NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum No. 33-262

Review of Industry-Proposed In-Pile Thermionic Space Reactors

Volume I. General

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D. R. Bartz, Manager
Research and Advanced Concepts Section

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FOREWORD

This work is one phase of a general review of industry proposals for in-pile thermionic space reactors. The survey was conducted for the National Aeronautics and Space Administration by the Energy Sources Group of the Propulsion Research and Advanced Concepts Section.

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ABSTRACT

This Memorandum, which is part of a three-part survey of industry-proposed in-pile thermionic reactor concepts and potential nuclear fuels for space application, summarizes the present status of development and the problem areas associated with design. For a given fuel and at low power levels – less than 200 kw(e) – the externally fueled concept, by virtue of its high attainable fuel-volume fraction, results in smaller cores than the flashlight or single-diode internally fueled concepts. At higher power levels the differences are less pronounced. None of the potential nuclear fuels for thermionic reactors have yet demonstrated the burnup capability required for high-power, long-life systems. Volume II of this series gives a more detailed review of thermionic reactor physics; Volume III surveys materials and nuclear fuels applicable to thermionic systems.

I. DESIGN CONCEPTS

A. Introduction

This Memorandum reviews industry-proposed in-pile thermionic reactor concepts for space powerplant application. Because the continuing development of thermionic diodes results in a design becoming obsolete in its details in a short time, the emphasis is placed on design philosophies. Volumes II and III (Ref. 1, 2) of this review give extended accounts of the reactor physics and nuclear fuels, respectively. The main conclusions given in Ref. 1 and 2 are included here. Overall plant design concepts have not received detailed investigation in this Memorandom series. The relative merits of various reactor proposals are discussed, based on information available up to August 31, 1965.

The emphasis on reactor physics and the materials properties is motivated by the unique problems encountered in thermionic reactor design in these areas. Figure 1 illustrates the system components, main interconnections, and fields of analytical study involved in a complex plant design.

One of the major obstacles is the difficulty of developing reliable, long-life diode elements, as witnessed by the abundance of reports dealing with the subject. The development status is presently such that a selection of the "best" design approach cannot be made today and must await further tests and development. However, in view of the considerable progress made during the last two

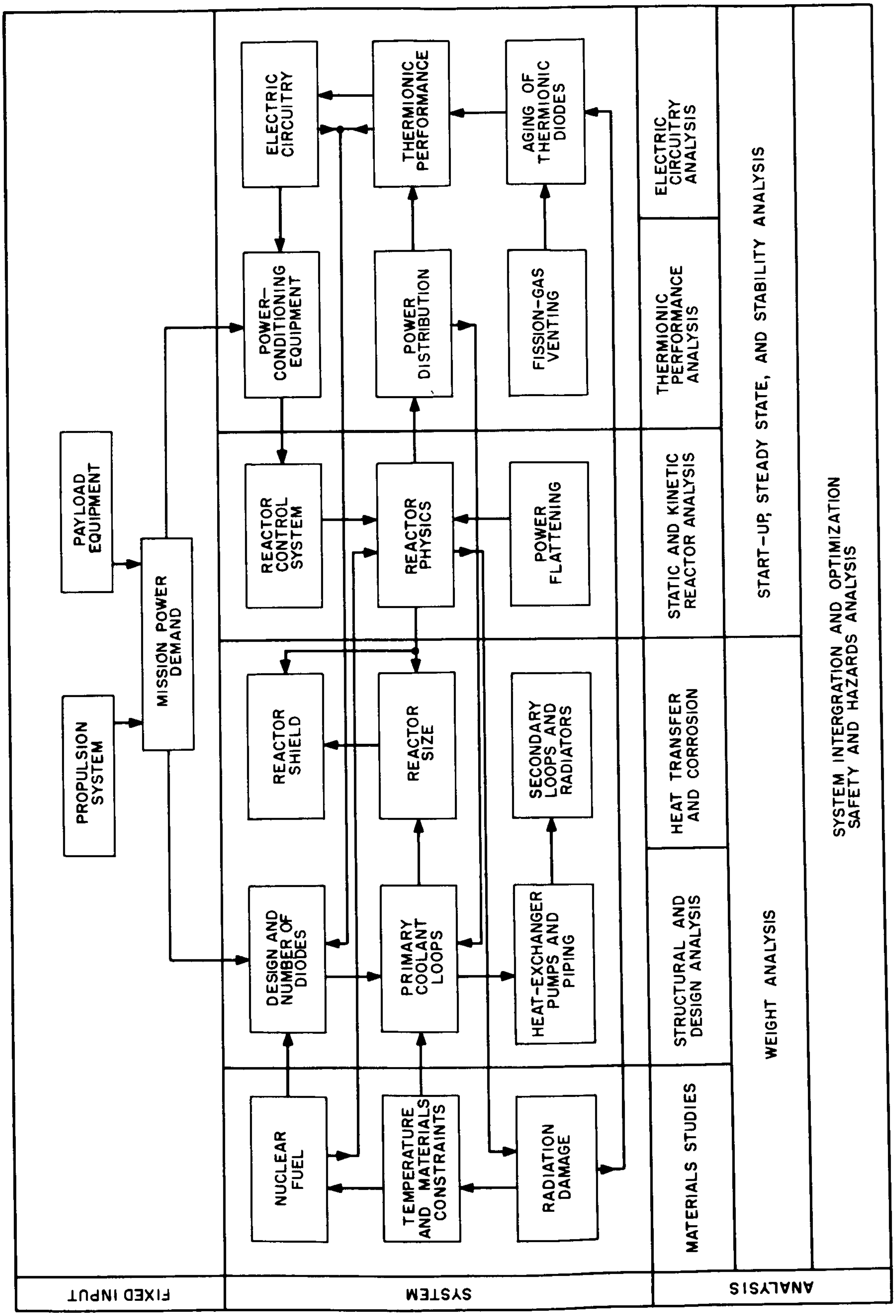

Fig. 1. In-pile thermionic system evaluation

years, the solution of current problems can be hopefully —and realistically—assumed.

In view of the uncertainties connected with thermionic diode design details, reactor physics investigations by various organizations naturally have been somewhat superficial. It is now fairly well recognized that important design feedback is provided by the requirements of integration into a reliable and efficient reactor core. Particularly, overall system stability must be studied, the results of which may have substantial influences on reactor and diode design. Since a dynamic analysis is presently lacking, only general speculations can be given.

B. Diode Design

The companies listed in Table 1 have proposed reactor designs complete enough to make some comparisons possible, at least with respect to design approach. In addition, several other organizations have studied thermionic diode design and performance.

Table 1. Industry-proposed in-pile thermionic reactor designs

Company	Design concept
Atomics International	Flashlight: Converted SNAP 8 reactor
Douglas Aircraft	Flashlight: 5-Mw(e) design study
General Atomic	Pancake: Single diode, coolant cross flow
General Electric	Flashlight: STAR C
Martin	Flashlight: 100-kw(e) design study
Pratt & Whitney	Flashlight: General parametric survey
Republic Aviation	Externally fueled concepts

Table 1 also gives the popular designations of the design concepts, which fall into two main categories: the internally fueled and the externally fueled concepts. The former places the nuclear fuel in the center and the diode structure around it. The emitter area per unit length is therefore determined by the fuel. The externally fueled concept places the diode structure around a central coolant channel with the nuclear fuel concentric and external. Here the emitter area is determined by the coolant channel radius. A further subdivision of types is provided by classifying the mode of electrical coupling: a series-stacked module (flashlight), or a single-diode module (pancake). In principle, either external or internal fueling can be employed, but practical considerations impose limitations. Referring to Fig. 2, which shows the three main diode types considered practical, one can infer the following design connections between fueling, cooling, and electrical coupling:

1. Since electrical losses put an upper limit on the diode length, a coolant cross-flow mode is natural for the single, or double, internally fueled diode. Axial coolant flow surrounding the diode structure gives an impractically flat reactor or, if diodes are stacked, leads to the flashlight concept. A radial cooling mode gives cross-connection possibility, which limits the power loss caused by casualty short and open circuits (Ref. 3). The price for the possibility of cross connections and the simplicity of a single-diode design is paid in the form of low fuel-volume fraction in the reactor and some complication and nonuniformity of coolant flow.
2. Stacking the diodes in series and eliminating electric cross connectors between individual diodes gives a compact assembly leading to increased core fuel-volume fraction. This arrangement results in the loss of the whole chain, should an open-circuit failure occur. Axial coolant flow is natural in this design. The complexity of the interconnecting electrodes introduces serious concern for the reliability of the structure. Another disadvantage is the limitation on venting of fission gases. The single-diode (pancake) design permits individual venting and, hence, logically mates with a vented fuel. In the flashlight concept the most direct approach is venting through the cesium-gas circuit, the effects of which are unknown at present. An unvented fuel, which may also mean a limited burnup, is therefore a logical choice, although it has been claimed that venting through the cesium space need not appreciably reduce the performance. This is still to be verified experimentally.
3. The externally fueled concept can adapt to either vented or unvented fuels; however, thermal expansion compatibility between fuel and emitter makes a cermet fuel most amenable to a simple design concept. The fuel-volume fraction is flexible, which is particularly useful in the design of the smaller criticality-limited reactors.

The above considerations indicate that diode design, fuel, and reactor concept are not totally interchangeable. In the proposed designs, several other factors have been considered, such as open-circuit-associated temperature rise in the fuel, testability, temperature flattening, and general reliability—the latter, particularly, receiving much discussion. So far no in-pile-tested module has shown high reliability, and some performance degradation is observed. On the other hand, the nature of the thermionic concept is such that it can withstand some failures. A 20–30% excess power capability is perhaps a reasonable estimate and with suitable electrical connections the consequences of a diode casualty are minimized.

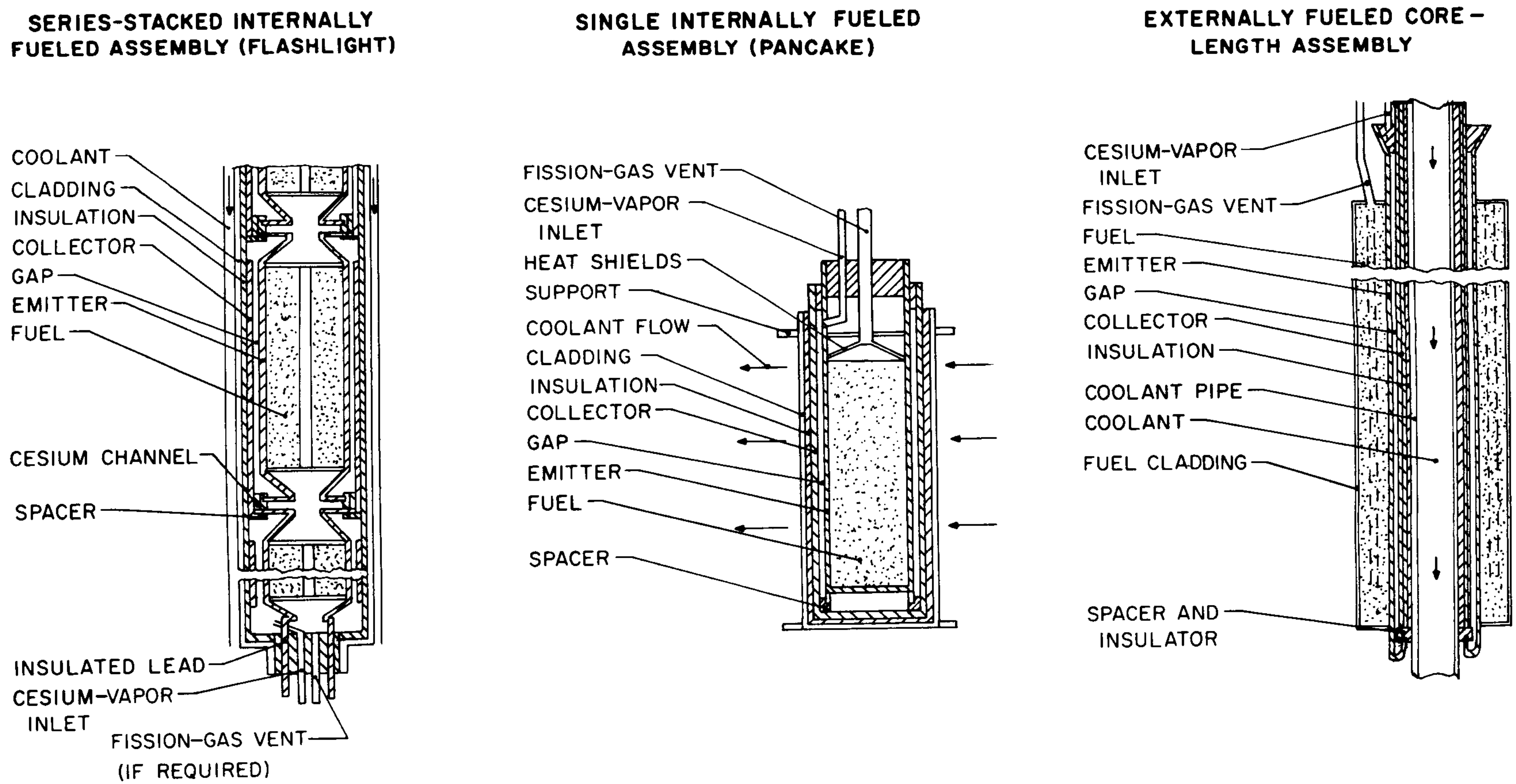

Fig. 2. Design principles for series-stacked, single, and externally fueled thermionic modules

The preceding discussion points out the primary general uncertainties. In addition, there are numerous specialized problems, which are more fully discussed in Volume III of this series (Ref. 2). It is obvious that each design concept has its strong and weak points. For instance, there might be reservations against the flashlight concept because of design complexity and nuclear-fuel constraints, but considering the progress to date one cannot rule it out as noncompetitive with the single-diode concepts.

Were it not for the limited choice of nuclear fuel that exists today, one would be biased to choose the externally fueled concept over the internally fueled one, since it offers greater flexibility and has several other desirable advantages (Ref. 4, 5). It is to be noted that originally several investigators studied the externally fueled concept, but abandoned it mainly because of presumed problems in finding a high-temperature insulator. Republic Aviation, which is the only company presently advocating the externally fueled concept, recommends designs circumventing this particular problem.

C. Reactor Design

Integrating the flashlight, single-diode, or externally fueled concept into a critical assembly leads to three types of reactor cores, illustrated in Fig. 3. Criticality, control, stability, and power flattening must be assured by proper design. The usual strategy is to iteratively approach a weight-optimized reactor considering criticality and power-flattening constraints only. However, a close investigation reveals that the unique power-producing mechanism in a thermionic reactor requires that stability considerations be considered from the outset of the design work. Some details of these aspects are discussed in Volume II of this study (Ref. 1).

Attempts have been made to express the main design parameters in the form of generalized analytical relationships, thus portraying inherent limitations and possibilities in in-pile thermionic reactor design. Such considerations are interesting, but are necessarily biased towards a particular design as part of parametric surveys. The broad spectrum of alternatives originally thought to exist has been narrowed down by experimental information obtained, but many problems remain, the most serious of which are connected with the need for a long-life diode. With the exception of power-conditioning equipment, which has developed into a substantial item [~ 5 lb/kw(e)], reactor structure and other system component information can be drawn from the work done for liquid-metal Rankine-cycle systems in spacecraft application.

It is of interest to note that as electrostatic thrustors provide a better match to Rankine-cycle systems (high voltage, low current), so do thermionic systems naturally match with electromagnetic thrustors (high current, low voltage). The potential weight saving in power-conditioning equipment is substantial if electromagnetic instead of electrostatic thrustors are used.

Ultimately the "best" design has to be determined from such difficult-to-establish criteria as reliability, lifetime, weight, and safety. The analytical and experimental information available at present is insufficient for a rational selection of a "best" design or even design concept. In particular, stability and safety constraints must be investigated for each proposed concept. Such studies are being pursued by several organizations, but only preliminary data are available.

Table 2 summarizes some design data. Although the quoted values are subject to change, they illustrate design approaches taken. The listed system weights should be viewed only as gross estimates. It appears, however, that cycle efficiencies of 8–12% with system specific weights of 30–20 lb/kw(e) are possible at power levels in excess of several hundred kw(e). Reactor (core plus reflector) specific weights account for 20–30% of the total system weight.

D. Reactor Physics

Despite the uncertainties in design details, some general comments can be made with respect to the reactor physical problems for an in-pile thermionic assembly. Weight and structural materials constraints make a fast, liquid-metal-cooled system most feasible. Nuclear fuel and reflector material mostly determine the critical loading, while structural components have a lesser influence. A small fast reactor has high neutron leakage, making reflector control possible. This is further aided by the fuel distribution needed for a uniform heat-generation profile, which requires increased fuel concentration towards the core boundaries.

In the criticality-limited low-power systems [<200 kw(e)], there may not be enough loading margin for appropriate fuel zoning. Atomics International, who has proposed a design based on SNAP 8 with the hydride elements replaced by thermionic assemblies (Ref. 6), finds that in this case variable diode length is necessary to obtain electrical matching to the core performance. However, this design incurs penalties because it was not originally evolved with thermionics in mind.

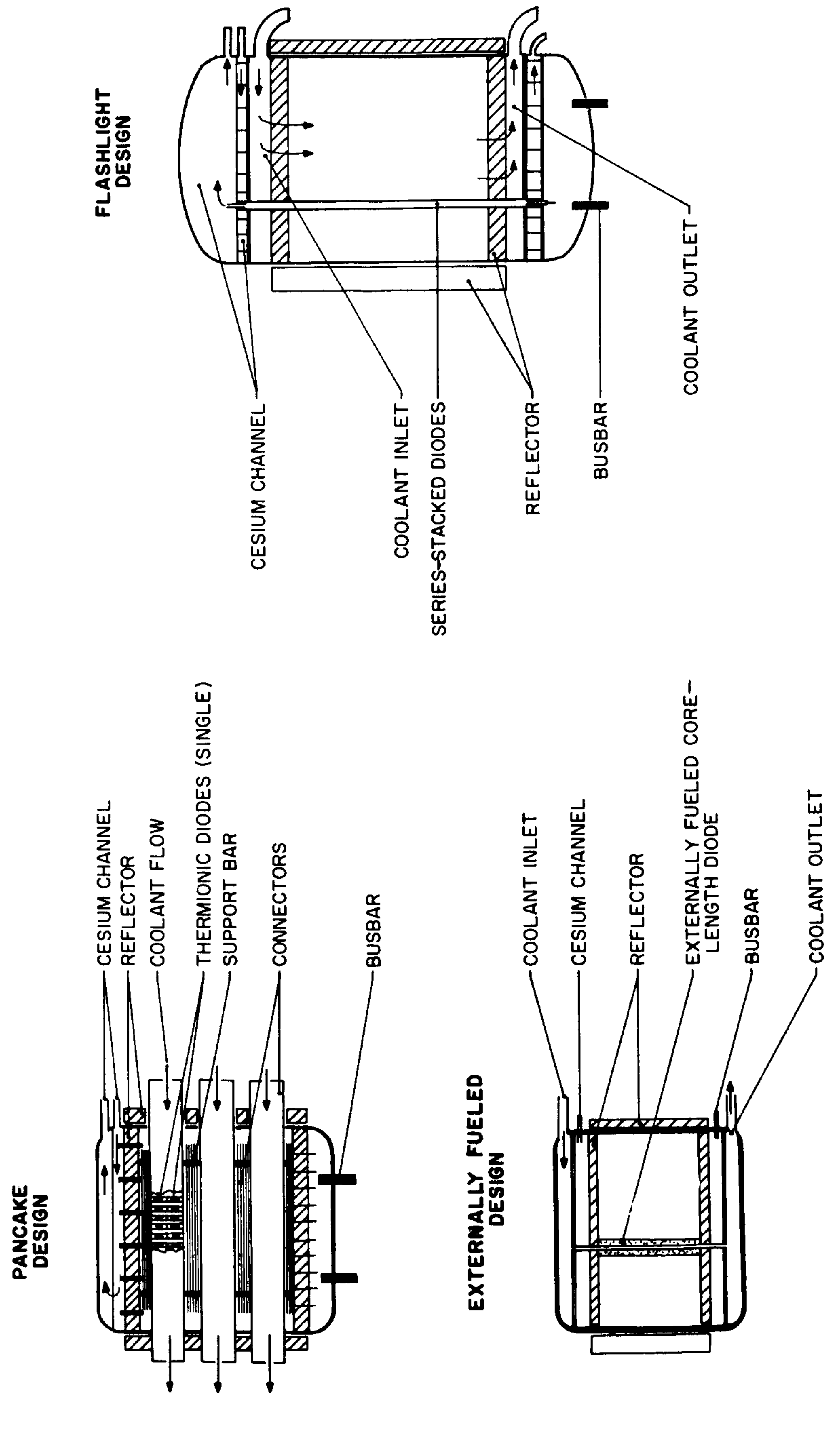

Fig. 3. In-pile thermionic reactor designs

Table 2. Comparison of industry-proposed in-pile thermionic systems

Company	System: Performance: Output, kw(e)	System: Performance: Efficiency, %	System: Specific weight, lb/kw(e)	Reactor: Thermal power, kw(th)	Reactor: Core: Diam., in.	Reactor: Core: Length, in.	Reactor: Reflector thickness, in.	Reactor: Fuel loading, kg U^{235}	Diode: Average current, amp/cm^2	Diode: Average power, w(e)/cm^2	Diode: Emitter temperature, °F	Diode: Collector temperature, °F	Comments
General	80	7.3	6.60	1,100	9.3	9.6	2.0	55	11.7	6.35	3300	2000	Pancake design with radial
Atomic	230	6.9	5.13	3,330	12.0	12.6	2.0	80	16.5	7.18	3300	2000	coolant flow
	2,000	7.4	4.34	27,000	23.3	21.6	2.0	187	15.2	7.25	3300	2000	Individual diodes with
			(not all				BeO	Uc-ZrC	W emitter		Area	14 cm^2	internal fuel
			of						Spacing			10 mils	Nb collector
			system)						Cs temperature			623°K	Al_2O_3 insulators
General	1,100	11	5.0	10,000	19.4	20.1	2.0	UO_2	10.6	7.0	3400	1600	20 diodes in "flashlight"
Electric			(not all				BeO		W emitter		Area	8.5 cm^2	Power flattening with fuel
			of				Radially		Spacing			7 mils	zoning and reflectors
			system)						Mo collector				Al_2O_3 insulators
Douglas	5,500	16.8	19.4	32,800	39.4	39.8	4.0	60 vol. %	5.7	6.2	3490	1810	20 diodes in "flashlight"
Aircraft			(for				Al_2O_3	UO_2-W	W emitter		Area	20.4 cm^2	Mo collector
			total				Radially	cermet	Spacing			10 mils	Al_2O_3 insulators
			system)						Cs temperature			610°K	Planned for manned mission
Martin	100				21.1	26.0	3.0			2.0			13 diodes in "flashlight"
Co.							Radially						Power flattening with fuel
							4.0						zoning, reflectors, and
							Axially						YHx moderator
							BeO						Peak/minimum ratio — 1.10
Pratt	1,000	9.16	10.5	9,160	24.0		2.0	292	6.64	5.32	3200	1330	Diodes in "flashlight"
&	2,500	11.9	22.9	27,300	43.0				4.09	3.23	3200	1750	configuration
Whitney	3,990	11.9	22.2	33,400	38.8	36.1	2.0	1150	6.16	4.42	3200	1780	Power flattening with fuel
	5,000	9.9	21.6	50,700	50.0				4.56	3.60	3200	1770	zoning on reflectors
	10,000	9.2	24.7	109,000	67.8		BeO	UC	4.12	3.25	3200	1730	Nb collector
									W-25 Re emitter				BeO insulators
													Spacing, 20 mils
Republic	1,000	10	4.4	10,000	34.5	8.4	4.0	565	15.65	12.2	3200	1400	Core-length diode externally
Aviation			(reactor				Radially	UO_2-W	Rh emitter			55 cm^2	fueled
			and				2.4	cermet	Spacing			12 mils	Power flattening by fuel
			reflec-				Axially		Mo collector				zoning and reflectors
			tors				BeO						Al_2O_3 insulators
			only)										

Compared to a flat power profile, the losses in electric output reach 50% if no attempts are made to match electric conversion with reactor design. In an in-pile thermionic system, reactor physics and diode design are intimately associated for an optimized system.

Techniques other than fuel zoning may be employed for power flattening. Moderator material may be introduced in zones, or the amount of nuclear fuel associated with each diode may be adjusted to give heat fluxes leading to uniform emitter temperatures throughout the core. Varying the fuel associated with a diode is more feasible for the externally fueled diode design because the diode electrode design can remain the same in all diodes. In the internally fueled design, the radii of the electrode structure would have to be adjusted. The desirability of adding some moderator material depends on the individual reactor concept. A softened neutron spectrum resulting from employment of a moderator generally increases the resonance absorption and the Doppler effect. This may be a desirable feature, but must be analyzed for each situation. Considering that a prompt-negative-temperature coefficient does not seem to exist adequately in a thermionic reactor, careful reactor-physics investigation is a prerequisite before further judgment can be passed on the relative reactor-physics merits of various design proposals.

II. NUCLEAR FUELS

A. Introduction

At the present time, available data on thermionic diode performance do not allow any definite conclusions to be drawn on the effect of fuel on cell performance. Both fueled and unfueled diodes have suffered from degradation problems. The tentative conclusions regarding fuels for in-pile thermionics must presently be based on data other than that obtained from thermionic diode tests.

Each of the three fuels under consideration at the present time, UC alloys, pure UO_2, and UO_2 cermets, presents its own set of unique problems.

B. Uranium Carbide

In the work reported in Ref. 7, Battelle Memorial Institute has found that UC has good chemical compatibility on a gross scale with tungsten and tungsten-10Re, but is incompatible with tungsten-25Re and molybdenum. Thermodynamics would predict incompatibility between tungsten and UC; however, it appears that the free energy of formation is not adequate to drive the reaction.

General Atomic has concluded that 3% excess carbon in UC is needed to obtain compatibility with tungsten. It is not clear that this is really required except to ensure against substoichiometric UC. Similarly, the addition of alloying constituents to UC may be improving oxidation resistance rather than achieving a true reduction of activity of UC. The improved oxidation resistance would result in less formation of CO during heating and consequently less free uranium. If it can be conclusively shown that alloying does reduce UC activity and improve compatibility, the addition of HfC, rather than ZrC or NbC, may be desirable because it is thermodynamically the most stable of the three, plus being desirable from a nuclear standpoint of obtaining a negative Doppler coefficient. Some penalty in additional loading for criticality would result; however, this may not be too severe.

C. Uranium Dioxide and Cermets

As a result of heating, UO_2 suffers from substoichiometry, which results in a flux of uranium through tungsten cladding. This effect is increased substantially by thermal cycling. Uranium on the surface of an emitter results in increased emissivity and evaporation of the uranium from the emitter surface and its subsequent condensation on the cooler portions of the cell. The effect of uranium on the collector is not known. The effect of recoil fission fragments on alumina, however, is known to be extremely detrimental. Whether or not sufficient uranium would condense on insulators to produce damage is not known.

In addition to the uranium flux problem in the UO_2 cermet, cermets of UC and UO_2 undergo growth from thermal cycling. Additions of other oxides to UO_2 to act as oxygen donors reduce growth but do not completely eliminate it in the UO_2-W cermets. Additions to UC have not as yet been tried, nor has the effect been investigated in UN-W cermets. At thermionic temperatures of 1800°C the tungsten matrix would have to be depended upon to retain fission products. This limits the allowed burnup with the current tungsten-alloy technology. The burnup limitation may be somewhat alleviated by reduction of fuel temperature to below 1600°C, where the UO_2 can provide some fission-gas containment.

Information is currently becoming available on strengthening of tungsten by the addition of second phases such as oxides and carbides. These have been shown to increase creep strength of tungsten by a factor as great as 18, but this must still be viewed as highly experimental. Thus, current limitations stemming from gas-pressure buildup as a result of fission may be considerably reduced.

When these fuels are coupled to a thermionic design concept, additional limitations arise. Venting to space presently appears feasible with both UC and UO_2 with proper design. Venting of UN to high-vacuum space is not possible because of vapor pressure. Venting to the cesium space appears to require a purge of cesium to eliminate fission product buildup. In the case of a sealed diode this gas buildup would be unacceptable both from a performance viewpoint and because of mechanical pressure. If purging through the cesium space is feasible, UC alloys, UO_2, and UN may be acceptable. The problem of venting in this manner, however, is not simply one of a suitable mechanical design. The effects of deposition of fuel and fission products on collector, emitter, and insulator structures may prove intolerable.

III. CONCLUSIONS

Thermionic diode development has made substantial strides in recent years. Integration into a nuclear reactor poses difficulties, but no insoluble problems are apparent.

If any of the systems presently contemplated achieve operational status, the advantages of this mode of power conversion over turbo-systems are apparent: simple single-phase hydraulics, straightforward (in a hydraulic sense) start-up, redundancy of conversion units, and elimination of massive rotating machinery.

At this time, the development status of the General Atomic single diode is further along than the competing concepts. Substantial in-pile and out-of-pile operations have been achieved. Some performance degradations have been observed in both cases. The General Electric flashlight concept has also had both in-pile and out-of-pile operation, but not utilizing diodes directly suitable for reactor use. The Republic Aviation externally fueled diode has not been subjected to any in-pile operation. Out-of-pile runs, however, have shown extremely encouraging results.

None of the potential fuels in thermionic reactor application have yet demonstrated an ability to achieve burnup levels in the neighborhood of 1 at. % as required for systems greater than several hundred kw(e). It is the opinion of the writers that the vented UC-ZrC has the most promise for achieving this goal without the need for means of restricting vaporization and decomposition. The writers are rather pessimistic about the ability of unvented UO_2-W cermets to achieve burnups in the neighborhood of 1 at. %. Matrix internal stresses around 15,000 psi are calculated at this burnup level, assuming no gas solubility. Tungsten creep strength of only 1000–3000 psi exists at thermionic temperatures. Burnups required at 50 kw(e) appear achievable for the UO_2-W cermet and UC-ZrC in their respective reactor concepts. The apparent sensitivity of the cermet to thermal cycling, however, still poses an unresolved problem. Limiting fuel temperatures to 1600°C may alleviate both the matrix-strength and thermal-cycling problems.

The flashlight, pancake, and externally fueled reactor concepts are rather closely coupled to specific fuel choices. The flashlight concept would eliminate the uncertainties of venting through the gas space with a cermet fuel if satisfactory burnup could be achieved. The pancake design has paid a substantial void-fraction penalty to permit ease of venting and hence logically mates with a vented fuel. The externally fueled concept can adapt to either a vented or unvented fuel; however, thermal expansion mismatch between fuel and emitter makes the cermet fuel most amenable to a simple design concept. These considerations are not absolute, but certainly indicate that fuel-reactor concept couplings are not totally interchangeable.

At lower power levels it is believed that the externally fueled core-length diode concept, by virtue of its superior fuel-volume fraction, can achieve a smaller reactor size than the pancake, even considering its use of lower-uranium-density fuel. It is possible that two such diodes can be axially stacked on a common coolant tube, thus maintaining a reasonable L/D ratio for high-power application. The greatest burden of the externally fueled concept for higher powers is in its coupling to cermet fuel. The feasibility of utilizing vented UC-ZrC fuel in this concept should definitely be investigated.

The flashlight arrangement is intermediate in attainable fuel-volume fraction among the three concepts. Its major drawback appears to be the undetermined feasibility of venting at higher burnups. At any power level this diode is the most complex and perhaps more prone to reliability problems.

A summary of the characteristics of the thermionic fuels and reactor concepts studied in this survey is given in Table 3.

With respect to the general stability and control problems associated with all thermionic systems, it appears that desirable axial expansion would naturally occur in the externally fueled, single core-length diode and that some measure of axial expansion could be built into the pancake and perhaps even the flashlight concept. The detailed neutronics of these systems must be investigated. The sensitivity of these systems to prompt coefficients and the lack of basic data make this a vital area for intensive attention.

The fundamental problem areas requiring additional investigation are summarized as follows:

1. Basic and sophisticated physics analysis is required to determine magnitudes of prompt temperature coefficients.

2. Stability analysis must be accomplished and control systems investigated in depth.

3. Basic causes of diode degradation must be resolved and alleviated.

Table 3. Summary of thermionic fuels and reactor characteristics

Thermionic fuels	
UC-ZrC (vented)	
Fundamental advantage:	Highest uranium density.
Fundamental disadvantage:	Chemically less stable than oxide in contact with tungsten.
Uncertainties:	Effect on tungsten emissivity and/or work function.
	Ability to achieve 1 at. % burnup.
UO_2 (vented)	
Fundamental advantage:	Higher uranium density than cermet. High burnup potential if capable of satisfactory venting.
Fundamental disadvantage:	Unrestricted vacuum vaporization rate very high.
	Vacuum decomposition with release of oxygen.
	Low thermal conductivity.
Uncertainties:	Ability to vent under conditions inhibiting vaporization and oxygen release. Effect of diffusion through clad and deposition on collector and insulator structures.
Cermets (unvented)	
Fundamental advantage:	Only fuel with *possible* satisfactory burnup in unvented concepts.
Fundamental disadvantage:	Distinct limiting mechanism (accumulation of fission gas) on burnup capability. Lowest uranium density.
Uncertainties:	Apparently poor thermal cycling characteristics.
	Ability to achieve 1 at. % burnup.
Thermionic reactor concepts	
Flashlight	
Fundamental advantage:	Higher fuel fraction than pancake.
Fundamental disadvantage:	Complexity of flashlight structure.
Uncertainties:	Venting through cesium space if venting required.
Pancake	
Fundamental advantage:	Single-diode simplicity. Ease of venting.
Fundamental disadvantage:	Low fuel-volume fraction.
Uncertainties:	Low fuel-volume fraction makes use of U^{233} desirable. Effect of small delay fraction on control margin more critical.
Externally fueled	
Fundamental advantage:	Highest fuel-volume fraction.
Fundamental disadvantage:	Thermal expansion mismatch to other than cermet fuel.
Uncertainties:	Ability to use UC-ZrC or UO_2 in concept.

4. Effects of fuel–clad interactions on thermionic performance is presently uncertain and must be firmly established.

5. Fuel irradiations must be carried to the required burnup levels at thermionic temperature to determine their performance capabilities.

6. Overall specific plant design must be accomplished to establish meaningful weight estimates for thermionic systems.

When the primary problem areas have been investigated sufficiently to permit a rational choice (or choices) for fuel, reactor concept, and overall system design, appropriate operating reactor experiments should logically follow. As a closing note, it should be remembered that the thermionic mode of power conversion has had more demonstrated operation under required system conditions than all other competing modes combined. Whether this situation will prevail is, of course, uncertain; but the present state of affairs speaks well for the accomplishments to date.

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