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AEC RESEARCH AND
DEVELOPMENT REPORT

GA-8309

THERMIONIC CRITICAL EXPERIMENT PROGRAM

by

S. C. Cohen

November 28, 1967

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THERMIONIC CRITICAL EXPERIMENT PROGRAM

by

S. C. Cohen

Project 278
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ABSTRACT

The Atomic Energy Commission has embarked upon a program of critical experiments to be performed at Gulf General Atomic in support of thermionic reactor development. The motivation behind this program is established through an examination of the unique features of a generic thermionic space power reactor and the related neutronic uncertainties and design problems. The overall objective of the critical experiment program is to compare integral neutronic data from a number of assemblies with detailed neutronic calculations in order to check analytical methods and cross section data used in the core design of thermionic space power reactors. This will be accomplished by constructing five categories of critical assemblies from the very simple in composition and configuration to the complex, culminating in a program of engineering mockup experiments.

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I. INTRODUCTION

Over the past few years, Gulf General Atomic has been deeply involved in the design and development of an in-pile thermionic fast reactor for space power application. A majority of the work has been directed toward the development of the thermionic converter itself. Significant progress has been made in this area, with several converters performing in-pile in the range of several thousands of hours. A considerably lesser effort has been directed toward the nuclear technology of thermionic reactors.

A number of thermionic reactor design studies have been performed,^{1,2,3} and parametric systems analyses have been carried out,⁴ however these efforts have contributed little to the testing and advancement of analytical reactor physics methods. The principal experimental neutronics contribution to date has been confined to spherical subcritical assemblies.⁵ These measurements have provided fast spectrum data for a few thermionic reactor materials. Although the results have provided a useful check on analytical methods for computing fast neutron spectra, the scope of subcritical experiments in providing neutronics data is limited.

In April, 1967, the Atomic Energy Commission embarked upon a series of critical experiments to be performed at Gulf General Atomic in support of thermionic reactor development. The overall objective of this program is to compare integral neutronic data from a number of assemblies with detailed neutronic calculations in order to check analytical methods and cross section data used in the core design of thermionic space power reactors. It is anticipated that by maintaining the analytical and experimental efforts entirely in phase, significant progress will be made in the normalization of cross section data, determination of deficiencies in analytical methods, determination of error limits in calculated results, and the ultimate improvement in methods.

The critical experiment program should provide a timely complement to the fast reactor physics analytical effort carried out under the thermionic reactor program at Gulf General Atomic. This work has contributed to the development of a versatile and relatively sophisticated fast reactor neutronics code, GAFGAR.⁶ Recently completed, this program has yet to

be checked against experimental data relating to thermionic reactor design.

An orderly progression of assemblies ranging from the very simple in composition and configuration to the complex are planned under the overall critical experiment program. This approach is designed to separate problems involving cross section uncertainties from those associated with the analytical methods. For example, the early experiments will incorporate bare, homogeneous assemblies which should be readily analyzable. These assemblies will provide clean integral data concerning the neutron cross sections of thermionic materials. The integral data will be augmented by differential neutron spectrum measurements. Subsequent measurements will focus upon configurational problems, such as the core-reflector interaction and the effects associated with core heterogeneities, leading ultimately to a program of zero-power mock-ups of thermionic reactors. A flexible program is anticipated, which will allow for a reorientation in light of unexpected results. Furthermore, the experience of over ten years of zero power neutronic experiments in the civilian power fast reactor program will be utilized to the benefit of this program.⁷

Sections II and III of this report furnish the motivation for the critical experiment program. The features of a generic thermionic reactor are outlined in Section II followed by a summary of directly related neutronics problems in Section III. Finally, an outline of the overall Thermionic Critical Experiment program is presented in Section IV.

II. FEATURES OF A GENERIC THERMIONIC SPACE POWER REACTOR

Although several design studies have been carried out at Gulf General Atomic and other laboratories, a single preferred or reference thermionic reactor design does not exist at the present time. Nevertheless, there are a number of features of a generic in-pile thermionic space power reactor that are independent of any one particular design. Several of these features give rise to core design problems and neutronic uncertainties, and have therefore heavily influenced the formulation of the overall critical experiment program.

2.1 Minimum Weight

The minimization of the overall power plant weight is one of the key requirements in the design of a thermionic space power reactor. Since the major contribution to the overall system weight for manned missions stems from the radiation shield, most design studies incorporate a shadow shield. This motivates a design criterion for ratios of reactor length to diameter in excess of unity. Furthermore, the desire to compact the reactor core to the limit of practicality precludes the incorporation of large quantities of diluent material. Finally, an accurate estimate of the multiplication constant throughout the core life is required in order to minimize the necessary control margin.

2.2 High Temperatures

A schematic diagram of a typical thermionic converter is shown in Fig. 1. The achievement of reasonable efficiencies demands high emitter temperatures, and depending upon the thermal conductivity and diameter of the fuel region, even higher peak temperatures in the fuel. Furthermore, in order to minimize the size and weight of the space radiator, it is desirable to dump waste heat at a high temperature. An emitter temperature of 1800°C and a heat sink temperature of approximately 800°C are representative design goals. These requirements

UNIT CELL THERMIONIC FUEL ELEMENT

Fig. 1 - Schematic Diagram of an In-Pile Thermionic Converter

approach the limits of material properties, and only ceramics, cermetts, refractory metals, and liquid metals are suitable in-core components.

High core temperatures coupled with the desire for core compaction force the control mechanism out into the reflector. Sufficient control margin must be available to compensate for the fairly substantial cold to hot swing in reactivity and for any fuel loss by evaporation. Reflector control is particularly suitable by virtue of the large neutron leakage fraction.

The high core temperatures imply diminished Doppler coefficients of reactivity. The temperature dependence of Doppler coefficients obeys a power law:

$$\frac{\partial k}{\partial T} \sim \left(\frac{1}{T}\right)^{\gamma}$$

where γ generally lies between 1.0 and 1.5 for fast reactors. Therefore Doppler coefficients, which are extremely important for the safety and control of fast reactors, can be diminished below their room temperature values by more than an order of magnitude in a thermionic reactor.

2.3 Tight Temperature Restrictions

The thermionic converter efficiency falls off markedly as the emitter temperature is reduced below some optimum operating temperature, as shown in Fig. 2. The dual requirements of high performance and high reliability demand an extremely flat power distribution within the reactor core. A design goal for peak-to-average power of less than 1.1 is significantly more stringent than in most civilian power fast reactors. A combination of fuel zoning and core reflection have been considered for achieving this goal.

2.4 High Fuel Density

The size and weight restrictions on thermionic reactor cores

Fig. 2 - Thermionic Converter Efficiency vs. Emitter Temperature

dictate the requirement for substantial fuel densities. At present, only the oxides, carbides, and cermets of uranium are serious fuel contenders from the metallurgical point of view. The uranium volume fraction in some of these materials is reduced in order to provide for fission product venting. Therefore even with fully enriched fuel, dilution with non-fissile material carries with it a substantial penalty in performance. This situation may be contrasted with that of a civilian power fast reactor, where the ratio of fertile to fissile material within the core is likely to be a factor of five or more. Thus, instead of a substantial prompt negative Doppler coefficient of reactivity, a high performance thermionic reactor could possess a significant prompt positive Doppler coefficient.

The size and weight restrictions place U^{233} fuel in a very favorable light, particularly for low power thermionic space power reactors. Figure 3 illustrates the substantial diminution in critical mass obtainable with U^{233} fuel.⁸ This fissile nuclide appears to be superior to U^{235} for thermionic reactors of power levels in the region of 50 kW and lower.

2.5 Low Atomic Mass Reflector

The function of the reflector in a thermionic space power reactor is to minimize critical mass and assist in power flattening. Aside from structural considerations, the principal constraint in the reflector design is low thickness and weight. Design studies indicate that on an equal thickness basis, the low atomic mass metals and oxides make the best reflectors for thermionic reactors. In particular, beryllium and beryllium oxide have received the most attention. Experience with systems consisting of low atomic mass reflectors surrounding compact fast reactor cores is limited, since civilian power fast reactors have large dilute cores reflected by high atomic mass materials.

Fig. 3 - Critical Mass as a Function of Enrichment in Reflected Fertile Spheres

The principal neutronic effect of the low atomic mass reflector is the creation of a highly spacially dependent neutron spectrum within the core. Figure 4 compares the spectrum at the core center with the spectrum adjacent to the BeO reflector in a 300 eKw thermionic reactor core. The large population of low energy neutrons adjacent to the reflector enhances the worth of refractory metals and Doppler coefficients in this core region.

2.6 Modular Converter Design

Several proposed core configurations for in-pile thermionic space power reactors have been considered. Most of the designs feature a modular fuel arrangement in order to build up voltage and diminish joule heating losses. In addition to diminishing the fuel volume fraction within the core, the principal neutronic result of the modular fuel configuration is an extremely small reactivity coefficient associated with fuel thermal expansion. In a fast reactor the thermal expansion coefficient and the Doppler coefficient comprise the entire prompt temperature coefficient of reactivity.

2.7 High Concentration of Refractory Metals

Tables I and II compare the core constituents and range of concentrations studied in the civilian power fast reactor physics program⁷ with those considered in thermionic reactor design studies. It is noteworthy that concentrations of refractory metals as high as 35% by volume have been considered for in-core use in thermionic reactors. By virtue of the high atomic mass of most refractory metals, the elastic and inelastic level structure is relatively complex. The status of cross section data over the appropriate energy region leaves a great deal to be desired, and experimental checks in a suitable spectrum are scarce or nonexistent.

Fig. 4 - Comparison of Thermionic Reactor Spectrum at Core Center and at Core-Reflector Interface

TABLE I

CONSTITUENTS OF CIVILIAN POWER FAST REACTOR CRITICAL EXPERIMENTS

<u>Material</u>	<u>Volume Fraction</u>
U-235	0.01-0.20
U-238	0.01-0.75
Oxygen	0.05-0.80
Carbon	0.10-0.75
Stainless Steel	0.05-0.80
Aluminum	0.15-0.40
Sodium	0.05-0.65

TABLE II

CONSTITUENTS OF GENERIC THERMIONIC REACTOR

<u>Material</u>	<u>Volume Fraction</u>
Fuel (Fully enriched carbide or oxide, U-233 or U-235)	0.05-0.40
Tungsten	0.05-0.10
Niobium	0.05-0.25
Molybdenum	0.05-0.10
Tantalum	0.01-0.05
Aluminum Oxide	0.01-0.05
Coolant (Li, Na, NaK)	0.10-0.30

2.8 Unique Reactivity Feedback Characteristics

By virtue of the thermionic principle, an in-pile thermionic reactor features a unique coupling between the electrical load and the reactor performance. A change in the load impedance, which causes a corresponding change in electrical current, is felt immediately by the emitter. The most direct effect is a change in the emitter temperature brought about by a change in the electron cooling. This brings about an instantaneous perturbation in the reactivity of the system by virtue of the Doppler coefficient of the emitter, and a consequent change in power level. The coolant, on the other hand, is lagging these events instead of leading, as in a conventional reactor system.

This unique reactivity feedback mechanism affecting in-pile thermionic reactors has prompted several independent studies of thermionic plant dynamics. Most of these investigations have employed analogue computers to study the transient behavior of thermionic reactor systems.⁹ This approach permits an accurate physical representation of the system, limited only by the precision of the input data. The input data on the thermomechanical properties of the reactor and even for the electron cooling, which has been measured over the complete range of diode operating conditions, can be accurately given. The weakest link in these studies is the neutronic parameters, and in particular the reactivity coefficients, used as input data.

III. NEUTRONIC UNCERTAINTIES AND RELATED DESIGN PROBLEMS

The features of a generic in-pile thermionic space power reactor and their implications relating to neutronic considerations have been outlined in Section II. By virtue of the unique features of thermionic reactors and the relatively limited experience in fast reactor technology in general (in comparison with the thermal reactor program), several areas of neutronic uncertainty in the core design of thermionic reactors can be cited. A qualitative discussion of several of these neutronic uncertainties is presented in this section, followed by an assessment of the major related core design problems. The safety considerations, in particular, are discussed in some detail.

3.1 Neutronic Uncertainties

3.1.1 Inelastic Scattering

Inelastic scattering cross sections in general are relatively poorly known. Experimental data are scarce, particularly for the differential cross section, $\sigma_i(E' \rightarrow E)$, and the analytically derived cross sections based upon statistical theory¹⁰ are usually employed in reactor analysis.

Despite the low energy tail created by the light reflector, the energy distribution at the high energy end of the spectrum in thermionic reactors is of principal concern for criticality considerations. Inelastic scattering is the primary mechanism for neutron energy degradation in this region. As discussed in Section II, the large quantity of refractory metals and high fuel densities in thermionic reactors give rise to large inelastic scattering cross sections. Furthermore, the high atomic mass of these materials denotes low threshold energies and tightly packed inelastic scattering levels.

Fast spectrum experiments at several laboratories have revealed considerably softer measured spectra than predicted. The discrepancies are frequently attributed

to deficiencies in inelastic scattering cross sections, although it is premature to draw any definite conclusions by virtue of the multitude of obscuring variables. Moldauer¹¹ has proposed a mechanism by which energy degradation from inelastic scattering would be considerably enhanced, however this model has not as yet gained wide acceptance.

3.1.2 Resonance Cross Sections

The level density for neutron cross section resonances goes roughly exponentially with atomic mass. Thus the high concentration of heavy metals in thermionic reactors implies large effective resonance cross sections. Fortunately, the magnitude of the resonance cross section goes inversely with the resonance energy, so that criticality in fast reactors is not extremely sensitive to the resonance capture in most materials. The effect is not insignificant, however, and Table III gives the number of captures per source neutron in the components of a representative 300 eKw thermionic reactor.

The concern with the resonance structure of thermionic materials is primarily in connection with the prediction of Doppler coefficients, which are exceedingly important in the control and safety of fast reactors.

TABLE III
NUMBER OF CAPTURES PER SOURCE NEUTRON IN A 300 eKw THERMIONIC REACTOR

Niobium	.039
Molybdenum	.009
Tantalum	.008
Tungsten	.036
Rhodium	.014
U-238	.004
U-235 (not incl. fission)	.086
Other	<u>.024</u>
TOTAL	.220

The median neutron energy of non-fissile Doppler coefficients in thermionic reactors lies in the range of 1 to 2 KeV, and for fissile Doppler coefficients, from 100 eV to 1 KeV. The resonances of most nuclides are only resolved up to relatively low energies. The upper energy limits for the resolved resonances of the tungsten isotopes¹², tantalum¹², and U-235¹³ are given in Table IV. The lack of information regarding the level structure of most nuclides in the bulk of the energy region contributing to the Doppler coefficient forces the analyst to apply a statistical treatment in the prediction of Doppler coefficients.¹⁴

TABLE IV

UPPER ENERGY LIMITS FOR RESOLVED RESONANCES OF REPRESENTATIVE THERMIONIC MATERIALS

W-182	281 eV
W-183	287 eV
W-184	2140 eV
W-186	334 eV
Ta-181	335 eV
U-235	65 eV

This approach makes use of average resonance parameters derived from the resolved resonance region, which are frequently highly uncertain. The recommended average resonance parameters from various authors may differ considerably, particularly for the fissile nuclides. For example, the predicted fissile Doppler coefficient in a thermionic reactor has been observed to vary in sign depending upon the set of average resonance parameters utilized. Furthermore, the uncertainty implicit in the statistical analysis itself may be quite large, as high as 100% for the fissile Doppler coefficient.¹⁵

3.1.3 Analysis of Doppler Coefficients and other Resonance Effects

In addition to uncertainties in the resonance cross section data, inherent approximations in the analysis of resonance effects introduce additional errors in the prediction of Doppler coefficients. Some of these approximations are necessary by virtue of computer storage or time limitations, whereas others are attributable to incomplete knowledge regarding the physics of the problem.

The most obvious error in the prediction of Doppler coefficients stems from an inaccurate computation of the low energy tail of the gross neutron energy spectrum. This may result from errors in the nonresonance cross sections of the materials comprising the core of the reactor, such as the inelastic scattering cross sections discussed above, or in the scattering resonance contributions from light or heavy elements, as discussed in the following paragraph. Or an error in the predicted spectrum may arise from incorrect or incomplete treatment of the core-reflector interaction, as discussed in a subsequent section. This problem may be partially alleviated by including a sufficiently large number of neutron energy groups in the calculation of the gross core spectrum.

Recent spectrum measurements with spherical subcritical assemblies have revealed the need to consider the self-shielding of heavy element scattering resonances both in the prediction of the gross spectrum and for the consideration of an additional "scattering Doppler effect".¹⁶

Although the need for accurate self-shielding calculations on the broad scattering resonances of light materials has been recognized for several years, the heavy element effects have only recently been recognized in conjunction with the thermionic reactor program. The actual quantitative significance of this effect in practical thermionic reactor core design calculations has yet to be fully explored.

Spectrum considerations aside, considerable uncertainty arises from the effect of resonance overlap, both from adjoining levels of the same resonance sequence, sometimes referred to as "self-overlap," or from levels of other resonance sequences, sometimes called "accidental overlap." Although prescriptions exist for the estimate of these effects, they are generally applied as second order corrections to the conventional isolated resonance treatment.¹⁷ Exploratory calculations indicate that by virtue of the high concentration of refractory metals and fissile material in a generic thermionic reactor, accidental overlap is a first order effect.¹⁸

At present, the prediction of the fissile Doppler coefficient is one of the most uncertain analyses in fast reactor physics. Experimental results in small sample geometry are generally in wide disagreement with theory. Both analysis and experiment have been criticized in the past for contributing to the discrepancy. At least one uncertainty in the measurements, the sample expansion effect, appears to have been overcome.¹⁹ On the other hand, the basic formulation in the analytical approach has been widely attacked. The single-level approach to the level structure, which is extended into the unresolved region, is a gross approximation.²⁰ Small errors in the predicted low energy flux or importance function may be considerably magnified by virtue of the delicate balance between fission and capture. Resonance self-overlap is a very significant effect in fissile nuclides by virtue of the low level spacings, and must be treated carefully.

3.1.4 The Core-Reflector Interaction

As discussed in Section II, a low atomic mass reflector surrounding the compact thermionic reactor core creates a highly spatially dependent neutron energy spectrum throughout the reactor core. In principle, this problem can be handled by increasing the number of groups in the transport

calculation of the neutron flux distribution. Figure 5 gives the maximum error in the power distribution for a thermionic reactor core as a function of the number of groups utilized in the transport theory calculation, assuming that an 18 group calculation is "exact." In practice, the number of groups is limited by computer memory capacity, which is determined by the complexity of the remainder of problem. For accurate power distribution tailoring, a two dimensional representation of the core and a high order expansion of the scattering kernel may be required. All of these factors plus the economics of time consuming computer calculations for design survey calculations must be considered in determining the optimum group structure. Furthermore, the uncertainty in reflector cross sections, particularly the n -2n reaction, may be the limiting factor.

3.1.5 Reactor Dynamics Analysis

The unique coupling between electrical load and reactor performance in thermionic reactors was pointed out in Section II. The analogue computer studies which have been performed to investigate the transient behavior of thermionic reactor systems have assumed the point kinetics model, or at best the two-node model of Cohn²¹ for reflected reactor kinetics. The strong spectral variation in thermionic reactors gives rise to considerable variation in reactivity coefficients throughout the core. Although neutron mean free paths are relatively large, the spacial effects in kinetics calculations may be significant. These effects have not as yet been satisfactorily investigated.

3.1.6 Two- and Three-Dimensional Considerations

Two-dimensional calculations are necessary for accurate predictions of several of the significant neutronic parameters in thermionic space power reactors. For example, a one-dimensional estimate of the maximum to minimum power ratio in a small, BeO-reflected thermionic core differed by more than 25% from the two-dimensional

Fig. 5 - Maximum Error in Power Distribution as a Function of Number of Groups

estimate. This discrepancy can be attributed to corner effects and streaming phenomena. The connector area above each diode consists largely of void, and a one-dimensional approximation to the reactor core is incapable of handling the streaming of neutrons through this volume. The two-dimensional transport approach is not devoid of difficulties, however. Aside from considerations of time consumption, which may be prohibitive for certain applications, present two-dimensional transport codes are limited to a low order P_n expansion of the scattering kernel and a relatively low order S_n approximation, depending upon the dimensions of the other variables. The quantitative effect of these approximations has not been fully explored.

Another parameter which requires more than one-dimensional analysis is the expansion coefficient of reactivity. In fact, for the pancake core design shown schematically in Fig. 6, the two-dimensional approximation to the actual geometry requires smearing the diodes into layers. The severity of this approximation has not been assessed. A three-dimensional transport calculation, of course, is unfeasible with the present generation of digital computers.

3.2 Major Neutronic Design Problems

The foregoing discussion implicitly suggests several neutronic core design problems in thermionic reactors. The major ones, in the opinion of the author, are listed below.

3.2.1 Minimization of Weight

The weight of the overall thermionic reactor power plant is intimately related to the weight and dimensions of the reactor core. Any built-in excess reactivity beyond the requirements for design performance carries with it a sizable penalty in system weight. For this reason, a highly accurate prediction of the critical mass and control margin is mandatory. Uncertainties in inelastic scattering cross sections and to a lesser extent, the resonance cross

Fig. 6 - Schematic Diagram of Pancake Reactor Concept.

sections, hinder this objective. Additionally, methods utilized in the prediction of the core-reflector interaction and three-dimensional effects contribute to uncertainties in the prediction of critical mass and control worths.

3.2.2 Power Distribution Flattening

As discussed in Section II, the design objectives for maximum to minimum power in a thermionic reactor core are unusually stringent. At present, a combination of fuel zoning and core reflection is planned to achieve these objectives. The major impediment to the accurate prediction of power distribution is the treatment of the core-reflector interaction. This includes a non-trivial geometrical problem associated with an asymmetric control drum configuration. To a lesser extent, the adequacy of methods for the treatment of two- and three-dimensional effects, such as streaming, is uncertain.

3.2.3 Control and Safety

These two design areas are closely related. The unique feedback characteristics of thermionic reactor systems were discussed earlier. In all likelihood, a control system design which takes these effects into account is feasible. Reflector control is likely, although the prediction of reflector control reactivity worths is complicated by geometrical complexities and the neutronic uncertainties associated with the core-reflector interaction.

On the other hand, the exceedingly small prompt reactivity feedback coefficients characteristic of thermionic reactor core designs give rise to considerable concern. From the point of view of control, this implies that small perturbations in load impedance or reactivity could evoke excessive temperature excursions. Furthermore, the prompt temperature coefficient from the highly enriched fuel may very well be positive, in which case the reactor may be unstable for certain fuel element designs. As discussed in the following section, schemes exist for the enhancement

of negative reactivity coefficients in thermionic reactors. However, the uncertainties in cross sections and analytical methods for the prediction of reactivity coefficients warrant an experimental investigation of these effects prior to a design decision which sacrifices performance.

3.3 Safety Considerations

The range of predicted reactivity coefficients from thermionic reactor design studies is given in Table V. Reactivity coefficients originating from beyond the emitter are of limited interest from the point of view of safety by virtue of their considerable delay. The breadth of the range for each tabulated coefficient reflects in part the intrinsic uncertainty in the coefficient, and to a greater extent, the variation in coefficients between reactor designs of different power levels. Expansion coefficients are of less interest for safety considerations than the more prompt Doppler coefficients. The Doppler coefficient for U^{233} fuel is more positive than that of U^{235} fuel because of the considerably larger fission width for this nuclide. However, the average resonance parameters of U^{233} are uncertain and measurements of its Doppler coefficient have not been performed.

TABLE V
RANGE OF REACTIVITY COEFFICIENTS

Fuel Expansion	-1 to $-3 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$
Fuel Doppler	
U^{235}	-1 to $+4 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$
U^{233}	+2 to $+8 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$
Emitter Doppler	-3 to $-12 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$

Stability studies and transient calculations for thermionic reactors have been carried out using computed reactivity coefficients as input data.²² The results can be generalized as follows. For U^{235} fuel in the carbide form, thermionic reactors are probably stable. For U^{235} fuel in the oxide form a thermionic

reactor may be stable or unstable, depending upon the specific design. Finally, for U^{233} fuel of either form, thermionic reactors are probably unstable. Furthermore, for small perturbations to load or reactivity, in stable systems resultant transients are quite severe by virtue of the small feedback coefficients.

A series of thermionic reactor transient studies involving hypothetical β 1.00 reactivity insertions were carried out which illustrated the risk of operating a thermionic reactor with positive fuel temperature coefficients of reactivity. For emitter coefficients in the range of -10^{-7} to $-10^{-6} \text{ }^{\circ}\text{C}^{-1}$, fuel melting transpires in a time span of the order of tens of milliseconds when the fuel coefficient is positive and in the range of $+10^{-7}$ to $+10^{-6} \text{ }^{\circ}\text{C}^{-1}$, too short a time span for a practical control system to take remedial action. On the other hand, for a negative fuel coefficient in the range of -10^{-7} to $-10^{-6} \text{ }^{\circ}\text{C}^{-1}$, fuel melting does not occur until the order of hundreds of milliseconds have transpired, a sufficiently long time span for a control system to terminate the excursion.

Neutronic studies have been performed which indicate that there exist one or more feasible schemes for the enhancement of reactivity coefficients. Dilution of the fuel with non-fissile resonance absorbers is one method. Calculations indicate that U^{238} added on an equal volume fraction basis with the fissile material is sufficient to cancel the positive fissile Doppler coefficient. Dilution of the fuel with tantalum on an equal number density basis should be sufficient to assure a significant negative Doppler coefficient. Furthermore, there appear to exist a few "super materials," such as Praseodymium-141 or Dysprosium-162, which could give rise to negative Doppler coefficients several times the magnitude for that of U^{238} on an equal number density basis.

Another scheme for the enhancement of negative Doppler coefficients is the addition to the core of small quantities of hydride moderator. This material can be placed in the cold regions of the core with little or no sacrifice in reactivity. Exploratory calculations indicate that the addition to the core of 10% by volume zirconium hydride increases the magnitude of the U^{238} Doppler coefficient by a factor of 5. This scheme, used in conjunction with fuel dilution, has the potential of enhancing the magnitude of negative Doppler coefficients by an order of magnitude or more. This would bring thermionic reactor temperature coefficients into the range of those of civilian power fast reactors.

IV. OUTLINE OF THE CRITICAL EXPERIMENT PROGRAM

As stated in the introduction, the purpose of the critical experiment program is to check analytical methods and cross section data used in the design of thermionic reactors, and to ultimately refine them where necessary. This will be accomplished by directing the program as closely as possible toward the estimated thermionic reactor neutronic uncertainties and design problems discussed in Section III. A series of critical assemblies are planned which progress from the very simple in configuration and composition to the complex, culminating in a program of engineering simulation, or reactor mockup experiments. The program is formulated in such a way as to separate problems involving cross sections and those associated with analytical methods to as great an extent as possible. Although the overall outline of the program has been planned in some detail, it is intended that sufficient flexibility in design and programmatics will exist to allow for a reorientation in light of significant surprises anywhere along the way.

The basic fuel element of the thermionic critical experiment is sketched in Fig. 7. It consists of a neutronically homogeneous rectangular parallelepiped made up of alternate layers of thin fuel foils and non-fuel foils. The design has been optimized to permit convenient variation in composition. Fuel elements will be stacked in building-block fashion on each of three beds of a split-bed assembly machine to form a near-cubical critical assembly when the beds are closed. A detailed description of all components of the Thermionic Critical Experiment is presented in a separate report.²³

Five categories of critical assemblies are planned, each of which will consist of one or more assemblies, depending upon time limitations. The progression of assembly categories is in order of complexity. The first two categories of assemblies are primarily intended to yield integral cross section checks of thermionic materials. In order to eliminate configurational complexities, the assemblies in these categories will be bare, neutronically homogeneous reactors. The assemblies in the first category will feature an exceedingly simple core composition - enriched uranium plus an elastic scatterer. Cross section checks will

Fig. 7 - Sketch of Thermionic Critical Experiment Fuel Element

be performed by inserting small samples of thermionic materials into a central void space within the core. Assemblies in the second category will contain mixtures of thermionic materials distributed homogeneously throughout the core itself. Cross section checks will be performed by measuring critical mass as well as small sample worths. In both categories, integral cross section data inferred by core multiplication measurements will be augmented by direct measurements of neutron spectra on a subcritical fraction of the assembly, using the pulsed-source, time-of-flight method.

The second two categories of assemblies are intended to shed light upon configurational problems. In the third category, one of the previous bare assemblies will be reflected on at least two faces by a low atomic mass material. The principal experiment will consist of flux and power distribution measurements. The fourth category will be directed toward heterogeneity problems. The formerly homogeneous core region in a reflected assembly will be subdivided into cells of varying complexity, approaching the degree of heterogeneity in a thermionic reactor. The final category consists of one or more zero power mockups of an actual in-core thermionic space power reactor. The program, as envisaged by Gulf General Atomic, is outlined in more detail below.

4.1 Category A; One-Region Homogeneous Core(s) with Simple Composition.

Composition

Fully enriched U-235 plus polyethylene ($[CH_2]_n$).

Configuration

Bare rectangular parallelepiped composed of neutronically homogeneous fuel elements.

Measurements

1. Critical Mass
2. Central worths (sometimes called "danger coefficients") for materials of interest to the thermionic reactor program.
3. Sample Doppler coefficients for materials of interest to the thermionic reactor program.

4. Subcritical spectrum at one or more values of the multiplication.

Discussion

The objective of the early measurements is to check the integral cross sections of materials of interest to the thermionic reactor program. The most expeditious approach is to assemble as "clean" a core as possible and to examine each material separately in the form of small samples. A "clean" core implies a simple geometry, one-region, neutronically homogeneous, and free of heavy mass materials with complex cross sections (except, of course, for the fissile material). This approach should permit unambiguous interpretation of small sample measurements. Furthermore, the subcritical spectrum measurements will augment the reactivity measurements by eliminating uncertainties concerning the energy distribution of the neutron flux.

The value to the reactor design effort of integral neutronic data is determined to a great extent by the degree of similarity between the neutron spectrum of the critical experiment and that of the design reactor. The approach in the first category of assemblies is to attempt a reasonable simulation of a generic thermionic reactor spectrum consistent with the constraint of maintaining a "clean" core. This constraint limits to some extent the correspondence in the high energy portion of the spectrum, which is determined in a generic thermionic reactor by the high concentration of inelastic scatterers. Several low mass elastic scatterers were investigated to attempt a simulation of the low energy portion of the spectrum, which is determined in a generic thermionic reactor by the return of neutrons from the low atomic mass reflector. It was determined that a small quantity of hydrogen, most conveniently bound in polyethylene, provides the best simulation of both the real and adjoint fluxes in the low energy portion of the spectrum. The simulation of this energy region is exceedingly important for meaningful Doppler coefficient measurements. Figure 8 compares the neutron spectrum for Assembly # 1 ($H/U^{25} = 0.9$) with the inner and outer core region spectra of a 300 kW thermionic reactor.

Fig. 8 - Polyethylene/Uranium Neutron Spectrum

The central worth measurements will be carried out by oscillating small samples of thermionic materials in and out of the core center through a narrow coolant channel milled in the fuel element end plates. The samples will be sufficiently thin to warrant an infinite dilution analysis. Reactivity measurements will be made by measuring the variation in the power.

A detailed description of the Doppler coefficient measurements is contained in a separate report.²⁴ The objective of these measurements is to compare experimentally and analytically determined Doppler coefficients of the constituents of thermionic reactors and of the proposed diluents for the enhancement of Doppler coefficients. Measurements on the non-fissile materials will precede those of the fissile nuclides. The temperature dependence of the Doppler coefficients will be determined up to approximately 600°C. The discussion here will be confined to a list of the salient features of this experiment.

1. The configuration, which is sketched in Fig. 9, consists of a spherical sample enclosed in a spherical void at the core center, and should be a calculable geometry.
2. A sensitivity of 10^{-7} to 10^{-8} $\delta k/k$ should be attainable.
3. The temperature of the sample will be elevated and lowered cyclically by a stream of helium gas. In-place heating and cooling of the sample has several virtues. The large reactivity spikes frequently incurred in the more conventional sample oscillation experiment are eliminated. There exist no oscillator or heater assembly perturbations to the flux distribution or reactivity. There are no positioning reproducibility problems.
4. Except for fissile material, there will be no resonance absorbers in the core to introduce significant fine structure in the energy distribution of neutrons seen by the sample. Furthermore, the absence of core heterogeneities precludes any significant degree of spacial fine structure in the flux. These factors considerably simplify the analysis of the Doppler coefficient measurements.

Fig. 9 - Doppler Coefficient Measurement Core Configuration

5. It is anticipated that in the clean geometry envisioned for the Doppler coefficient measurements, the sample expansion coefficient, which frequently dominates the Doppler signal in the measured temperature coefficient of reactivity for fissile samples, will be calculable. Two methods will be employed, however, to minimize the expansion effect. The first is a reduction in density of the sample. Feasibility calculations indicate that the expansion coefficient diminishes much more rapidly than the Doppler coefficient with a reduction in sample density. The second consists of constructing a sample composed of powdered fissile material contained in a matrix of material with an extremely low coefficient of thermal expansion, such as Vycor.
6. The flexible fuel element design permits the addition to the core of a $1/v$ absorbing material, such as boron, for the purpose of depleting the magnitude of the adjoint flux at low energies. A change in the adjoint flux can have a significant effect on the character of the fissile Doppler coefficient, to the extent of changing its sign as well as its magnitude.

The subcritical spectrum measurements will be performed by the pulsed-source, time-of-flight method using the Gulf General Atomic linear accelerator. Neutron spectra will be measured in the energy region from approximately 15 Mev down to a few electron volts. Two considerations are important in the planning of these measurements. The first concerns the degree of similarity between the spectrum in the subcritical assembly and the fundamental mode spectrum characteristic of the critical assembly. Very little experimental information is available in this area. The second consideration concerns the calculability of the source-assembly subcritical configuration. The latter point is considerably more vital than the former, since the cross sections and their treatment are the major areas of uncertainty. Nevertheless, it is desirable to perform the subcritical spectrum measurements at reasonably high values of the multiplication in

order to approximate the effect of leakage on the spectrum in the critical assembly. Measurements of the spectrum at two or more values of the subcritical multiplication, time permitting, could shed considerable light on this question.

The foregoing considerations have led to the configuration shown in Fig. 10 for the subcritical spectrum measurements. The assembly geometry is a finite slab with transverse dimensions considerably greater than the thickness, so that the transverse leakage has a small influence on the spectrum at the center of the slab. Should this be the case, a diffusion theory approximation to the transverse leakage should be adequate for the spectrum calculation. The source is placed at a sufficient distance from the slab to subtend a fairly small angle at the boundaries. A source distribution normal to one face of the slab can then be used in the spectrum calculation. The emergent spectrum is measured at an angle sufficiently removed from the normal direction to avoid uncollided source neutrons.

Exploratory calculations were performed to assess the merits of the proposed scheme for the subcritical spectrum measurements. The results suggested that for an assembly with a multiplication of $5(k_{\text{eff}} \approx 0.8)$, a width to thickness ratio of approximately 2.5, a collimator at roughly 45° to the normal, and a measured source spectrum characteristic of U^{238} photoneutrons, the angular flux spectrum is nearly identical to the fundamental mode spectrum of the infinite slab.

4.2 Category B; One-Region Homogeneous Cores with Complex Composition.

Composition

- i) Fully enriched U-235 plus one or more thermionic reactor materials (such as tungsten, niobium, molybdenum, tantalum, aluminum, oxygen, carbon, sodium, or lithium). Polyethylene may be included in one or more of the cores.
- ii) Fully enriched U-233 plus one or more thermionic reactor materials.

Fig. 10 - Plan View of Configuration for Subcritical Measurements

Configuration

Bare rectangular parallelepiped composed of neutronically homogeneous fuel elements.

Measurements

1. Critical Mass.
2. Central worths for materials of interest to the thermionic reactor program.
3. Subcritical spectrum.

Discussion

Considerable information should be available concerning the cross sections of thermionic reactor materials and their treatment from measurements in Category A. Wherever possible, refinements will have been made in the case of problem areas. Whereas the prior measurements will have been performed in a contrived spectrum, the spectrum in assemblies of this category will be determined at least in part by the thermionic materials themselves. The ultimate objective in this category is to achieve a homogeneous, one-region mockup of a thermionic reactor. Small quantities of polyethylene may be added to at least one assembly to introduce neutrons at the low energy end of the spectrum which would normally be filled by neutrons returning from the reflector.

At a minimum, two U-235 assemblies will be constructed in this category. The first will contain a prominent refractory metal, such as tungsten or niobium. Figure 11 compares the predicted neutron spectrum for a mixture of tungsten, U^{235} , and polyethylene of the number density ratios, $N^W/N^U/N^H = 2/1/0.5$, with the inner and outer core region spectra of a 300 eKw thermionic reactor. The comparison in the high energy region is considerably improved by virtue of inelastic scattering in the tungsten. Central worth measurements in this spectrum will provide a useful augmentation to the earlier results in a somewhat harder spectrum. The final assembly in this category will contain

Fig. 11 - Tungsten/Uranium Neutron Spectrum

a mixture of a sufficient number of thermionic reactor materials to provide a reasonable bare, homogeneous mockup of a thermionic reactor. At this point in the program, measurements of the critical mass and subcritical spectrum should suffice.

Measurements of central worths and subcritical spectra will be carried out by techniques similar to those employed in Category A. It is anticipated that the experience achieved in the previous subcritical spectrum measurements with assemblies of simple composition will considerably enhance the value of spectrum measurements for the complex assemblies in the present category.

At least one assembly fueled with fully enriched U^{233} is also anticipated for this category, after experiments in Categories C and D are carried out with U^{235} . Measurements of critical mass and subcritical spectra will be carried out on assemblies fueled with U^{233} . The timing for the first U^{233} core will depend upon the ease of licensing an assembly fueled with U^{233} .

4.3 Category C; Two-Region Homogeneous Core(s) with Complex Composition.

Composition

The final core composition from Category B.

Configuration

Rectangular parallelepiped composed of neutronically homogeneous fuel elements, reflected on two or more faces by a low atomic mass material.

Measurements

1. Critical Mass.
2. Flux and power distributions.
3. Reflector worths.
4. Spatially-dependent spectrum*

*To the extent feasible.

Discussion

The next step in the critical experiment program is directed toward configurational problems, in particular the core-reflector interaction. Having gained confidence in the analysis of a bare assembly consisting of a homogeneous mixture of thermionic reactor materials, the final assembly in Category B. will be reflected on two faces by an appropriate thickness of low atomic mass material, probably beryllium or beryllium oxide. Reflection in only one dimension will facilitate the analysis somewhat, since the configuration will be separable in the diffusion theory sense. This simplification will draw attention to reflector cross sections and the core-reflector interaction without the additional complication of corner effects. The ability of two-dimensional transport methods to handle these effects will be examined in conjunction with a subsequent core reflected on four faces.

Flux and power distribution measurements will be carried out by conventional small foil activation techniques. Reflector worth measurements will be directed toward an understanding of reflector control problems. Along these lines, reflector modules may be partially loaded with boron or some other strong absorber to simulate configurations envisioned in reactor design studies. Subcritical spectrum measurements are considered as an optional feature in the planning of this category of assemblies. Measurements at the high energy end of the spectrum may be unfeasible by the time-of-flight method because of the increased decay constants of assemblies reflected by low atomic mass materials. This effect and the feasible configurations for spatially dependent subcritical spectrum measurements will be investigated in considerable detail in the near future.

4.4 Category D; Two-Region Heterogeneous Core(s) with Complex Composition.

Composition

The final core composition from Category B or from subsequent thermionic reactor design studies.

Configuration

A core-reflector configuration studied in Category C. The core region will be semi-homogeneous or severely heterogeneous.

Measurements

1. Critical Mass.
2. Flux and Power Distribution.

Discussion

It is anticipated that the initial assembly in this category will contain a very simple core heterogeneity. One conceivable core configuration, which is sketched in Fig. 12, consists of layers of homogeneous core material from Category B separated by void. This configuration has the virtue of being simple and at the same time imposes a severe test on methods for treating streaming effects. Various reflector configurations, both normal and parallel to the orientation of the void, may be examined. An additional core in this category may feature the simulated heterogeneity of actual thermionic converters. The remainder of the core composition and the overall configuration, however, will be maintained as simple as possible.

This category of assemblies will be used to examine the effectiveness of one- and two-dimensional transport theory calculations in treating core heterogeneities and streaming effects. The experience gained in the analysis of assemblies in Categories A through C should permit the separation of these effects from other potential neutronic uncertainties. The measurement of critical mass coupled with an extensive series of flux maps should provide sufficient experimental data to understand these effects.

Fig. 12 - Conceivable Core Configuration for Layered Heterogeneity

4.5 Category E; Engineering Mockup Cores.

This final category of assemblies represents a departure from the basic neutronics technology program encompassed by Categories A through D. Whereas the previous assemblies emphasized calculable configurations for the purpose of separating the neutronics uncertainties, in the present category calculability is secondary to engineering similitude. All of the engineering complexities of the reactor core, including simulated or actual converters, electrical connectors, core reflectors, reflector control drums, and heat removal components will be included, although the first assembly may be constructed "dry", using aluminum or some other suitable coolant simulant. The final core will be a zero power critical experiment for the initial core of the Thermionic Reactor Experiment Program.

The anticipated experimental program in the mockup series of cores will be engineering oriented. In addition to critical mass determinations, detailed power distribution measurements will be carried out to determine the effect of power flattening. Reactivity worths of the converter components and other in-core constituents, such as coolant, structure, and heat removal components will be measured. The coolant void coefficient will be a determination of considerable interest. The isothermal temperature coefficient over a limited range of the temperature may also be determined. The worth of the control drums as a function of orientation and the interaction effects between the various control drums will be measured.

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The intentional lack of detail in plans for the latter stages of the program is evident. It is not considered unlikely that the results from the early assemblies or an unexpected change in the direction of the thermionic space reactor program may bring about a reorientation in the critical experiment program as outlined above. The Thermionic Critical Experiment Program was initiated in April, 1967. A rough time schedule for the neutronic technology portion of the program, Categories A through D, is given by the following.

Category A

Subcritical Spectrum	Month 9
Critical Mass and Initial Neutronics Measurements	Months 10-11
Central Worths	Month 12
Doppler Coefficients	Months 13-15

Category B

Months 17-25

Category C

Months 26-31

Category D

Months 32-36

The neutronic technology program comprises experiments and the subsequent analysis on roughly seven to eleven assemblies over an approximate three year time span. It is felt that such a program at this stage in the evolution of thermionics will be of considerable significance to the development of space nuclear power.

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