B-6

EXTERNAL-FUEL THERMIONIC REACTORS*

early
-mid 60s

By

M. J. Abbate, C. L. Eisen, B. Raab, A. Schock
Republic Aviation Division of Fairchild Hiller Corporation
Farmingdale, New York

Abstract

The concept of the external-fuel thermionic converter, in which the fuel surrounds an inner emitter annulus, is introduced and the major advantages of its use in a thermionic reactor are discussed. In-core reactors, ranging from 15-ekW to megawatts, can be designed based on external-fuel converter modules of fixed emitter and collector dimensions. Sizes and weights of typical reactors in this power range are shown.

Introduction

Most in-core thermionic reactor designs are based on internally fueled cells, i.e., the nuclear fuel is contained within a surrounding cylindrical emitter. At Republic Aviation, we have been experimenting with converters and analyzing reactor designs based on externally fueled cells, with the fuel surrounding an inner emitter annulus. The collector-coolant tube is positioned within the emitter. Figure 1 illustrates the cell configuration in cross section. The emitter and collector dimensions can remain fixed for a wide range of reactor power levels; only the fuel thickness and number of cells are changed to satisfy the nuclear and electric constraints for reactors of widely varying electric output.

Among the advantages arising from the external fuel configuration are fuel ventability, low fuel temperature drop, easy power and temperature flattening, low open-circuit temperature rise, simple coolant channel geometry, and high fuel volume fraction.

The inherently high fuel volume fraction capability of the configuration makes it practical to design external-fuel reactors bridging the spectrum from approximately 15-ekW to megawatts.

The externally fueled configuration also permits the design of very long diodes without excessive ohmic loss in the electrodes, a fact which permits a single (double-ended) converter to extend the full length of the reactor core. As

---

* Research supported by the U. S. Atomic Energy Commission

will be seen, this concept permits elimination of the high voltage insulator from the reactor core, where fast neutron damage might seriously degrade its physical properties with time. *

The internal cooling feature also lends itself readily to the use of a heat pipe for collector cooling, as well as to flow-through liquid metal or even water cooling, if this should be desirable, e.g., in laboratory testing.

These advantages will be discussed in greater detail in the following section. This will be followed by a description of the size and weight characteristics of a family of reactors based on the full-length external-fuel concept, with heat pipe cooling. Sample radiator and shield weights are also calculated based on nominal input values of radiator specific weight and shield thicknesses and locations.

Summary of Advantages of External Fuel Design

1. Venting of Fission Products

At thermionic fuel temperatures venting of fission products may be necessary to prevent fuel swelling. The external-fuel configuration permits venting directly into the inter-diode space and thence to space or to a storage condenser.

2. Testing of Fueled Diodes

To maximize the reliability of a thermionic reactor, each converter module will have to be thoroughly tested prior to assembly of the reactor core. It is clearly desirable to conduct these performance tests out-of-pile, by electrical heating, since in-pile testing does not readily lend itself to a routine checkout procedure for large numbers of converters, and also requires subsequent assembly of radioactive modules.

---

* Based on a conception of J. P. Davis of Jet Propulsion Laboratory, Propulsion Research & Advanced Concepts Section.

With the external-fuel configuration, electrically-heated testing of the complete, fueled converters can be readily accomplished by radiofrequency induction. Figure 2 shows a full-length converter under test by rf-heating. *

3. Power and Temperature Flattening

Since thermionic performance is a very sensitive function of emitter temperature, thermionic reactors require a much higher degree of temperature flattening than conventional reactors. To achieve this, internally-fueled designs usually postulate power flattening by compositional variation. In the external-fuel design, flattening can be readily achieved geometrically by varying the fuel volume associated with each diode, since this can be done without changing diode dimensions or performance. As a result, power flattening can be attained with a uniform fuel composition. In addition, the use of full-length converters makes is possible to shape the axial heat generation profile to compensate for heat loss to the emitter leads.

4. Fuel Temperature Drop

Fuel temperature drop is the difference between emitter temperature and maximum fuel temperature. Under certain design conditions for internally fueled cells (large cell diameter or ceramic oxide fuel) this can be excessively high, leading to a design compromise between maximum fuel centerline temperature and emitter temperature. In any practical design, particularly where the fuel is to be vented, the maximum fuel temperature must be limited in order to reduce its volatility and enhance its chemical and mechanical stability.

For given values of fuel thermal conductivity, emitter heat flux, and fuel volume fraction, the fuel temperature drop in the externally fueled design is only

---

* Experimental development supported by U.S. National Aeronautics and Space Administration.

40-50% of that in the internally fueled design. This advantage, which can be demonstrated mathematically, arises simply due to the geometric re-arrangement of heat flow path, since the heat flows radially inward rather than outward.

5. Open-Circuit Temperature Rise

In efficient thermionic converters, electron cooling accounts for a major fraction (> 50%) of the emitter heat flux. Under these conditions, open-circuit failure (e.g., loss of cesium) of an internally fueled diode can lead to an emitter temperature rise of several hundred degrees. Such temperature excursions of a given fuel-emitter subassembly may result in fuel melting and eventual failure propagation.

In the external-fuel diode, the open-circuit temperature rise is substantially reduced by an additional cooling mechanism not available in the internal-fuel designs, i.e., heat transfer to adjacent fuel elements. Radiative heat transfer between the fuel elements is sufficient to limit the open-circuit temperature rise to about $\frac{1}{3}$ of the corresponding value of the internally fueled design. Moreover, an additional reduction of the open-circuit temperature rise can be achieved by providing thermal contact or noble gas atmosphere between adjacent fuel elements.

6. Cell Length

In general, a maximum possible cell length is desired in order to minimize the number of cells which must be series-connected over the height of the reactor core. This is desirable in order to keep unfueled volume to a minimum, to reduce complexity in design and assembly, and to minimize the effect of emitter temperature non-uniformity due to heat conduction in the emitter lead.

The limitation on cell length arises from the build-up of ohmic losses in the electrodes of the diode itself as its length is increased. This not only consumes useful power, but causes different parts of the diode to operate at different voltage points on the I-V characteristic, thereby further degrading power output.

Ohmic losses can be minimized by increasing the thickness (cross-sectional area) of the electrodes, particularly the emitter electrode. In internal-fuel designs, the cross-sectional area of the emitter can be raised either by decreasing its inner diameter, which leads to an undesirable reduction in fuel volume fraction, or by increasing its outer diameter and hence its circumference, which raises the diode current per unit length and diminishes the resultant reduction in ohmic loss. In the external-fuel configuration, by contrast, increasing the emitter and/or fuel thickness does not affect the emitter surface area. Therefore, the electrical conductance can be increased without simultaneously raising the diode current, thus obtaining the full benefit in ohmic loss reduction. As a result, for a given fuel volume fraction and power density, the optimum length for external-fuel diodes is greater than that for internal-fuel diodes, which makes it practical to design and operate a single (double-ended) converter which extends over the full length of the reactor core. The full-length module introduces several advantages of its own:

a) Ceramic seals and leads are located beyond the ends of the reactor core.

b) Fuel-emitter thermal expansion contributes to reactor stability.

c) A high voltage insulator is not needed within the reactor core.

This last advantage can be realized either if a non-conductive coolant is used, if a separate liquid metal loop is used to cool each parallel group of modules, or if heat pipes are used for cooling. The parametric study results presented in the next section are based on heat pipe cooling, although use of the other cooling options yield similar results.

7. Fuel Volume Fraction

Because the fuel is the outermost element, with the largest cross-sectional area, the external-fuel cell will tend to have the largest fuel volume per cell when compared with the internal-fuel cells of similar volumetric power density.

A high fuel volume fraction is especially important in low power systems since these are usually criticality limited. Our studies have shown that the external-fuel configuration permits practical designs with fuel volume fractions of over 80% by the use of full-length diodes, and volume fractions of more than 65% with stacked diodes. Thus, criticality can be achieved in extremely small reflected core volumes since such cores are virtually homogeneous blocks of fuel pierced by a number of small holes containing converters. This makes it possible to design an in-core thermionic reactor with fewer than 20 converter modules, which would produce 10-to-15-ekW.

Higher power reactors are not so clearly limited by criticality requirements. However, the high fuel-volume fraction possible with the external-fuel design results in an enhanced capability for power flattening by fuel distribution, and also permits a wide latitude in choice of fuel itself, either as to isotope(U-233, U-235), composition, enrichment, diluent fraction (e.g., high metal-fraction cermets), or the possible addition of resonance absorbers to enhance stability by increasing the fuel Doppler coefficient.

Heat-Pipe Cooled System

The simple cylindrical coolant channel realized in the external-fuel design makes it practical to consider the use of heat pipes for collector cooling (Figure 3). In order to keep the heat pipe diameter small and thereby limit the core volume devoted to the coolant space, the effective length of each pipe is minimized by introducing a liquid metal heat exchanger at each end of the reactor. The condenser ends of the pipe extend into the heat exchanger tubes and are cooled by a cross-flowing liquid metal (e.g., NaK). In this design option, the high voltage insulator is in the heat exchanger section where fast neutron flux is considerably reduced.

The designs were based on an axial heat transfer limit imposed by the vapor flow speed. Although vapor speeds approaching Mach 1 have been achieved in high-performance heat pipes,(1) the designs were conservatively based on a limiting vapor speed of Mach 0.3.

In order to permit a broad survey of large numbers of design variables to see how these effect reactor size and weight, a computer program (PASER) was constructed which optimizes converter electrode dimensions to minimize overall system weight. In any one calculation diode length is specified so that the optimization in effect produces the minimum core diameter consistent with the specified output electric power and number of converters. Diode length and number of converters are then varied in discrete steps for given output electric power, thereby covering the complete range of system variables at the disposal of the designer.

In order to permit the analysis of a large number of cases a number of simplifying assumptions were made in the PASER program:

1. Critical size was assumed to be a function only of fuel volume fraction; the variations in volume fractions of the non-fuel materials were assumed to be of secondary importance.

2. A large number of one-dimensional 26-group neutron transport calculations were run to determine radial and axial reflector savings and geometrical buckling for the necessary range of fuel volume fractions, with other materials being represented in typical volume fractions. These calculations were then correlated and used to determine critical core size in the parametric survey calculations.

3. Emitter temperature was taken to be constant over the length of the diode and emitter lead was optimized for maximum efficiency.

4. The diode current-voltage characteristic was taken to be a straight line tangent to the point of maximum power.

With these assumptions, converter internal losses are accurately taken into account both as to ohmic dissipation and as to variations in local voltage along the length of the converter. The program then proceeds to optimize emitter diameter, emitter thickness and collector thickness for minimum system weight. Both radiator weight and shield weight are calculated based on the following assumptions:

Radiator specific weight = 1.15 kg/m^2 (2 lb/ft^2)

Radiator emissivity = 0.84

Shields: 5.08 cm tungsten
96.4 cm LiH

Shielded angle = 15 degrees

Among the more significant results of the survey is the finding that, at least for systems in the submegawatt power range, optimum converter length is in the range of 20-to-25 cm. It was also seen that decreasing the emitter diameter of each converter (and hence the power per converter) and increasing the number of converters invariably resulted in a decrease in overall system size and weight.

These findings are illustrated in Figure 4 for the 360-ekW system. It can be seen that for emitter diameters greater than 1.15 cm, a converter approximately 23 cm in active length is optimum. This optimum is a broad one; the weight penalty paid for a 20cm converter length for a fixed total number of converters is less than 1 percent.

Converters of approximately 1.25 cm in emitter diameter and 20 cm in length have been built and successfully tested in the laboratory; however, for conservativeness in mechanical design the reference designs selected at the various power levels are based on converters with emitter diameters in the range of 1.5 to 1.75 cm. The results for systems ranging from 15 to 3600 ekW are shown in Table 1.

It should be noted that all of the systems could be designed with modules of identical size; this would merely result in slightly off-nominal output power at each power level.

More exact design calculations done at the 360-ekW power level, which take into account the actual emitter temperature distribution and true converter current-voltage characteristic as well as more precise nuclear calculations indicate that the PASER calculations result in an underestimate of system size and weight by some 3-to-6 %. From Figure 4 it can be seen that this can be compensated by a decrease in emitter diameter to the range of 1.2 to 1.3 cm, if desired.

Conclusions

External-fuel thermionic reactors are seen to offer a number of design advantages over the more common internal-fuel designs. Static design calculations illustrate the extreme flexibility of the concept in satisfying a wide range of power requirements without variation in converter design. This makes it practical to build and prove the feasibility of an in-core thermionic reactor at a modest power level and to confidently extrapolate the experience so gained to larger, more costly, systems.

References

(1) KEMME, J., "High Performance Heat Pipes," Thermionic Conversion Specialist Conference, Palo Alto, California, 1967.

Table 1. PASER-Calculated Reference Designs -- Heat Pipe Cooled Systems

Output Power (ekW)	15	30	60	360	1200	1800	3600
No. of Diodes	18	36	90	468	1386	2106	4920
Active Diode Length (cm)	20.3	20.3	20.3	22.9	22.9	22.9	22.9
Emitter Diameter (cm)	1.74	1.74	1.50	1.62	1.75	1.74	1.57
Heat Pipe ID (cm)	0.980	0.980	0.890	0.955	1.00	1.07	0.935
Power Per Diode (watts)	833	832	666	769	865	854	731
Net Efficiency (%)	11.1	11.1	11.0	10.9	11.0	11.0	10.9
Fuel Volume Fraction	0.813	0.720	0.629	0.397	0.33	0.319	0.307
Core Diameter (cm)	22.1	25.1	29.7	57.1	100	122	167
Core Volume (cu. M)	0.0079	0.010	0.014	0.059	0.18	0.27	0.50
Uranium Inventory (kg)	50	58	71	190	483	6884	1231
Core Mass (kg)	74	97	132	524	1721	2512	4615
Reactor Mass (kg)	322	383	477	1376	3677	5196	9194
Shield Mass (kg)	569	624	708	1378	2720	3571	5755
Radiator Mass (kg)	24	49	99	593	1994	2996	6059
Total Mass (kg)	915	1056 ↓	1284	3347	8393	11764	21008
Burn-up (a/o per yr.)	0.105	0.185	0.308	0.710	0.862	0.914	1.08
Volts	3.6	7.2	18.0	47.0	70	108	123

Emitter Temperature = 2000°K
Collector Temperature = 1000°K
Cesium Reservoir Temperature = 620°K

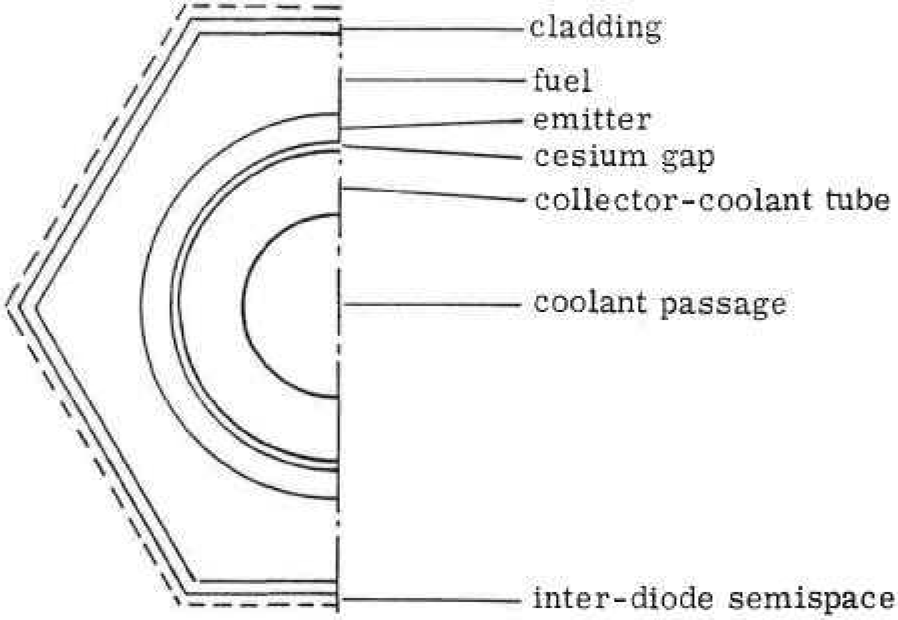

Figure 1. Externally fueled cell in Cross Section

Figure 2. External-Fuel Diode Under Test by RF-Heating

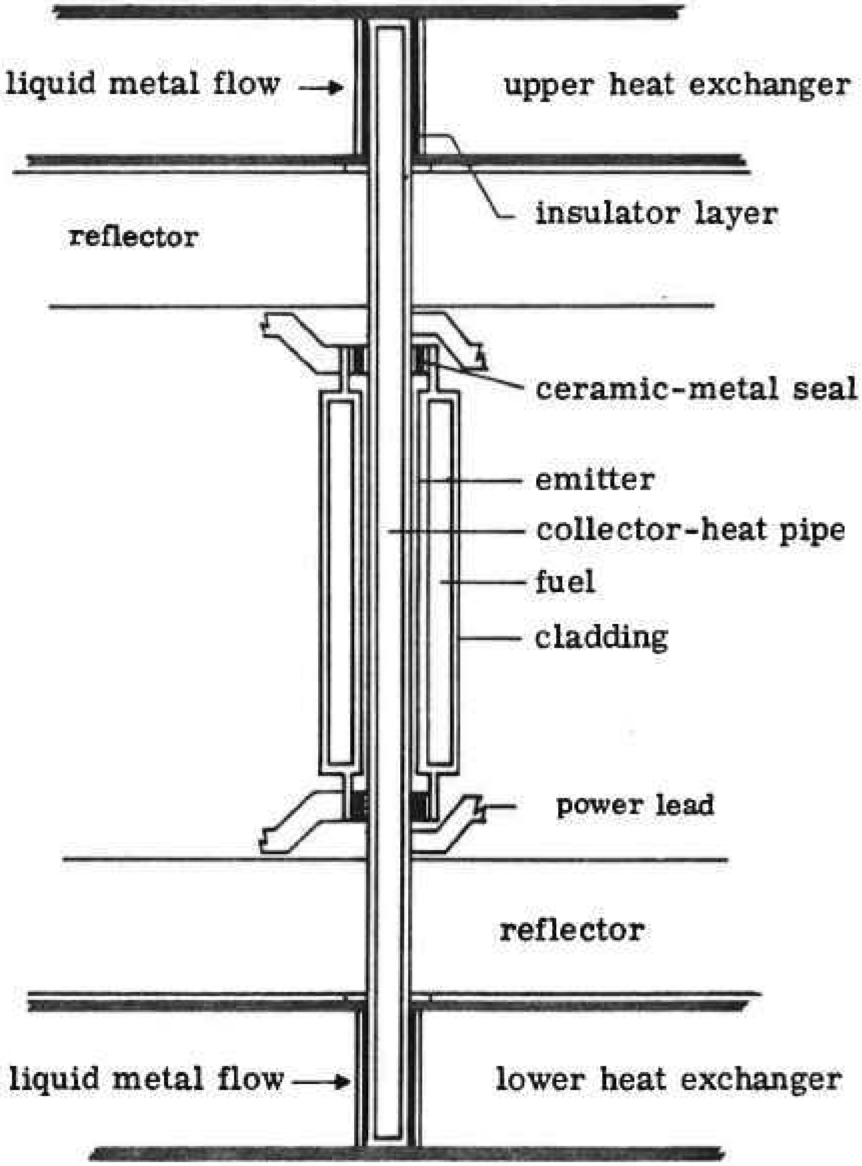

Figure 3. Schematic Drawing of Heat-Pipe Cooled Full Length Module

DISCUSSION

Speaker of paper B-6: A. SCHOCK

BUSSE (Euratom):

Mr. SCHOCK presented the interesting external fuel-concept with a quite impressive list of advantages. I would like to ask him if he could comment also on the disadvantages of this concept. In what way would this concept be inferior to the normal concept with interior fuel?

SCHOCK (USA):

First, the fuel element geometry is more complicated and therefore is more difficult to make. Hexagon fuel elements with a hole have been made of course but it is not quite as easy as making a simple cylindrical element that expands outward. Another problem occurs with the full-length diode. If one gets into megawatts power, or above, one must stack the core. The advantages of the external fuel concept are not so clear in this case.

DAVIS (USA):

I would like to add a few comments. I think that one of the major uncertainties in this design concept is the long term maintenance of the inter-electrode gap and spacing between modules for these relatively long 8 to 10 inch diodes. Also at least as far as our analysis is concerned, these diodes are not exactly "Ferraris" in performance; there are some losses due to the increase in I^2R performance degradation of both the emitter and the collector. In general I think their performance is somewhat below what could be achieved by much smaller internally fuelled diodes. But the penalty is not profound.

GROSS (Germany):

Mr. SCHOCK said that the fuel is not overheated because you concentrate the heat, but can you give some data on the radial heat fluxes along the fuel which you expect. Secondly, you said that the ceramic-metal seal is not inside the neutron flux. Looking at your figure 3, I would expect that high fluxes of fast neutrons would be just there, where your metal-ceramic seals are.

SCHOCK:

Let me answer the second question first. I said that the high voltage insulator, that is the insulator that sees the reactor voltage rather than the individual diode voltage, is outside of the core. With regard to the first question, our emitter heat flux is the same as everybody else's emitter heat flux; of course the heat flux becomes smaller as you get further away from the emitter. It is not obvious, but if you go through the mathematics, you find that for a given fuel volume fraction and a given fuel conductivity and a given emitter heat flux, the ΔT in the fuel is about half as much when you go from the outside to the inside as the other way round.