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FAST CRITICAL EXPERIMENTS IN SUPPORT OF
THERMIONIC REACTOR PHYSICS

by

S. C. Cohen, R. A. Moore, J. L. Russell, Jr.,
D. A. Sargis, and R. Sharp

August 26, 1968

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ABSTRACT

The objective of the Thermionic Critical Experiment is to compare integral neutronic data from a series of critical assemblies with detailed neutronic calculations and to check analytical methods and cross section data used in the core design of thermionic space power reactors. An orderly progression of assemblies ranging from the very simple in composition and configuration to actual zero-power mockups of thermionic reactors is planned. The early experiments will feature bare, homogeneous assemblies which will provide clean integral data concerning the cross sections of thermionic materials. The integral data will be augmented by differential neutron spectrum measurements by the pulsed source, time-of-flight method.

Assembly No. 1, a bare, neutronically homogeneous mixture of fully enriched uranium and polyethylene, was taken critical on May 10, 1968. The composition was chosen to provide a reasonably clean neutronic simulation of the neutron spectrum for a thermionic reactor core reflected with beryllium oxide. Measurements completed to date include critical mass, sub-critical neutron spectrum, and central reactivity worths of thermionic reactor materials. The results of these initial experiments are compared with analysis.

The final series of experiments with Assembly No. 1 will be the measurements of sample Doppler coefficients for thermionic reactor materials, after which the fuel elements for Assembly No. 2 will be fabricated. Assembly No. 2 will consist of a bare, neutronically homogeneous mixture of a number of thermionic reactor materials. Subsequent experiments will focus upon configurational problems, such as the core-reflector interaction and effects associated with core heterogeneities.

I. INTRODUCTION

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 over-all 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.

A preferred reference thermionic reactor design has not as yet been established, however there are a number of characteristics common to most conceptual designs. The features of a generic in-pile thermionic reactor which most significantly influence the neutronic characteristics are: (1) high fuel densities, (2) low atomic mass reflectors, (3) high concentrations of refractory metals, (4) extremely high operating temperatures, (5) tight temperature restrictions, and (6) modular fuel elements. Principal neutronic design problems concern the diminution of reactor size and weight, the flattening of core power, and reactor safety and control.

The elimination of neutronic uncertainties facilitates the solution of reactor design problems. In a generic thermionic reactor, the principal neutronic uncertainties relate to the inelastic and resonance cross sections of heavy core constituents, the high energy cross sections of light reflector materials, the analysis of reactivity coefficients, the treatment of the core-reflector interaction, and the modeling of complex core heterogeneities.

These areas of neutronic uncertainty have strongly influenced the formulation of the critical experiment program.

An orderly progression of assemblies ranging from the very simple in composition and configuration to the complex are planned. This approach is intended to separate problems involving cross section uncertainties from those associated with analytical methods. The first experiments will incorporate bare, homogeneous assemblies and will provide analyzable integral data concerning cross sections of thermionic reactor materials. Subsequent experiments will focus upon configurational problems, such as the core-reflector interaction and the effects associated with core heterogeneities, leading ultimately to a zero-power mockup of a thermionic space power reactor. A flexible program is anticipated, which will allow for re-orientation in light of unexpected results or a redirection of the thermionic reactor program.

A detailed outline of the program follows in Section II. A brief description of the facility is contained in Section III. Section IV contains the results obtained to date with Assembly No. 1.

II. OUTLINE OF THE CRITICAL EXPERIMENT PROGRAM

Five categories of critical assemblies are planned, each of which will consist of one or more assemblies, depending upon time limitations. The progression of assemblies will be in order of complexity. The first two categories of assemblies are primarily intended to yield integral cross section checks of thermionic reactor materials. In order to eliminate configurational complexities, the assemblies in these categories will be bare, neutronically homogeneous reactors. The first assembly features a simple core composition, enriched uranium plus an elastic scatterer. Cross section checks are 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 reactor materials distributed homogeneously throughout the core. Integral cross section data inferred from core reactivity 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 third and fourth 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 critical mass and power distribution will be of primary interest in this system. 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 will consist of one or more zero power mockups of an actual in-core thermionic space power reactor. A condensed outline of the critical experiment program is presented below.¹

Category A: One-Region Homogeneous Core with Simple Composition

Composition

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

Configuration

Bare rectangular parallelepiped composed of neutronically homogeneous fuel elements.

Principal Measurements

1. Critical mass.
2. Reactivity worths of thermionic reactor materials.
3. Sample Doppler coefficients for materials of interest to the thermionic reactor program.
4. Subcritical spectrum.

Category B: One-Region Homogeneous Cores with Complex Composition

Composition

1. Fully enriched U-235 plus one or more thermionic reactor materials (such as tungsten, niobium, molybdenum, tantalum, aluminum, oxygen, carbon, sodium, or lithium).
2. Fully enriched U-233 plus one or more thermionic reactor materials.

Configuration

Bare rectangular parallelepiped composed of neutronically homogeneous fuel elements.

Principal Measurements

1. Critical mass.
2. Reactivity worths of thermionic reactor materials.
3. Subcritical spectrum.

Category C: Two-Region Homogeneous Core(s) with Complex Composition

Composition

The final core composition from Category B.

Category C: Continued

Configuration

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

Measurements

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

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 investigated in Category C. The core region will be semi-homogeneous or severely heterogeneous.

Measurements

1. Critical mass.
2. Flux and power distribution.

Category E: Engineering Mockup Core(s)

Whereas the previous assemblies emphasized calculable configurations for the purpose of separating neutronic uncertainties, in this category calculability is secondary to engineering similitude. It is anticipated that the zero power critical experiment for the initial core of the Thermionic Reactor Experiment Program will be conducted under this category.

Measurements

1. Critical mass.
2. Flux and power distribution.
3. Reactivity worths of converter, structural, and coolant components.
4. Coolant void coefficients.
5. Control drum worths.
6. Isothermal temperature coefficient.

III. DESCRIPTION OF THE CRITICAL FACILITY

The Thermionic Critical Facility includes the reactor building, an office building which houses the reactor control room, and a fuel assembly building. The critical assembly is mounted on a split-bed assembly machine on the first floor of a structural steel platform at the center of the reactor cell. A condensed description of the principal components of the facility is given below.²

Assembly Machine

The assembly machine, shown in Figure 1, consists of a frame supporting two sets of tracks, one inclined and one horizontal, that carry two movable beds. A third bed is rigidly fixed to the center of the assembly machine. The inclined bed provides gravity scram capability. Two speeds of closure are available and controlled by separate motors. The assembly machine is surrounded by a cage, which allows free access to the core components by hands and arms, but not the trunk of the body, in order to prevent the so-called "fat man" accident.

Fuel Elements

Fuel elements consist of stacks of fuel foils interleaved with foils of other materials. The packet of foils is drilled and held together between two stainless steel endplates. The endplates are supported on uranium metal posts which provide structural integrity and fix the thickness of a fuel element. Additionally, the posts provide a reliable one-dimensional prompt core expansion mechanism for reactor safety. A closeup of two stacked nominal-sized fuel elements, each of which is $2\frac{7}{8} \times 2\frac{7}{8} \times 1.03$ ", is shown in Fig. 2.

The endplates are milled to provide thin air coolant channels. The provision for air cooling permits the attainment of rapid temperature equilibrium for relatively high power experiments (~ 100 watts). An additional fuel element feature is the inclusion of recessed conical springs

Fig. 1 Photograph of Shutdown Critical Assembly on Beds of Assembly Machine

Fig. 2 Photograph of Two Nominal Sized Fuel Elements

restrained by the screws which hold the endplates to the posts through a threaded sleeve of Phenoxy plastic. In the event of a spurious temperature rise, the Phenoxy threads would fail (at $\sim 100^{\circ}\text{C}$) and allow the conical spring to expand, thus providing a rapid core separation and reactor shutdown.

Matrix Assembly

The fuel elements are stacked into three independent matrices to form three sections of the reactor core. Each matrix consists of an interlocking array of fuel elements. Core stability is accomplished by mating pins and recesses provided in each of the screws which hold down the fuel element endplates. Figure 1 shows the assembly in its shutdown state.

Control/Safety Elements

The safety and control elements consist of slightly undersized fuel elements inserted into one face of the core inside stainless steel guide channels. The guide channels are inserted into the horizontal bed core section, as shown in Figure 1. The total travel of each element is approximately four inches. The control/safety element motion is accomplished by a magnetic coupling which attaches the drive rod to a lead screw. A pneumatic piston and spring backup are positioned on the coupling so that breaking the magnet current releases the drive rod and allows the spring and air pressure to drive the control/safety element out of the core. A minimum of three control/safety elements is provided in any core.

Control Console and Instrumentation

The control console, shown in Fig. 3, is designed for one-man operation of all reactor systems. The basic controls are on a sloping panel using diagrams with lighted indicators to show contact closures, bed positions, control/safety element positions, and source position. Three neutron level indicating strip chart recorders are located on the upper portion of the vertical panel in front of the operator.

The nuclear instrumentation consists of two log N-Period ion chamber channels, two linear photomultiplier channels, two linear ion chamber channels, and one BF_3 proportional counter channel.

Fig. 3 Photograph of Control Console

IV. RESULTS TO DATE WITH ASSEMBLY NO. 1

The principal constituents of Assembly No. 1 are fully enriched uranium and polyethylene. The polyethylene is incorporated in a sufficient quantity ($N^H/N^{U-235} \approx 0.8$) to simulate the average core spectrum at low energies in a reflected generic thermionic reactor.¹ Fuel elements are constructed from 0.001" foils of fully enriched uranium and 0.002" foils of polyethylene. The volume fractions and number densities for the constituents of an average fuel element are given in Table I.

Table I

CONSTITUENTS OF FUEL ELEMENT FOR ASSEMBLY NO. 1

<u>Constituent</u>	<u>Elements</u>	<u>Volume Fraction</u>	<u>Number Density (atoms/b-cm)</u>
Uranium		0.476	
	U-235		.02146
	U-238		.00155
	Oxygen		.00020
Polyethylene		0.232	
	Carbon		.00917
	Hydrogen		.01834
Stainless Steel (304)		0.108	
	Iron		.00665
	Chromium		.00188
	Nickel		.000790
Inconel-X		0.010	
	Nickel		.000640
	Chromium		.000152
	Iron		.000079

Critical Mass

Assembly No. 1 was taken critical on May 10, 1968. The measured critical mass was 98.83 kgms. of enriched uranium, or 78 fuel elements (including control/safety elements). The pre-critical prediction for the critical mass was 76.7 fuel elements, a 1.8% deviation in mass from experiment. The analysis made use of one- and two-dimensional discrete ordinates transport theory^{3,4} and incorporated ENDF/B cross sections⁵ for the principal core constituents. Utilization of other cross section sets^{6,7} gave rise to less than 0.5% change in the predicted k_{eff} . The analysis included a correction of $0.9\% \frac{\delta k}{k}$ for core reflection by structural components. The effect of core heterogeneity was determined to contribute less than $0.1\% \frac{\delta k}{k}$.

Fuel Block Reactivity Worths

The reactivity worth of several fuel blocks, including the control/safety elements, was measured as part of the reactor safety program. The control/safety elements were calibrated using the "rod drop" method and the incremental period method for the element of least worth. Fuel element worths were measured against the control/safety elements.

The comparison between measured and predicted fuel block worths is given in Table II for the core configuration sketched in Figure 4. Note that positions H-5, H-11, and H-17 are the control/safety elements. The analysis was performed using a synthetic three-dimensional transport method incorporated into the GAPER code.⁸

Subcritical Spectrum

The spectrum of a subcritical ($k_{eff} \approx .63$) section of Assembly No. 1, consisting of a slab 4 fuel elements wide and 11 fuel elements high, was measured from 6 Mev to 100 eV using the pulsed-source, time-of-flight method. A plan view of the configuration for the spectrum measurement is shown in Figure 5. A depleted uranium target spaced 14 in. from the center of one face of the assembly provided an isotropic, pulsed neutron source spectrum which was measured separately. An extensive combination

Fig. 4 Assembly No. 1 Core Configuration

Fig. 5 Configuration for Subcritical Spectrum Measurement

Table II
COMPARISON BETWEEN MEASURED AND PREDICTED
FUEL BLOCK REACTIVITY WORTHS

<u>Fuel Block Position</u>	<u>Measured Worth</u>	<u>Predicted Worth</u>
C-26	\$ 1.43 $\pm$.03	\$ 1.452
H-26	\$.753 $\pm$.01	\$.760
H-25	\$.396 $\pm$.01	\$.391
H-17	\$ 1.94 $\pm$.04	\$ 2.039
H-11	\$ 1.94 $\pm$.04	\$ 2.039
H-5	\$ 1.20 $\pm$.01	\$ 1.179

boron carbide-boric acid shield, designed to eliminate room return, surrounded the source. The emergent spectrum from the subcritical assembly was extracted through a collimated 50 meter flight path positioned at 42° to the normal of the assembly.

The angular flux spectrum was computed using discrete ordinates transport theory in an S_{10} approximation. The conventional ENDF/B data for U-235⁵ were used down to ~ 20 Kev, and unresolved resonance parameters recently recommended by Pennington⁹ were used below 20 Kev. The GAM-II code¹⁰ was used to obtain 27 group, P_1 cross sections, and the GANDY code¹¹ was used to perform the self-shielding calculations in the unresolved resonance region. The assembly configuration was approximated by infinite slab geometry, incorporating a DB^2 correction to account for transverse leakage. Using the measured source spectrum, the neutron source was included in the calculation as a surface source normal to one face of the slab. The measured and predicted spectra were normalized at 1.80 Mev and are compared in Fig. 6.

Fig. 6 Comparison between Measured and Predicted Subcritical Spectrum for Assembly No. 1

Reactivity Worths

Central reactivity worths of thermionic reactor materials were measured in Assembly No. 1 by inserting small samples into the core center through a fuel element coolant channel. A photograph of the oscillator mechanism used to insert the samples during critical operation of the assembly is shown in Fig. 7. The samples, measuring 3/4" diameter by 0.020", were mounted in a slot in a stainless steel strip which was continuous throughout the coolant channel. Reactivities were measured by the period method.

Multigroup cross sections used in the analysis of the central reactivity worth measurements were obtained using the GAM code,¹⁰ and in some cases, the recently developed GAF/GAR/GAND code.¹² A comparison between measured and predicted central reactivity worths is given in Table III.

Table III
CENTRAL REACTIVITY WORTHS IN ASSEMBLY NO. 1

<u>Sample</u>	<u>Measured*</u> <u>Reactivity Worth</u> <u>(¢/mole)</u>	<u>Predicted</u> <u>Reactivity Worth</u> <u>(¢/mole)</u>
U-235	+ 55.6 ± 2.1	+ 65.8
U-233	+ 99.9 ± 3.8	+ 126.8
U-238	+ 5.16 ± .66	+ 7.46
Tungsten	- 4.61 ± .49	- 6.35
Niobium	- 4.74 ± .58	- 1.79
Tantalum	- 25.1 ± 1.1	- 24.1
Hafnium	- 20.0 ± 0.9	- 22.9
Dysprosium	- 30.5 ± 1.3	- 100.5
Vanadium	- 1.00 ± 0.71	+ 2.11
Zirconium	- 1.36 ± 1.04	+ 1.37
Aluminum	+ 0.879 ± .64	+ 1.23
Stainless Steel	- 1.40 ± .50	+ 0.93
Polyethylene	+ 40.5 ± 1.4	+ 45.1
Beryllium	+ 32.9 ± 2.9	+ 46.5
Carbon	+ 0.719 ± .32	+ 1.77
Boron-10	- 88.1 ± 3.4	- 109.0

* ± is the probable error

Fig. 7 Photograph of Oscillator Mechanism for Reactivity Worth Measurements.

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