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FOR DESIGN OF
SUBCRITICAL WATER-IMMERSED SNAP REACTORS
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EXPERIMENTAL INVESTIGATIONS
FOR DESIGN OF
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(Title Unclassified)

By

W. H. HENEVELD

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I. INTRODUCTION

The primary goal of the Aerospace Safety Program is the development of inherently safe SNAP reactor systems. A major consideration in the safety of an operational SNAP reactor is the potentially large excess reactivity associated with submersion of the reactor in water. One method for preventing criticality is to design reactors that are intrinsically subcritical under this adverse condition, yet are not impaired with respect to their normal functioning. This approach requires an understanding of both reactor design requirements and the reactivity effects of water immersion. Analytical studies of low-power (SNAP 10A) and higher-power (SNAP 8) applications conclude that intrinsic subcriticality can be achieved with acceptable modifications. This preliminary analysis shows that all reactor design parameters, including core composition, core geometry and reflector geometry are involved in determining an optimum intrinsically subcritical design; also, that the selected location of a primarily thermal poison in the core geometry to utilize the shift in neutron spectrum in a water environment can aid in attaining intrinsic subcriticality.

The ultimate purpose is to provide, by means of analysis and experiment, the necessary understanding to apply an intrinsically subcritical design criteria to all SNAP reactor designs. A large variation of present design parameters will be encountered and since the effects of water immersion cannot be determined by simple analytical approaches, a close coordination of experimental and analytical effort is required. Thus experiments at this time were primarily directed toward providing a normalization for calculational models rather than a basis for a specific reactor design.

Of primary importance in all these studies is the determination of reactivity of the SNAP reactor in a water environment. A basic condition assumed throughout these studies is the ejection of the beryllium reflector prior to immersion of the system in water. The measurement of the excess reactivity of a SNAP 10A type core (SCA-4) immersed in both distilled water and seawater includes the extremes of water environment which can be anticipated.

Ideally, the SNAP reactor should be designed to contain sufficient cold, clean, excess reactivity for performance at operational conditions, yet remain subcritical when immersed in water as a result of an accident during handling or

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launch, i. e., be intrinsically subcritical. Two approaches to the design of an intrinsically subcritical water immersed core were investigated in this study.

A. UTILIZATION OF THE SHIFT IN THERMAL NEUTRON ENERGY BY NON- $1/v$ ABSORBERS

The increased moderation associated with the introduction of water into and around the system results in a significant increase in system reactivity and a shifting of the thermal spectrum from a peak around 0.1 ev to lower energies. This effect may be used to advantage by introducing an absorber into the system whose energy dependence makes it more effective in a water immersed core than in an operational (beryllium reflected) system. Europium, samarium, and cadmium all exhibit large resonances at or above the energy corresponding to the peak of the zirconium-hydride spectrum, whereas gadolinium has its zero-energy resonance near the peak energy of the water spectrum. Gadolinium introduced into the system will provide a significant difference in poisoning ability between the operational and water-immersed core.

An examination of the radial flux distribution in a water-immersed core without a beryllium reflector reveals a large peak in the thermal neutron flux just a few centimeters distance into the water reflector region. This results from a large current of thermal neutrons that are returned to the core. By placing a strong thermal neutron absorber on the core vessel, a large fraction of the neutrons, which thermalized in the water reflector, will be removed before returning to the core. In the operational reactor, neutron flux in the beryllium is reflected with less energy loss, and consequently in less thermal neutron production. Thus the same amount of absorber applied to the core vessel in the operational environment has proportionally less effect. The experiments performed in this study were designed to measure the relative worth of gadolinium when applied to the core vessel and to the fuel cladding in both the operational (beryllium reflected) SCA-4A system and water immersion (SCA-4B) system. Coatings with values of $\Sigma_a t$ (at 0.025 ev) ranging from 0.1 to 0.3 were applied to each fuel rod; values of $\Sigma_a t$ up to 0.3 were applied to the surface of the core vessel.

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B. VARIATION OF CORE GEOMETRY TO MAXIMIZE THE ADVANTAGE OF A BERYLLIUM REFLECTOR OVER WATER

For SNAP reactor reflectors, beryllium is more efficient than water. The selection of a core shape with high radial leakage will maximize the importance of the radial reflector and subsequently enhance the advantage of beryllium over water. It should be possible then to design a core which is subcritical in water (without a radial beryllium reflector), and yet have sufficient control with the beryllium reflector to meet the operational requirements. Experimental studies of these effects will provide an evaluation and normalization of calculational methods. The experiments described in the core geometry section of the report are designed to provide information on the relationship between critical height and core radius for water-immersed, uranium-zirconium hydride cores. The configurations studied included cores with and without axial reflectors of beryllium oxide for equivalent diameters ranging from 8.16 to 11.35 in. The critical heights, reactivity coefficient of height changes, and flux distributions were measured.

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II. SUMMARY

The experimental results are presented as normalization for establishing the reactivity of SNAP type cores immersed in water and for evaluating methods that reduce the positive reactivity effect of water immersion. The design of an intrinsically subcritical core will involve a combination of factors, including core composition, core geometry, beryllium oxide axial reflectors, and the use of gadolinium poison. The experimental results offered in this report provide a basis for these designs. Additional experimental effort is required to study the effect of core composition and the combined effects of all these factors.

The excess reactivities of a SNAP 10A type core measured during seawater and fresh water immersions were \$9.54 and \$11.60, respectively.

The greatest measured reactivity worth of gadolinium on the fuel cladding of a SNAP 10A type core was \$10.65 in a water environment. The measurements denote that greater reactivity reductions could be obtained with increased gadolinium poison. The maximum possible reactivity effect of gadolinium on the SNAP 10A type core vessel in a water environment was measured as \$9.12. This reactivity effect is not sufficient to overcome the cold, clean excess reactivity of the present SNAP 10A type reactor, indicating that additional means (such as limiting core dimensions) must sometimes be employed to achieve subcriticality in water environments.

Critical dimensions were obtained of several cores immersed in water. The effects of BeO axial reflectors were considered. From this data curves were plotted (Figure 10) which furnish a normalization for evaluating calculated methods that can be used in studies of geometry variations in SNAP reactor designs.

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III. DESCRIPTION OF CRITICAL ASSEMBLIES

A. SCA-4A ASSEMBLY

All operational environment studies were conducted with the SCA-4A reactor (SNAP 10A type) which is located in the SNAP Critical Facility at the Santa Susana Nuclear Field Laboratory. A detailed description of the facility and system components is summarized briefly here.*

The reactor core is composed of 37 rejected S2DR fuel moderator elements each 12.25 in. long with 1.25-in. diameter. Each element is a δ -phase of Zr + 10 wt % of 93% enriched uranium alloy converted to the hydride. The fuel-moderator volume is 520 in.³ and contains 4.71 kg of U²³⁵. All the elements are clad in Hastelloy-N tubes which have been coated internally with a ceramic containing Sm₂O₃. The 37 elements are contained in a cylindrical core vessel, 9 in. diameter by 16 in. long, and are arranged in a hexagonal array measuring nominally 8 in. across the flats and 9 in. across the corners.

The beryllium reflector surrounds the core vessel and is adjustable radially and axially for parametric studies. For this experiment the basic reflector block was varied from 12 in. high and 2 in. thick to 12 by 3 in. As seen in Figure 1 the reflector is divided into four quadrants which house the two active and two stationary beryllium drums. The stationary drums are positioned to the fully inserted or most reactive position at all times. The active drums are used for reactor control and are capable of 135° rotation.

B. SCA-4B ASSEMBLY

The SCA-4B reactor, located in Building 012, Santa Susana Laboratory, was used for the water immersion studies. A detailed description of the SCA-4B machine is presented in NAA-SR-9871,[†] a summary of which follows. This machine (Figure 2), using SCA-4A fuel elements, allows for complete water flooding of the core and/or reflector regions. Thirty-seven fuel elements are contained in the core tank which is fixed to the upper support structure. A top tank is also fixed to the upper structure and welded to the top of the core tank. The base tank is bolted to the moveable lower assembly which is raised during operation to a position where the base tank surrounds the core tank. The bottom

*D. W. Clifford, "Interim Report on the SNAP Critical Assembly 4A (SCA-4A) Experimental Results," NAA-SR-10245 (March 20, 1965)
[†]S. Yee, "SNAP Critical Assembly -4B Phase III Water Immersion Experiments," NAA-SR-9871 (December 1, 1964)

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Figure 1. SCA-4A Critical Assembly Machine

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Figure 2. SCA-4B Critical Assembly Machine

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of the core vessel is perforated to allow simultaneous filling of the core and base tank. Water levels in the base tank and top tank are determined by sight glass readings using a remote TV camera for viewing.

C. SCA-4B MODIFICATION

The basic SCA-4B machine previously described was modified to perform the water immersion core geometry studies discussed in this report. A larger base tank replaced the original base tank and top tank. Grid plates capable of holding up to 721 0.45 in. diameter fuel elements were suspended in the base tank. A core loading diagram for the 14 ring configuration is shown in Figure 3. Dimensions of the base tank (22-1/2-in. diameter by 31-1/2 in. high) allowed a 3 in. minimum for the water reflector in the axial and radial directions. Figure 4 is a photograph of the modified machine.

Fuel tubes 0.45-in. diameter and 24 in. long contained SCA-5 fuel pellets. These pellets are composed of $\text{ZrH}_2\text{-UO}_2$ containing 10 wt % UO_2 , enriched to 93.22 wt % U^{235} . Beryllium oxide pellets 1-in. long, 0.41-in. diameter were used to provide Be axial reflection when required. Figure 5 is an exploded view of the fuel element assembly. Because the fuel tubes are not completely

Figure 3. Typical Half-Section of SCA-4B Core Loading
(Normal 14-Ring Configuration - 547 Elements)

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Figure 4. Modified SCA-4B
Critical Assembly Machine

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Figure 5. Fuel Element Assemblies

filled with pellets, water was added to each tube above the fuel column to provide for complete axial water reflection. The inner seal plug shown in the top element (Figure 5) was originally intended to separate water in the tube from the fuel or beryllium oxide column. The plug and water were later replaced with a lucite rod to simulate an internal water reflector as described in the next section.

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IV. EXPERIMENTAL PROCEDURES

A. EXCESS REACTIVITY

To measure excess reactivities of water immersed cores that are greater than 25¢ supercritical, poison splines were inserted until the core was completely immersed in an infinite water reflector. These splines were placed in selected locations throughout the core to minimize flux perturbations. The worth of individual splines was determined from the differences in reactor periods measured at a constant water level, with and without the spline inserted. Individual spline worths were all less than 25¢.

B. GADOLINIUM POISON EXPERIMENTS

The objective of this experimental series was to establish the worth of gadolinium applied to the fuel elements and core vessel in operational and water immersion environments. The SCA-4A and -4B machines containing SCA-4A fuel elements were used to acquire the data reported herein. A coating of gadolinium was applied to mylar tape which was then attached to the various surfaces with an adhesive. Mylar tapes were supplied having base thicknesses varying from 0.001 to 0.005 in., with gadolinium oxide coatings varying from $\Sigma_a t$ of 0.1 to $\Sigma_a t$ of 2.0. The tape was cut into strips to match the circumference and length of the elements (4 in. by 12.25 in.). These strips were attached to the outside of the core vessel with adhesive and thin steel bands. The oxide coating on the mylar is a mixture of iron oxide and gadolinium oxide to provide the desired $\Sigma_a t$ concentration. A base point was taken with a tape coated only with iron oxide so that the reported results of measurements are always net reactivity worths due to gadolinium.

In the operational system (SCA-4A) the experimental procedure consisted of applying the necessary layers of unpoisoned tape to the core vessel and determining the critical configuration on the control drums. Boron splines of known worth were inserted in the core to decrease the reactivity of the system by the amount expected from the gadolinium, and were then removed as the gadolinium was applied to the core vessel. This procedure was followed in order to minimize drum movement and the corresponding uncertainties in the effect of gadolinium poison on the drum worths.

A similar procedure was followed in applying the poison to the fuel elements; however, it was necessary to increase the reflector thickness to 3.00 in. to supply the excess reactivity required for this experiment.

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The poison experiments were repeated in the water immersed system and additional boron splines were required to contain the increased excess of the totally immersed system. The use of a greater number of splines required an additional study of spline worths and flux distribution perturbations from the splines.

Finally, the effect of gadolinium as a poison in a system immersed in seawater was determined by replacing the fresh water in the reactor complex with seawater.

C. CORE GEOMETRY EXPERIMENTS

The objective of this experimental series was to ascertain the critical configuration for cores of various radii immersed in an infinite water environment. Critical heights were to be determined for hexagonal cores having 10 to 14 rings of fuel elements or equivalent diameters ranging from 8.16 to 11.35 in., respectively. Critical heights were established for both bare and beryllium oxide axially reflected cores.

The procedure in each case was essentially the same. Pellets were inserted in each tube to the predicted critical height. The reactor was brought to critical by loading the fuel tubes. The fuel height was adjusted to a minimum critical configuration for a specified number of elements. Then an additional pellet was added and the excess reactivity measured to find the incremental pellet worth.

All excess reactivity measurements were obtained with, or corrected to, a water level in the tank equivalent to 3 in. over the top of the fuel or beryllium oxide. For most core configurations this was simulated in the fuel tubes by placing 3 in. of lucite rod in each tube over the fuel/beryllium oxide column as shown in the lower element in Figure 5. Initially, in each tube 3 in. of water over an internal water-seal plug served for axial reflection. The top element is shown in Figure 5. After a comparison with 3 in. of lucite without an internal plug revealed only a negligible difference in reactivity; the use of water in the tubes was discontinued except for the 10-ring configuration.

Axial and radial flux distributions were ascertained by using detectors consisting of U^{235} pins taped to the fuel elements and to a lucite holder placed in the radial reflector region.

Beryllium axial reflection was effected by inserting one-inch pieces of beryllium oxide to the desired length above and below the fuel pellets. (See Figure 5.)

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Figure 6. Axial Flux Distributions

Figure 7. Radial Flux Distributions

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V. RESULTS OF EXPERIMENTS

A. EXCESS REACTIVITY

1. Operational Environment (SCA-4A)

A system reactivity of \$5.25 was established prior to the application of gadolinium to the core vessel. This reactivity was later increased to \$10.50 by increasing the beryllium reflector thickness to provide sufficient reactivity to measure the effect of gadolinium applied to the fuel elements.

2. Water Immersion Environment (SCA-4B)

Following the operational core measurements, the SCA-4B water immersion assembly was loaded with the same SCA-4 fuel elements as those applied for operational experiments. Numerous boron splines were necessary to control the excess reactivity of the system when completely water flooded. Initially 46 splines were positioned toward the outside of the core to minimize any differences in individual spline compositions. This was reduced to 40 splines and a redistribution effected to compromise between spline worth uncertainties and central flux peaking. When a radial flux distribution indicated that considerable central flux peaking still remained, more splines were moved toward the center, reducing the total number of installed splines to 37. The axial and radial flux distributions with this spline loading are illustrated in Figures 6 and 7. As shown in Figure 6 the axial flux distribution is weighted toward the bottom of the core. This is possibly due to the upper grid plate and cover plate which separate the top tank water from the core water. There is also a possibility that a thin air gap exists between the upper grid plate and the cover plate due to the present setting of the Up limit switch on the base tank drive system. At the present travel limit the base tank overflow line is in line with the top of the core. As a result of the spline worth measurements, the excess reactivity of the submerged core was evaluated as $\$11.60 \pm \0.35 .

The value of \$11.60 for the water-immersed SNAP 10A core can be compared to that of \$13.70 previously reported by L. I. Moss.* The value of \$11.60 is regarded as the more exact one since the present procedure (dispersing poison splines throughout the core to permit full radial reflection) greatly reduces the

*L. I. Moss, "Experiments With Water-Reflected, Undermoderated, Zirconium Hydride Critical Assemblies," NAA-SR-8490 (Sept. 15, 1963)

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flux perturbations incurred during the measurement of large excess reactivities. Compensation for the excess reactivity was accomplished by removing the radial water reflector from as much as 1/3 of the core length. This is a major change in configuration and results in a significant flux perturbation.

3. Seawater Immersion Environment

Immersion of the SNAP 10A core in seawater results in a reactivity loss of \$2.06 for a total excess reactivity of \$9.54.

B. GADOLINIUM EXPERIMENTS – OPERATIONAL ENVIRONMENT (SCA-4A)

1. Core Vessel (Poisoned)

Unpoisoned mylar attached to the core vessel in a series of three 5-mil layers resulted in a total reactivity effect of +15¢. Poisoned mylar containing gadolinium in the form of Gd_2O_3 was then affixed with concentrations of $\Sigma_a t = 0.1, 0.2, 2.0, 6.0,$ and 10.0 . The smallest values were measured directly; the value for 2.0 was measured by the poison spline technique. The values for 6.0 and 10.0 were obtained by the bump period technique with respect to the critical drum position in the $\Sigma_a t = 2.0$ instance. Period measurements were used in lieu of drum calibration curves to eliminate any errors due to interaction effects between the control drums and the poison mylar films. The results, shown in Table 1 and Figure 8, have been corrected for the effect of the mylar and adhesive.

TABLE 1
EFFECT OF GADOLINIUM ON THE
SCA-4A CORE VESSEL

$\Sigma_a t$	Negative Reactivity Worth (\$)
0.1	0.27
0.2	0.69
2.0	1.51
6.0	2.19
10.0	2.44

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Figure 8. Gadolinium Reactivity Worth on Core Vessel Wall

2. Fuel Elements (Poisoned)

The operational measurements of gadolinium on the fuel cladding were conducted with poison concentrations corresponding to $\Sigma_a t$ values of 0.1, 0.2, and 0.3. A reflector thickness of 2.0 in. was used to measure the worth of the unpoisoned and $\Sigma_a t = 0.1$ poison concentrations. The thickness was increased 0.5 in. for the $\Sigma_a t = 0.2$ experiment and another 0.5 in. for a total thickness of 3.00 in. for the $\Sigma_a t = 0.3$ experiment. The results of these measurements, presented in Table 2 and Figure 9, are corrected for the worth of unpoisoned mylar and adhesive, and for the change in reflector configuration.

C. GADOLINIUM EXPERIMENTS - WATER-FLOODED ENVIRONMENT (SCA-4B)

1. Core Vessel (Poisoned)

To determine the worth of the mylar and adhesive on the core vessel, several layers of unpoisoned tape were applied. The worth of 0.008 in. (2 layers) was -13¢, and an additional 0.012 in. was worth -3¢, totalling a negative worth of 16¢ for 0.020 in. of mylar tape. These values were used to ascertain the net worth due to gadolinium. The findings of the experiments with various gadolinium concentrations applied to the outside of the core vessel are presented in

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TABLE 2
EFFECT OF GADOLINIUM ON
THE SCA-4A FUEL
ELEMENTS

$\Sigma_a t$	Negative Reactivity Worth (\$)
0.1	3.80
0.2	6.40
0.3	8.75

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Figure 9. Gadolinium Reactivity
Worth on Fuel Cladding

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Table 3 and plotted in Figure 8 in addition to the operational data added for comparison. Axial and radial flux distributions taken with $\Sigma_a t$ of 10.2 are included in Figures 6 and 7.

TABLE 3
EFFECT OF GADOLINIUM
ON THE SCA-4B
CORE VESSEL

$\Sigma_a t$	Negative Reactivity Worth (\$)
0.2	3.68
2.2	7.82
4.2	8.56
6.2	8.72
10.2	9.12

Following the core vessel measurements, the reference configuration with 37 splines without mylar was re-established, and the critical steady-state was determined within 4¢ of the initial value.

2. Fuel Elements (Poisoned)

All fuel elements were clad with successive gadolinium concentrations of $\Sigma_a t = 0.1$ and in two steps exhausted the excess reactivity of the system. These results are tabulated in Table 4 and plotted in Figure 9.

TABLE 4
EFFECT OF GADOLINIUM
ON THE SCA-4B FUEL
ELEMENTS

$\Sigma_a t$	Negative Reactivity Worth (\$)
0.1	5.41
0.2	10.65

TABLE 5
WATER-IMMERSED BARE CORE RESULTS

Number of Rings	Equivalent Diameter (in.)	Critical Number of Pellets	Excess Reactivity (ϵ)	Corrected Critical Height (in.)	Critical Weight (kg)	Incremental Pellet Worth (\$)
14	11.35	20	10	8.48	43.867	1.19
13	10.51	23	48	9.61	42.65	1.10
12	9.67	27	18	11.43	43.32	0.84
11	8.83	35	3.9	14.90	46.99	0.50
10*	8.16	51	-5	22.1	59.41	0.212
						(Average of top four)

*See text for modified 10-ring configuration (10 rings plus 12 elements)

Figure 10. Critical Core Dimensions

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3. Effect of Seawater

After removing all poisoned tape, the fresh water in the system was replaced with seawater and the reactivity effects were measured.

The worth of a gadolinium concentration of $\Sigma_a t = 4.0$ on the core vessel was -\$6.79 in the seawater system. This is compared to -\$8.57 for the worth of the same concentration in fresh water; that is, \$1.78 less negative worth in seawater; however, the excess reactivity, without poison, in seawater was reduced by \$2.06 as previously mentioned. Inasmuch as the worth of gadolinium poison is reduced in seawater, the excess reactivity of the core with gadolinium is essentially the same (a difference of 28¢) whether immersed in fresh water or seawater.

D. BARE CORE GEOMETRY EXPERIMENTS (Without BeO Axial Reflectors)

A total of five bare cores, from the 14-ring to the modified 10-ring core (to be described), were assembled for the first half of this experiment. The results are summarized in Table 5 and presented graphically in Figure 10. The measured critical heights for the bare cores are 0.3 to 0.5 in. less than the minimum predicted value.* The corrected critical height (column 5, Table 5) was obtained by converting the measured excess reactivity at the just critical configuration to fractional pellet length and subtracting from the measured configuration. The conversion factor was extracted from the incremental pellet worth data presented in column 6, Table 5.

A calibration of the worth of interstitial and radial water in the 3-in. region above the fuel in the 14-ring core indicated a total worth of \$1.58. This worth decreased to 25¢ for the 10-ring core.

Water temperatures throughout the experiment averaged from 28 to 30°C. During long runs the water temperature was raised by the pump from an initial reading of 24°C to a high of 34°C. These temperature variations did not significantly affect the subsequent measurements.

Axial and radial flux distributions, depicted in Figures 11 through 15, were measured for each core using U^{235} pins.

*Calculated using multi-group diffusion theory

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Figure 11. Radial and Axial Flux Distributions (10-Ring Core, Water Immersed)

Figure 12. Radial and Axial Flux Distributions (11-Ring Core, Water Immersed)

Figure 13. Radial and Axial Flux Distributions (12-Ring Core, Water Immersed)

Figure 14. Radial and Axial Flux Distributions (13-Ring Core, Water Immersed)

Figure 15. Radial and Axial Flux Distributions (14-Ring Core, Water Immersed)

Initially, the 10-ring core was sub-critical when fully loaded (23-3/4 in.) with fuel pellets. The configuration was then modified as follows: 4 pellets were removed from each tube, the corner tubes were placed in the center of flats in the 11th ring, and two additional tubes were added for a total of 283 tubes loaded. The data from this configuration are presented in Table 5. A subsequent experiment to determine the effect of moving three tubes in the above configuration from the flats to the corners revealed a total reactivity gain of 8¢.

E. BERYLLIUM OXIDE AXIALLY-REFLECTED CORES

1. Determination of Infinite Reflector Length

Four and six inches of beryllium oxide were added to the top of the fuel during the 12-ring bare core experiment. With a fuel loading of 25 pellets per tube, the excess reactivity

with 4 in. of beryllium oxide axial reflector above the fuel was 11¢ while with 6 in. of beryllium oxide above the fuel, the excess reactivity was only 14¢. Since the 2-in. addition of beryllium oxide to the existing 4-in. beryllium oxide reflector increased the reactivity by only 3¢, it was concluded that 4-in. of beryllium oxide axial reflector in a water reflected environment is essentially an infinite reflector.

2. Critical Core Dimensions With Four-Inch Reflector

Based on the results of the foregoing experiments, the critical dimensions were established of the water immersed cores axially reflected with 4-in. of

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beryllium oxide. Data obtained from cores containing 4 in. of axial reflector above and below the fuel column are summarized in Table 6. A comparison of critical fuel heights with predicted values (Figure 10) shows excellent agreement. A comparison with the values and predictions for the bare core experiments suggests that the calculated worth of the beryllium oxide axial reflector requires some correction.

During the 12-ring core configuration, 5 additional pellets were added and the excess reactivity associated with each addition was determined. These results are shown in Table 6.

Axial flux distributions were ascertained for the 11-, 13-, and 14-ring cores. Radial distribution was also taken on the 14-ring core since the radial distribution for the beryllium oxide reflected cores was not significantly different from the bare cores. Flux distributions are presented in Figures 16 through 18.

TABLE 6

CRITICAL DIMENSIONS FOR BERYLLIUM OXIDE AXIALLY-REFLECTED CORES
(Four Inches BeO Above and Below Fuel)

Number of Rings	Equivalent Diameter (in.)	Critical Number of Pellets	Excess Reactivity (ϵ)	Corrected Critical Height (in.)	Critical* Weight (kg)	Incremental Pellet Worth (ϵ)
14	11.35	16	29.4 ± 0.8	6.76	34.97	188 ± 13.8
13	10.51	19	62 ± 2.2	7.94	35.24	151 ± 12
12	9.67	23	1.0	9.82	37.22	92.4 ± 3.7 (24th) 82.0 ± 3.5 (25th) 87.0 ± 5.1 (26th) 84.0 ± 4.5 (27th) 71.0 ± 3.5 (28th)
11	8.83	32	36 ± 0.8	13.28	41.88	40.0 ± 2.7

*Total weight of fuel pellets in the core corrected to the critical height, column 5.

*Total weight of fuel pellets in the core corrected to the critical height, column 5.

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Figure 16. Axial Flux Distributions
(11-Ring Core, BeO Reflected)

Figure 17. Axial Flux Distributions
(13-Ring Core, BeO Reflected)

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Figure 18. Flux Distributions
(14-Ring Core, BeO Reflected)

3. Intermediate Reflector Lengths

Additional experiments were performed with 4-in. of beryllium oxide below the fuel column and 0, 1, 2, and 4-in. of beryllium oxide above the fuel. The worths of these increments of axial reflector were measured in water and in air and are discussed in the succeeding paragraphs.

The worth of three increments of beryllium oxide axial reflector, within the fuel tubes, submerged in water was determined during the 33 pellets/tube loading in the 11-ring core. The fuel loading was then increased to 36 pellets/tube and beryllium oxide reflector worth measurements repeated with the lucite removed and the water level brought to the top of the fuel column to give the worth of beryllium oxide in air. These results are tabulated in Table 7.

Direct comparison of the worth of beryllium oxide in water and in air is not valid since the worth measurements were made with different length cores. By using the beryllium oxide reflector worths (in water) presented in Table 7, a tabulation of approximate critical fuel lengths can be interpolated as shown in Table 8. It is assumed here that the incremental worth of beryllium oxide reflector above the core is equal to that below the core. It is also assumed that a

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TABLE 7
 REACTIVITY WORTH OF AXIAL REFLECTOR

BeO Reflector	BeO Worth in Water*	BeO Worth in Air†
First inch above core	$47.5 \pm 0.8\%$	$48.8 \pm 3.3\%$
Second inch above core	$27.0 \pm 1.0\%$	$20.0 \pm 3.0\%$
Total of third and fourth inches	$15.0 \pm 2.2\%$	$19.0 \pm 4.0\%$
Total Worth	$89.5 \pm 2.5\%$	$87.8 \pm 6\%$

*33 pellets/tube

†36 pellets/tube

TABLE 8
 CRITICAL DIMENSIONS INTERPOLATED
 FOR INTERMEDIATE
 AXIAL REFLECTORS
 (11-ring core)

Axial Reflector (in.)	Critical Fuel Length (in.)
0	14.9 (measured)
1	14.1 (interpolated)
2	13.6 (interpolated)
4	13.28 (measured)

constant fuel pellet worth of 40% could be applied in conjunction with all axial reflector length studies. This approximation could introduce errors of 0.1 to 0.2 in. into the interpolated critical lengths shown in Table 8.

Finally, the worths of 3 in. of lucite and water in the interstices over 2 in. beryllium oxide and over the bare core were measured as $37.6\% \pm 1.1\%$ and $1.45 \pm 8.5\%$, respectively.

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F. ADDITIONAL MEASUREMENTS

1. Modified Core Configurations

During the 14-ring core configuration an experiment was conducted to measure the reactivity changes for various modifications to the normal 547 element, 14-ring hexagonal core. In general, tubes were removed from the corners of the 14th ring and placed in the "flats" of the 15th ring in the combinations shown in Figures 19 through 23. All modifications resulted in an increase in reactivity over the normal core as follows:

<u>Configuration</u>	<u>Reactivity Increase (ρ)</u>
1	14.3
2	7.0
3	6.4
4	18.5
5	8.1

The statistical error associated with each of the above measurements is $\pm 1\rho$.

TYPICAL HALF-SECTION
REACTIVITY GAIN = 14.3 ρ

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Figure 19. Configuration 1

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TYPICAL HALF-SECTION
REACTIVITY GAIN = 7¢

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Figure 20. Configuration 2

TYPICAL HALF-SECTION
REACTIVITY GAIN = 6.4

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Figure 21. Configuration 3

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THIS POSITION VACANT
IN OTHER SECTION

TYPICAL HALF-SECTION
REACTIVITY GAIN = 18.5¢

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Figure 22. Configuration 4

TYPICAL HALF-SECTION
REACTIVITY GAIN = 8.1¢

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Figure 23. Configuration 5

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Figure 24. Fuel Element X-rays

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2. Fuel Lengths and Weights

At the completion of the experiment, 72 fuel tubes containing 36 pellets each were selected at random from the last core loading of 331 tubes. These tubes were x-rayed to determine fuel column lengths, pellet positioning in the tube, and relative pellet densities. The x-rays revealed that the majority of the gaps between pellets were approximately 0.010 in. in addition to larger gaps caused by lodged chips between pellets. The average fuel column length (36 pellets) was 15.375 ± 0.10 in. which yields an effective pellet length of 0.427 in. per pellet. A print of one of the x-rays is shown in Figure 24.

A variation in pellet densities was also observed; however no quantitative data are available. While the variation in pellet densities was quite noticeable, the random loading of pellets in the tubes produces only a slight $\pm 0.09\%$ variation of fuel weights between tubes.

Average fuel column weight, obtained by weighing 260 tubes containing 36 pellets, was 146 ± 0.13 gm of $\text{ZrH}_2\text{-UO}_2$ material. Using the equivalent diameter (Table 5), homogenized fuel density of 3.135 gm/cc ($\text{ZrH}_2\text{-UO}_2$) was calculated. The pellet compositions are:

10 wt %- UO_2 (in fuel)

87.45 wt %-U (in UO_2)

93.22 wt %- U^{235} (in U).

G. ERROR ANALYSIS ON CORE GEOMETRY AND GADOLINIUM EXPERIMENTS

The principle source of error in these experiments is the determination of water level for the steady-state and period measurements. It is estimated that the manometer can be read to an accuracy of $\pm 1/32$ in.

When an excess reactivity of \$1.00 is to be determined, a number of cumulative measurements are involved. Large excess reactivities also result in lowering the water level to a region of high specific worth, e. g., 3 to 5¢ per $1/32$ in. As shown in Table 6 statistical errors in pellet worths for the 13- and 14-ring cores are as high as 7 to 8%. As the amount of excess reactivity decreases, the water level rises to a region of low specific worth and the uncertainty in the

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worth measurement decreases accordingly. For excess reactivities of 25 to 75¢ the statistical error drops to 2 to 3%.

All statistical errors calculated in this experiment are for a 67% confidence level.

Measurements of fuel column lengths were taken from fuel tubes in which pellets had been tamped down. However, during the transfer of elements from the loading station to the reactor tank, the pellets are free to slide in the tubes and may not completely re-seat when the elements are installed in the tank. In one experiment the core was assembled without tamping the pellets and a steady-state critical level was attained. The reactor was then shut down, the core tapped and shaken, and a second steady state achieved. A measurable difference (1/16 in.) was noted in critical water level amounting to a reactivity gain of 6¢. Since the usual procedure is to tamp the pellets in the tube following a change in pellet configuration, it is evident that the maximum error due to unseated pellets is about 6¢.

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