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AN ENRICHED UO_2 -
ZrH CRITICAL ASSEMBLY

AEC Research and Development Report

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CONTENTS

	Page
I. Introduction	1
II. Assembly Configuration	1
III. Instrumentation	5
IV. Experiments	7
A. Reactivity Measurements	7
B. Activation Measurements	25
C. Intrinsic Behavior Measurements.	26
V. Conclusions	29
References	30

TABLES

I. Dimensions of the Four Critical Configurations	8
II. Densities of Materials in Each Reactor Region	9
III. Reactivity Coefficient Measurements	24
IV. Reactivity Worth, Cents per Gram	24

FIGURES

	Page
1. SNAP Critical Assembly (SCA)	2
2. Critical Assembly Machine	3
3. Instrumentation Block Diagram.	6
4. Graphite Thickness Variations	10
5. Critical Mass <u>vs</u> Graphite Reflector Thickness, Four Assemblies .	11
6. Reactivity <u>vs</u> Time, Hemisphere and Cap Closure (Crit Number 4) .	12
7. External Reflector Sample Device.	13
8. Reactivities of Reflector Elements External to the SNAP Critical Assembly (R the Distance from the Reactor Center to the Sample .	15
9. Reactivity <u>vs</u> Reflector Thickness	16
10. Effect of Cadmium Sheet Location on Reflector Worth	17
11. Sample Tube Changing Device	18
12. Section of Upper Hemisphere Showing Sample Tube Configuration .	20
13. Sensitivity of SCA Corrected for Self Shielding - $3.7\phi/\text{cm}^2$ of 1/v Thermal Neutron Absorber Sample 1.3 cm Above Center of Assembly	21
14. Reactivities as Measured in the SNAP Critical Assembly	22
15. Reactivity Worth of Neutron Moderating Materials	23
16. Power Distribution <u>vs</u> Radius of Reactor (Four Reflector Thicknesses).	27
17. Normalized Foil Activations <u>vs</u> Radial Position	28

I. INTRODUCTION

The SNAP (System for Nuclear Auxiliary Power) Program to furnish nuclear reactor auxiliary power for application in space necessitates a minimum weight reactor system. The core configuration for these systems is in a region of reactor design in which little experimental work has been performed. Therefore, a critical assembly which simulated a SNAP reactor was fabricated and operated to substantiate and augment nuclear calculations.

II. ASSEMBLY CONFIGURATION

The SNAP Critical Assembly (SCA) is a pseudospherical nuclear reactor with a fixed hydrogen moderator, U-235 fuel, and a beryllium and graphite reflector. The critical assembly core is made up of segments of cold pressed zirconium hydride with 8% by weight UO_2 powder. The uranium is 93.17% U-235. These powder compacts were cold pressed at a pressure of 30 tons/in² to form solid blocks having ~80% of theoretical density. Identical blocks of zirconium hydride, containing no fuel, were also formed. The blocks are fitted together to form cylindrical rings of varying heights, as shown in Figure 1. An inner reflector of machined beryllium ~1-inch thick and an outer reflector of graphite of variable thickness surround the core. The graphite portion of the reflector is built in pieces which are removable, thus allowing adjustment of reactivity in small increments. Outer surfaces of the core and the two reflectors are approximately spherical.

The critical assembly is constructed in two hemispheres, having horizontal faces which are brought in contact. The upper hemisphere is stationary, while the lower hemisphere including the control cap (an assembly of beryllium and graphite plates located at the base of the lower hemisphere) is mounted on the movable lower base of the assembly machine. The reactivity worth of the control cap is adjustable by changing the location of some of the reflector plates from the cap to the adjacent core, or vice-versa.

The machine that holds the critical assembly, shown in Figure 2, is so designed that reactivity can be inserted at a rate no greater than that predetermined from safety considerations. Energizing the machine first brings the two

Figure 1. SNAP Critical Assembly (SCA)

Figure 2. Critical Assembly Machine

hemispheres to a 2 inch separation in a period of ~ 6 minutes. At this point the closure becomes non-linear, being controlled by rotation of a cam so machined that the reactivity insertion rate is less than $0.010\% \Delta k/\text{second}$. Complete closure of the hemispheres is achieved in ~ 30 minutes. The lower hemisphere contacts the upper hemisphere and lifts it ~ 0.02 inches. A limit switch on the cam then terminates the motion. Assembly is completed by raising the control cap. During the assembly process, positions are indicated by Selsyn transmitters on the drive motors operating receivers connected to a digital readout at the control console. Closed circuit television is used to read a dial micrometer that measures lower hemisphere position (accurate to 0.001 inches) over the last 3 inches of travel. A second dial micrometer (accurate to 0.0001 inches) gives the position of the upper hemisphere. Neutron multiplication measurements are made at various stages of assembly, so as to estimate the reactivity of the system.

The system is isolated during operation in a gas-tight room. The room air is maintained at a negative pressure corresponding to 0.5 inches of water. The wall thickness is sufficient to provide satisfactory shielding for the operating personnel for incidents of less than a 50 Mw-sec energy release.

III. INSTRUMENTATION

The operating instrumentation block diagram is shown in Figure 3. Four U-235 fission chamber counting channels are provided. These are equipped with Westinghouse No. 6376 chambers, Atomic Instruments No. 218 linear amplifiers and associated preamplifiers, and Atomic Instruments No. 131 scalars. In addition, the output of each of two of the amplifiers is used to operate a Hewlett-Packard No. 523-B electronic counter in conjunction with a 560-A digital (printing) recorder. The ionization chambers are a Westinghouse No. 6937 and an Atomics International Huntsinger type (boron lined), driving a Keithley 410 logarithmic and 412 linear micro-micro ammeter respectively. The chambers are located around the sides and above the top of the assembly.

Subcritical multiplication measurements are made with the four counting channels. Stable period determinations are made by plotting the output of a recorder (count rate vs time) on semi-log paper and drawing the best (visual) straight line through the points. The count rate is observed for more than two decades of rise.

Additional instrumentation is provided for the requirements of various experiments. These will be discussed in Section IV.

Figure 3. Instrumentation Block Diagram

IV. EXPERIMENTS

Measurements made with the SCA are of three general types: 1) reactivity, 2) activation, and 3) intrinsic behavior of the nominally steady state system.

Reactivity measurements are those in which the response of the reactor as a multiplying system is observed when changes are introduced into the configuration or properties of the reactor system. The response of the reactor is interpreted to explain the change in criticality of the system.

Activation measurements are those in which detectors made of materials that become radioactive as a result of neutron absorption are placed in the reactor. After the reactor is operated at a fixed power for a predetermined time, the detectors are removed and monitored to determine their radioactivity. The relative activations of various materials gives insight into the behavior of neutrons in the reactor system.

Intrinsic behavior measurements of a nominally steady state assembly allow relating the observed fluctuations in neutron flux (with no configuration change) to some of the properties of the system, i. e., the ratio of prompt neutron lifetime to effective delayed neutron fraction.

A discussion of the experiments follows.

A. REACTIVITY MEASUREMENTS

1. Critical Loading

The reactor core was first loaded with non-fueled zirconium hydride blocks with the maximum graphite reflector surrounding the core. The neutron source was placed in the center of the core, the entire assembly closed to the operating configuration, and an initial count rate determined. The hemispheres were then separated and a number of zirconium hydride blocks replaced by fuel bearing zirconium hydride blocks and the reactor again assembled. The new count rate over that for the first configuration was related approximately to the change in the multiplication factor.

The process of replacing non-fueled blocks with fueled blocks was repeated, maintaining so far as possible the spherical geometry, until the reactor was critical. The outside layer of graphite reflector was removed and a new approach to critical made. The process of removing graphite layers and then increasing fuel

loading to achieve criticality was repeated, until no non-fueled blocks remained in the core. This is the standard operating configuration. In all, four critical configurations were achieved; the pertinent quantities are listed in Table I. The average densities of the elements in each region is given in Table II. The graphite reflector arrangement for each of the configurations is shown in Figure 4. The variation of critical mass with graphite reflector thickness is shown in Figure 5.

TABLE I
DIMENSIONS OF THE FOUR CRITICAL CONFIGURATIONS

Assembly	Outer Radius of Region (cm)				Mass of U-235 - for Criticality (gm)
	Region 1 UO ₂ -ZrH ₂	Region 2 ZrH ₂	Region 3 Be	Region 4 Graphite	
1	12.28	13.87	17.15	25.4	2070
2	12.51	13.87	17.15	23.5	2222
3	13.06	13.87	17.15	21.6	2540
4	13.81	13.87	17.15	19.7	3000

Multigroup diffusion theory calculations of the four configurations gave calculated k_{eff} 's of 1.019, 1.010, 1.005 and 0.993 respectively.¹

The amount of material on the control cap is adjusted such that the maximum reactivity insertion rate is 0.010% Δk sec. The reactivity insertion rate as a function of time is shown in Figure 6.

2. External Reflectors

The small size of SNAP reactors results in extremely high leakage (on the order of 45%). Because of this high leakage the importance of reflecting material outside the core is quite high. To measure the relative abilities of various materials to reflect neutrons back to the system, a remotely controlled device was fabricated which positioned samples at various distances from the reactor. The device is shown in Figure 7. A remotely operated turntable or "lazy susan" is free to rotate in order to bring the samples into position where

TABLE II
DENSITIES OF MATERIALS IN EACH REACTOR REGION

Material	Atoms/cm ³
Region I - Fueled Region	
U ²³⁵	0.000697 x 10 ²⁴
U ²³⁸	0.0000505
Oxygen	0.00157
Hydrogen	0.0472
Zr (as ZrH ₂)	0.0248
Zr (metal)	0.000377
Aluminum	0.00124
Stainless Steel	0.00063
Region II - Hydride Spherical Shell	
Hydrogen	0.0493 x 10 ²⁴
Zr (as ZrH ₂)	0.0259
Zr (metal)	0.000377
Aluminum	0.00124
Stainless Steel	0.00063
Region III - Interface Inside the Be Casting, Largest Fuel Can, and Beryllium Reflector	
Beryllium	0.1167 x 10 ²⁴
Zirconium	0.00154
Aluminum	0.00161
Stainless Steel	0.00074 (volume fraction)
Region IV - Graphite Reflector	
Carbon	0.0796 x 10 ²⁴

Figure 4. Graphite Thickness Variations

Figure 5. Critical Mass vs Graphite Reflector Thickness,
Four Assemblies

Figure 6. Reactivity vs Time, Hemisphere and Cap Closure
(Crit Number 4)

Figure 7. External Reflector Sample Device

a traveling electro-magnet can pick them up and position them. Sample position is indicated by a Selsyn transmitter and receiver and a digital readout. The samples were circular plates 18.3 cm in diameter and 1.9 cm in thickness. Liquid samples were contained in a steel can of approximately the same dimensions.

The assumption of angular isotropy of those neutrons leaking from the reactor and being scattered back by the reflector sample leads to a reactivity relationship that is, to a first approximation, linear in the reciprocal of the fourth power of the distance from the reactor center. That this is the case is borne out by the results displayed in Figure 8.

The above samples were positioned outside of the beryllium and graphite reflector. In order to continue the external reflector experiments up to the fuel region, the top cap (a section of reflector similar to the control cap located in the lower hemisphere) was removed and various amounts of the material under investigation placed in this location. The measured reactivities for the various amounts of different materials in this position are shown in Figure 9.

In order to estimate the relative importance of sub and epi-cadmium neutrons entering into the reflector at the top cap location, the following experiment was performed. The reflector was built up of the layers described in the previous experiment with a 0.040 inch thick sheet of cadmium positioned on top of the sample layers. The change in reactivity as the cadmium sheet was relocated between layers and below the sample was measured and compared with the previously determined reactivity worth of the sample (with no cadmium) as a function of thickness. The results are displayed in Figure 10. It is seen that complete isolation of the reflector from the core for neutrons of energies less than about 0.5 ev has less than a 10% effect for nickel and beryllium but about a 50% effect for hydrogenous reflecting materials.

3. Internal Reactivity Measurements

Reactivity traverses have been made through the core utilizing a remotely controlled device that can position samples in a hole located in the top hemisphere. The remotely operated positioning device was located above the top hemisphere of the SCA, as shown in Figure 11. It was composed of a "lazy susan" so arranged that sample tubes could be positioned over a central hole in the top hemisphere of the reactor. Sample tubes were then lowered into the hole by the

Figure 8. Reactivities of Reflector Elements External to the SNAP Critical Assembly
(R the Distance from the Reactor Center to the Sample)

Figure 9. Reactivity vs Reflector Thickness

Figure 10. Effect of Cadmium Sheet Location on Reflector Worth

Figure 11. Sample Tube Changing Device

electro-magnet assembly. The sample tubes were aluminum tubes (1.6 cm in diameter) in which fuel blocks (1.27 cm in diameter and 1.27 cm in length) and test material were so arranged that reactivity measurements could be made with the test material either at 1.3 cm above the center of the reactor or at positions farther out from the center. A schematic drawing of the configuration is shown in Figure 12. The samples tested varied from reactor poisons that only absorb neutrons to moderators considered to have no neutron absorbing characteristics. The results are displayed in Figures 13 through 15 and in Table III.

Reactivity measurements 1.3 cm above the center of the core also included cadmium covered samples in order that the effective neutron spectrum could be approximated. Resonance absorbers with resonance peaks at widely varying energies were measured at the bottom of the reactivity measuring hole, both bare and cadmium clad. In addition to the resonance absorbers, boron was measured in the same configuration. Various concentrations of each material were measured by dispersing the material in powdered graphite in containers of the above dimensions. The effect of self-absorption was eliminated by extrapolating the measured worths to zero concentration. The results are given in Table IV. Also included are the measurements of epi-cadmium reactivity effects in aluminum, copper, and zirconium. The estimated standard deviation is 5 to 10%. From these cadmium ratios, it is possible to adjust the calculated energy dependent neutron densities in order that there is correspondence between analysis and experiment. The results are consistent with a neutron spectrum with a maximum occurring above 0.13 ev (Reference 2).

Such a spectrum is higher in energy than would be expected on the basis of distortion of a Maxwellian distribution by the strong thermal absorption of U-235. It is believed to be due to binding of the hydrogen in zirconium hydride, with quantization of energy levels.

4. Subcritical Reactivity Calibrations

Due to an imposed operational limitation on available excess reactivity, it is not feasible to do reactivity calibrations at the SCA by the usual "rod bump" stable period method. For calibrations involving a change of reactivity of more than about 30 cents, both subcritical multiplication and rod drop techniques have been employed.

Figure 12. Section of Upper Hemisphere Showing Sample Tube Configuration

Figure 13. Sensitivity of SCA Corrected for Self Shielding - $3.7\phi/\text{cm}^2$
of $1/v$ Thermal Neutron Absorber Sample 1.3 cm Above
Center of Assembly

Figure 14. Reactivities as Measured in the SNAP Critical Assembly

Figure 15. Reactivity Worth of Neutron Moderating Materials

TABLE III

REACTIVITY COEFFICIENT MEASUREMENTS
(Samples were located 1.3 cm above the center of the reactor)

Element	Weight (grams)	$\rho_{\text{element-fuel}}$ (cents)	$\rho_{\text{element-void}}$ (cents)	$(\rho_{\text{element}} - \rho_{\text{void}})/$ weight (cents/gm)
Aluminum	4.37	-2.6	-0.3	-0.07
Beryllium	2.95	-1.2	+1.1	+0.37
Bismuth*	6.51	-	0.0	0.0
Carbon	2.61	-1.9	+0.4	+0.15
Copper	14.24	-4.4	-2.1	-0.147
Iron	12.46	-3.6	-1.3	-0.104
Lead	18.91	-2.3	0.0	0.0
Mercury†	17.77	-	-13.3	-
Nickel	15.0	-5.1	-2.8	-0.187
Sodium*	1.14	-	0.0	0.0
Sulphur	3.12	-2.3	0.0	0.0
Tin*	5.72	-	-0.1	-0.017
Uranium- 0.4% U-235	31.19	-4.4	-2.1	-0.067
Yttrium	7.32	-2.7	-0.4	-0.055
Zirconium	10.21	-2.4	-0.1	-0.0098

*Measured inside stainless steel container. Sensitivity inside is 0.81 times normal sensitivity as measured with copper in both positions.

†Sample is self-shielded

TABLE IV
REACTIVITY WORTH, CENTS PER GRAM

Element	Bare	Cadmium Covered
Aluminum	-	+0.037
Boron	-158	-29.1
Copper	-	-0.006
Erbium	-20.8	-5.7
Gadolinium	-230	-5.1
Lutetium	-7.4	-6.6
Mercury	-5.3	-0.41
Samarium	-154	-9.6
Zirconium	-	+0.19

The usual subcritical multiplication method assumes that only the fundamental mode of the neutron density is of importance, even when the reactor is subcritical. At the SCA, two factors tend to increase the importance of the other modes: 1) the source (after the initial approach to critical) is located outside the assembly and the source term in the flux expression therefore emphasizes higher modes, and 2) the fission chambers are positioned outside of the reactor and thus see only leakage neutrons. Higher modes have greater leakage probabilities than the fundamental mode.

These difficulties are avoided in the rod drop technique. In this method the reactor is first brought to its operating level and held there for several minutes to allow equilibrium with the delayed neutron precursor concentration. A negative step of reactivity is then introduced. For several seconds after the step, the neutron source (i.e., the precursors) is in the fundamental mode distribution of the critical reactor. For small changes this is in effect identical to the fundamental mode of the new configuration. The effect of the higher modes is believed to be negligible.

A subcritical calibration of the control cap gives 70 cents as the total reactivity worth for a particular assembly configuration. The worth of the cap was also measured by means of a rod drop experiment. The measured neutron flux vs time was interpreted by means of AIREK, a reactor kinetics code, to give a control cap worth about 10% greater than that given by the subcritical calibration.

5. Temperature Coefficient Measurements

The assembly was heated by means of heat lamps directed on the outer reflector. Thermocouples were used to measure the temperature at various locations in the core and reflector. Reactivity changes were observed on four uninterrupted cycles of heating and cooling. The data was analyzed to give a temperature coefficient of $(-2.47 \pm 0.03) \times 10^{-5}/^{\circ}\text{C}$ over the range 30 to 65°C.

B. ACTIVATION MEASUREMENTS

Activation of U-235 foils in the reactor gives the power distribution and the effective endpoints at which the neutron density extrapolates to zero. The foils are 0.0025 cm in thickness and 1 cm² in area. The activated foils

are removed from the assembly and placed in a scintillation counting apparatus consisting of a sodium iodide crystal coupled optically to a photomultiplier, the output of which goes to a linear amplifier and a scaler. Gamma activity (in this case due to the fission products) time decay of each foil is monitored and plotted. The curves are read at a specific time in order to determine the relative activations.

Gamma activity monitoring was chosen over beta counting because the errors introduced by slight variations in foil thicknesses and weights and small geometrical changes are either easily corrected (on a mass basis) or are negligible. The importance of self-shielding in beta counting increases the magnitude of these errors.

The power distribution as given by bare U-235 foils, was measured for the four critical configurations. The results are shown in Figure 16.

Bare and cadmium covered resonance and threshold detectors were also activated in order to measure the spatial distribution of neutrons as a function of neutron energy. The normalized activities, plotted as a function of the radius of the reactor, are shown in Figure 17. Since the fissioning of thorium is by neutrons with energies above 0.5 Mev, that of cadmium covered U-235 by neutrons above 0.5 ev, that of bare U-235 by neutrons of all energies, and the activation of cadmium covered indium by neutrons with energies near 1.4 ev, the results imply that the spatial distribution of neutrons in the reactor may be approximated by a single mode independent of the energy of the neutrons.

C. INTRINSIC BEHAVIOR MEASUREMENTS

The ratio of prompt neutron lifetime to effective delayed neutron fraction was measured in the fourth assembly configuration by both the noise analysis³ and the Rossi-alpha⁴ methods. The noise analysis method interprets the departure of the frequency distribution of neutron density fluctuations from the constant distribution of truly random fluctuations in terms of the above ratio. The Rossi-alpha method utilizes a multi-channel counting system to observe the time decay of neutron density following the introduction of a random burst of neutrons in the slightly subcritical reactor.

The results are in good agreement, giving a value of the ratio of 0.00165 seconds. Using a calculated effective delayed neutron fraction of 0.0085 (Reference 5), this gives ~14 microseconds for the prompt neutron lifetime.

Figure 16. Power Distribution vs Radius of Reactor
(Four Reflector Thicknesses)

Figure 17. Normalized Foil Activations vs Radial Position

V. CONCLUSIONS

The information obtained in these experiments has led to the design and construction of the SNAP experimental reactor which has been operated at 50 kw and 1200°F outlet temperature.⁶

REFERENCES

1. C. M. Podeweltz, "SNAP 10 Critical Assemblies," NAA-SR-MEMO-5315, May 24, 1960
2. R. Brehm, personal communication
3. C. E. Cohn, "Determination of Reactor Transfer Functions by Pile Noise Analysis," Transactions of the ANS, Vol 1, No. 1, Paper 21-3 (1958)
4. J. D. Orndoff, "Prompt Neutron Periods of Metal Critical Assemblies," Nuclear Science and Engineering, 2, (1957) pp 450-460
5. L. A. Wilson, "SNAP II Experimental Reactor Physics Analysis," NAA-SR-3607, June 1959
6. John A. McCone, talk before American Rocket Society Meeting, Washington, D.C., November 19, 1959