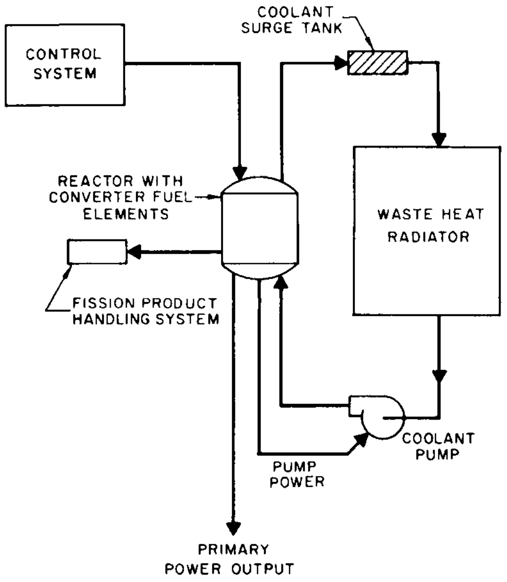

Fig. 3. Schematic Diagram of a High Power Reactor Thermionic Space Power Plant

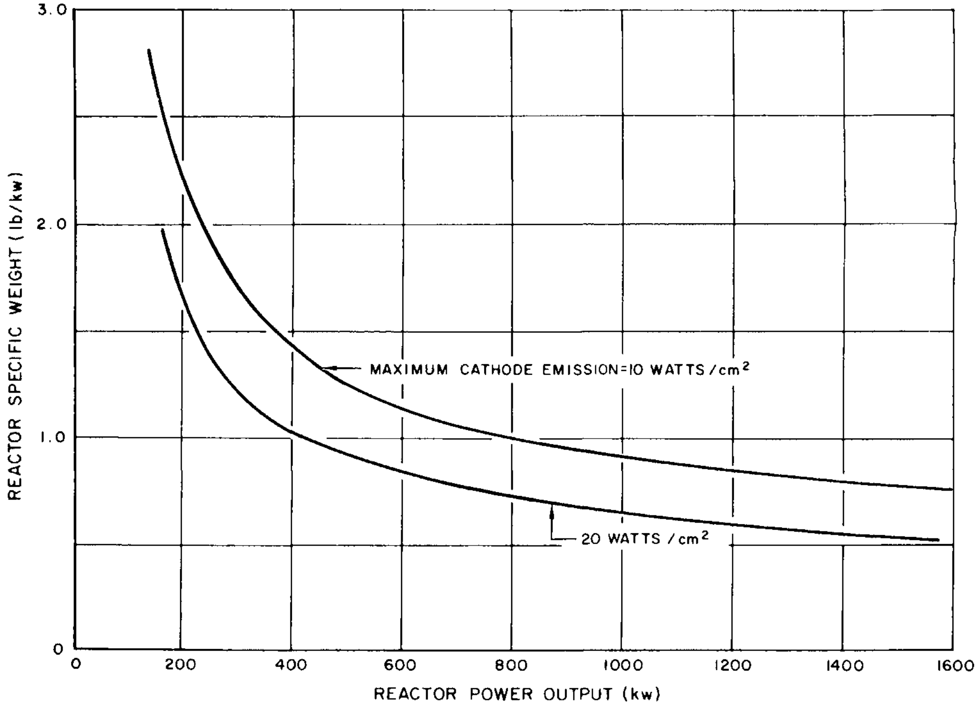

Fig. 4. Reactor Specific Weight vs Power