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CONTROL WORTH
OF
SLIDING REFLECTORS
FOR
ZIRCONIUM HYDRIDE REACTORS

AEC Research and Development Report

Atomics International Division
Rockwell International

P.O. Box 309
Canoga Park, California 91304

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D. S. BOST

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ABSTRACT

Results of measured and calculated worth of sliding reflectors on the SNAP Critical Assembly 4A (SCA-4A) critical assembly are presented.

Two quadrants on opposite sides of SCA-4A were fitted with new tapered beryllium reflectors. The existing reflectors and control drums were used in the other two quadrants. The new reflectors were cut to allow measurement of the worth of sliding reflectors over a range of angles (30, 60, and 90°) and strokes (2, 2-3/4, and 3-1/2 in.).

A maximum worth of \$8.01 was obtained for both 90° segments open 3-1/2 in. Two-dimensional DOT III calculations in R, Z geometry gave a worth of \$6.54.

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I. INTRODUCTION

The 5-kwe Reactor⁽¹⁾ uses a tapered beryllium reflector with sliding segments for reactivity control. This configuration results in a minimum shield diameter and a minimum shield weight. Sliding reflector segments for reactivity control represent a significant departure from previous SNAP reactors, which used rotating control drums.

The amount of control which may be obtained from tapered sliding segments is a function of the specific reflector geometry. Experiments were performed in the SCA-4A facility⁽²⁾ to quantify the control worth as a function of circumferential angle and stroke. Analysis of the experiments was made using the two-dimensional transport theory code, DOT III.⁽³⁾

a. Side View of 90° Segment Closed

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b. Side View of 90° Segment Open

c. Top View of 90° Segment Open

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Figure 1. SCA-4A, Fitted With Tapered Beryllium Reflectors

II. DESCRIPTION OF SCA-4A REFLECTOR MODIFICATIONS

Two quadrants on opposite sides of the reactor were fitted with new tapered beryllium reflectors. An aluminum support structure was fabricated to position the new reflector quadrants on the existing fall-away fixtures. Photographs of SCA-4A, fitted with the new reflectors, are shown in Figure 1.

Existing SCA-4A reflector and control drums were used in the remaining quadrants. These were shimmed to a thickness of 2-1/2 in. and a length of 12 in.

The new reflector quadrants were fabricated in pieces, to allow measurement of the worth of sliding segments over a range of angles (30, 60, and 90°) and strokes (2, 2-3/4, and 3-1/2 in.). Each quadrant was cut into one 60° piece and two 15° pieces. By rearranging the pieces, sliding segments of 30, 60, and 90° could be centrally located between the existing fixed reflector and control drums. The pieces were held together by aluminum straps, bolted to the back. Horizontal cuts were made in each quadrant at 1, 1-3/8, and 1-3/4 in. above the axial center of the reflector. The two layers of 3/8-in. thick pieces could be individually attached with screws to either the upper fixed reflector or to the lower sliding segment. This arrangement allowed the segment openings of 2, 2-3/4, and 3-1/2 in. to be axially centered.

The new reflector was tapered from a 1-1/4 in. thickness at the top to a 3-1/2 in. thickness at the bottom. The reflector length was 12-1/4 in., which is equal to the active fuel length of the core. The taper angle was $\sim 10.4^\circ$.

The inner surface of the reflector was machined to be concentric with the core vessel, with a clearance of 0.06 in. The outer surface was machined to flat surfaces of 15° each.

The support structure was designed so that the sliding segments moved along the taper angle. The segments were moved manually. Spacer blocks were provided, so that the segments could be positioned accurately, in 1/2 in. increments. The blocks were removed after the supporting bolts were tightened. The support structure was also designed to allow the open segments to be moved toward the core vessel, thus closing the gaps between the segments, core vessel, and fixed reflector adjacent to the control drums.

d. Side View of 30° Segment Open

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e. Fall-Away Fixture Open

Figure 1. SCA-4A, Fitted With Tapered Beryllium Reflectors

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III. EXPERIMENTAL PROCEDURE AND RESULTS

A. PROCEDURE

The series of measurements which were made for each segment angle are shown in Table 1. The procedure used was to hold Segment No. 1 in the closed

TABLE 1
SLIDING SEGMENT OPENINGS WITH STROKE VARIATIONS

Segment No. 1 Opening (in.)	Segment No. 2 Opening (in.)								
	0	0.5	1.0	1.5	2.0	2.5	2.75	3.0	3.5
Stroke = 3.5 in.									
0	X	X	X	X	X	X		X	X
0.5		X		X		X			X
1.5				X		X			X
2.5						X			X
3.5			X		X			X	X
Stroke = 2.75 in.									
0	X	X	X	X	X		X		
0.5		X		X			X		
1.5				X			X		
2.75			X		X		X		
Stroke = 2.0 in.									
0	X	X	X	X	X				
1.0			X		X				
2.0		X		X	X				

position, and then measure the worth of Segment No. 2 in 1/2 in. increments. Segment No. 1 was then opened to each of the values shown in Table 1, and the worth of Segment No. 2 was remeasured. In order to reduce the total number of measurements, Segment No. 2 was moved in coarser increments, after the

initial calibration. It was felt that the shape of the worth curves would not be significantly altered by the position of Segment No. 1. Because of the time required for individual measurements, it was not possible to perform the entire series of measurements using small increments.

Two methods of measuring reactivity were specified to be used for the first series of measurements. This series was the measurement of 90° segments with a 3-1/2 in. stroke, which obviously would have the greatest worth. At the conclusion of these measurements, the decision was to be made as to which method was felt to give the superior results, and that method used for the remainder of the experiments. The two methods are the inverse kinetics and the inverse counting techniques, which are described in detail in Reference 4. The inverse kinetics method may also be called the critical reactor method, and the inverse counting method may also be called the subcritical reactor method.

The two methods were specified, because it was known that the excess reactivity with the segments closed would exceed the worth of the two control drums, and it was expected that, with both 90° segments 3-1/2 in. open, the reactor would be subcritical. The excess reactivity could be controlled with poison splines (small B₄C-filled tubes) inserted into the interstices between fuel elements through holes in the grid plate, but a method was also needed for measurement in the event of insufficient reactivity. The subcritical method provided this capability.

In the critical reactor method, the reactor was brought to critical for each segment opening by inserting control drums, with poison splines having been added or removed as required. The segment worth was then obtained from the summation of reactivities obtained from control drum and poison spline calibrations. The control drums were calibrated, using the inverse kinetics method. The worth of the poison splines were measured by inserting or removing one spline in various locations, and measuring the change in excess reactivity.

In the subcritical method, a Cf²⁵² source was placed in the middle of the central fuel element. This is a special fuel element, with segmented fuel which can be disassembled. Count rates were obtained from the startup channels (fission chambers) for conditions of subcriticality which are known. Using these calibration points, count rates can be taken for an unknown subcritical

configuration, and the amount of negative reactivity calculated. Using the subcritical method, it was possible to obtain segment worth with both control drums fully inserted and with a constant spline configuration.

Due to the independence of the subcritical method from control drum and poison spline calibrations which changed with segment openings, it was chosen to be used for the remainder of the experiments.

B. RESULTS

1. Fuel Loading

Fuel loading was initiated on January 9, 1973, with both 90° segments closed and with the control drums and fixed reflectors shimmed to a 2-1/2 in. thickness. Criticality was achieved upon the addition of the 28th element, with an excess reactivity of 16¢. The remaining nine elements were loaded in a stepwise manner, along with poison splines, to maintain an excess reactivity of less than one control drum.

2. Control Drum and Poison Spline Calibration

Upon completion of the full 37-element loading, both control drums were calibrated, using the inverse kinetics method. The calibration curve obtained is shown in Figure 2.

The worth of the poison splines was measured by inserting or removing one spline in each of the eight radial locations shown in Figure 3, and measuring the change in reactivity. Later, when one 90° segment had been opened 3-1/3 in., the worth of poison splines was remeasured. The results for both sets of measurements are shown in Figure 4.

Using the spline and drum calibrations, the available excess reactivity was calculated to be \$5.88.

The worth of each of the fall-away quadrants was measured, using the inverse kinetics method. The quadrants rotate 15° away from the core vessel. This may be seen clearly in Figure 1e. A value of \$4.60 ± 0.30 was obtained for each 90° segment.

Figure 2. Control Drum Worth

Figure 3. Spline Configuration

Figure 4. Spline Worth

Figure 5. Segment Worth Measurements

TABLE 2
30° SEGMENT WORTH
(\$)

3.5 in. Stroke

Segment No. 1 Opening (in.)	Segment No. 2 Opening (in.)							
	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5
0	-	0.25	0.48	0.71	0.96	1.15	1.32	1.49
0.5	0.18	0.39	-	0.94	-	1.38	-	1.73
1.5	0.70	-	-	1.45	-	1.88	-	2.23
2.5	1.10	-	-	-	-	2.31	-	2.65
3.5	1.48	-	1.93	-	2.42	-	2.84	3.00

2.75 in. Stroke

Segment No. 1 Opening (in.)	Segment No. 2 Opening (in.)					
	0	0.5	1.0	1.5	2.0	2.75
0	-	0.24	0.49	0.74	0.95	1.26
0.5	0.17	0.41	-	0.91	-	1.46
1.5	0.70	-	-	1.43	-	1.93
2.75	1.19	-	1.68	-	2.21	2.50

2.0 in. Stroke

Segment No. 1 Opening (in.)	Segment No. 2 Opening (in.)				
	0	0.5	1.0	1.5	2.0
0	-	0.24	0.45	0.71	0.92
1.0	0.47	-	0.98	-	1.39
2.0	0.91	1.17	-	1.63	1.86

3. Sliding Segment Worth

The worth of one 90° segment was measured in $1/2$ in. increments, using the critical method. Up to an opening of $1-1/2$ in., there was sufficient worth in the control drums to obtain the segment worth from the drum calibration curve. At an opening of 2 in., it was necessary to begin removing poison splines. The segment worth from 2 to $3-1/2$ in. was obtained from the addition of spline worth and control drum worth. At a segment opening of $3-1/2$ in., the spline worth were remeasured, obtaining the results shown in Figure 4. The segment worth was remeasured as it was being closed in $1/2$ in. increments. The appropriate values of spline worths in Figure 4 were used. The segment worth curve generated is shown in Figure 5.

The Cf^{252} source was installed, and the worth of the 90° segment was measured, using the subcritical method. The worth curve obtained is also shown in Figure 5. There was reasonably good agreement between the two methods, up to a 2 in. segment opening. Beyond that point, the subcritical method yields a higher worth than the critical method. Since the critical method was so dependent on spline worths, which change with segment opening, it was felt that the subcritical method would produce more consistent results. Spline and drum configuration is constant; only the segment configuration is changed.

The complete series of measurements shown in Table 1 were performed for segment angles of 30° , 60° , and 90° . The results are given in Table 2 through Table 4. The combined worth of both segments, moving together, are shown as a function of stroke in Figure 6, and as a function of angle in Figure 7. The angular variation in Figure 7 was extrapolated to 360° for comparison with analytical results, which are discussed in Section IV.

When the segments were open $1-1/2$ and $3-1/2$ in., they were moved toward the core vessel, to measure the worth of the gaps between the segments, the core vessel, and the fixed reflector adjacent to the control drums. These gaps may be seen clearly in Figure 1c. The results of these measurements are shown in Figure 8.

TABLE 3

60° SEGMENT WORTH
(\$)

3.5 in. Stroke

Segment No. 1 Opening (in.)	Segment No. 2 Opening (in.)							
	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5
0	-	0.41	0.84	1.30	1.65	1.97	2.28	2.55
0.5	0.48	0.89	-	1.72	-	2.47	-	3.03
1.5	1.41	-	-	2.52	-	3.47	-	4.00
2.5	2.17	-	-	-	-	4.27	-	4.78
3.5	2.73	-	3.63	-	4.46	-	5.16	5.45

2.75 in. Stroke

Segment No. 1 Opening (in.)	Segment No. 2 Opening (in.)					
	0	0.5	1.0	1.5	2.0	2.75
0	-	0.32	0.82	1.22	1.65	2.10
0.5	0.39	0.87	-	1.69	-	2.53
1.5	1.40	-	-	2.68	-	3.56
2.75	2.32	-	3.12	-	4.02	4.54

2.0 in. Stroke

Segment No. 1 Opening (in.)	Segment No. 2 Opening (in.)				
	0	0.5	1.0	1.5	2.0
0	-	0.56	0.94	1.34	1.73
1.0	0.99	-	1.86	-	2.64
2.0	1.84	2.22	-	3.04	3.48

TABLE 4
90° SEGMENT WORTH
(\$)

3.5 in. Stroke

Segment No. 1 Opening (in.)	Segment No. 2 Opening (in.)							
	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5
0	-	0.38	1.10	1.73	2.31	2.88	3.34	3.77
0.5	0.71	1.14	-	2.41	-	3.53	-	4.46
1.5	1.83	-	-	3.88	-	5.18	-	5.83
2.5	3.02	-	-	-	-	6.23	-	7.00
3.5	3.71	-	5.12	-	6.41	-	7.54	8.01

2.75 in Stroke

Segment No. 1 Opening (in.)	Segment No. 2 Opening (in.)					
	0	0.5	1.0	1.5	2.0	2.75
0	-	0.54	1.13	1.72	2.22	2.90
0.5	0.69	1.30	-	2.49	-	3.58
1.5	2.03	-	-	3.87	-	5.05
2.75	3.26	-	4.50	-	5.72	6.43

2.0 in. Stroke

Segment No. 1 Opening (in.)	Segment No. 2 Opening (in.)				
	0	0.5	1.0	1.5	2.0
0	-	0.51	1.16	1.73	2.23
1.0	1.41	-	2.70	-	3.78
2.0	2.56	3.18	-	4.53	5.00

Figure 6. Sliding Segment Worth vs Stroke

Figure 7. Sliding Segment Worth vs Angle

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Figure 8. Radial Gap Worth

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4. Uncertainties

Because of the large perturbations introduced by splines, drums, and segment configuration, it is difficult to assign values to the uncertainties or errors in the experiments. With no change in reactor configuration (i. e., startup, shutdown, startup), critical positions were reproduced to within 3¢. Certain reactor configurations were repeated periodically throughout the experiment, to check on reproducibility. These base configurations were reproduced with an error of $\pm 10\%$ over the entire program, and with $\pm 3\%$ during the measurements with any one segment.

IV. ANALYTICAL METHOD AND RESULTS

A. RESULTS

Analytical results were only obtained for a segment stroke of 3-1/3-in. Two-dimensional calculations were made in both R, Z and R, θ geometry. Meaningful results were only obtained from the R, Z geometry calculations. In R, θ geometry, a considerable variation in segment worth could be obtained, depending upon the specific transverse leakage representation which was used.

In the R, Z geometry model, it was necessary to assume that the entire reflector was tapered, and that the segment opening encompassed the full reactor circumference. A worth of \$13.07 was obtained for the 3-1/2 in. stroke under these conditions.

Assuming that the worth is linearly proportional to angle, the worth of one 90° segment is \$3.27, and the worth of both 90° segments is \$6.54. These may be compared to the experimental worths of \$3.71 to \$3.77 for one segment, and \$8.01 for both. The analytical worth is low, by 12 to 18%.

From Figure 7, it is apparent that the angular variation in worth is non-linear. Extrapolation of the experimental worth to the full 360° gives a value of \$14. The analytical worth at 360° is therefore low, by ~7%.

The calculated excess reactivity with segments closed was \$4.43. This must be corrected for the fact that one-half the reflector is not tapered. This correction increases the calculated excess reactivity to about \$5.00. The measured excess reactivity was \$5.88. Difference of this magnitude are typical for this assembly, as may be seen in Figure 9.

Attempts were made to synthesize the three-dimensional geometry of the system, using axial leakages from the R, Z calculations in R, θ calculations. These leakages were input to the R, θ calculations as absorption cross sections. In one instance, leakages were obtained from a zone 3-1/2 in. high, comparable to the segment stroke. The worth obtained for both segments was \$9.85, which is 23% larger than the experimental worth. In the other instance, the leakages were obtained over the total core length. This gave a worth of \$13.41, which is 67% larger than the measurement. In both instances, the excess reactivity with segments closed was comparable to the measured reactivity. The first case

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Figure 9. Excess Reactivity vs Reflector Thickness

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gave an excess reactivity of \$5.57, and the second gave \$5.92. The problem obviously lies in representing the open segments in R, θ geometry. No solution to this problem was discovered during the course of the study.

B. METHOD

Two-dimensional calculations were performed, using the DOT III code. Five neutron energy groups and the S_4P_0 approximation were used. Zonewise, 5-group cross sections were obtained from a group collapse of a 28-group APC⁽⁵⁾ calculation of SCA-4A with a 2-1/2 in. reflector. The standard 28-group library⁽⁶⁾ was used in APC.

In order to test the accuracy of the 5-group cross sections, a series of calculations was made of SCA-4A with various reflector thicknesses, ranging from 0 to 3-1/4 in. A reflector thickness of 3-1/4 in. is the maximum capability of SCA-4A. Both 28-group and 5-group calculations were made. The 5-group cross sections were held constant for all cases. The results are shown in Figure 9. It may be seen that the difference is small, with the largest difference occurring at the extremes in reflector thickness. The differences that exist are in the direction that would produce lower values for segment worth. Also shown in Figure 9 is the measured reactivity as a function of reflector thickness.⁽⁷⁾ It may be seen that the calculations underestimate reactivity by about \$1 in the region of interest. The difference in slope between measured and calculated reactivity is also in the direction that would produce lower calculated segment worth.

Sketches of the R, Z and R, θ models used are shown in Figures 10 and 11. In R, Z geometry, it was necessary to stair-step the tapered reflector as shown. It was also necessary to assume that the entire reflector was tapered, whereas, in fact, the control drums and fixed reflector surrounding the drums had a constant thickness of 2-1/2 in. In R, θ geometry, the calculational model encompassed only 90° of the reactor, as indicated in Figure 11. This was possible, due to the symmetry which is obvious.

Figure 10. R, Z Model

Figure 11. R, θ Model

A homogeneous representation of the core, internal reflector, and combined grid plate and fuel element end caps was used throughout. The volume fractions used in the various zones are given in Table 5. The atom densities for the materials are given in Table 6. Dimensions and mesh spacing used in the DOT III calculations are shown in Figure 12 and Figure 13.

TABLE 5
VOLUME FRACTIONS

Zone	Material	Volume Fraction
Core	Fuel	0.8364
	Hastelloy N Cladding	0.0311
	Glass	0.0084
	Void	0.1241
Internal Reflector	Beryllium	0.8766
	Void	0.1234
Lower Grid Plate and End Caps	Type 316 Stainless Steel	0.582
	Hastelloy N	0.284
	Void	0.134
Upper Grid Plate and End Caps	Type 316 Stainless Steel	0.258
	Hastelloy N	0.451
	Void	0.291
Reflector	Beryllium	1.0

TABLE 6
ATOM DENSITIES
(atoms/b-cm)

Element	Material				
	Fuel	Hast-N	Type 316 SS	Glass	Be
U ²³⁵	0.001425				
U ²³⁸	0.0001053				
Zr	0.03534				
H	0.065				
Ni		0.06903	0.01016		
Mo		0.009462	0.001243		
Cr		0.007239	0.01559		
Fe		0.00270	0.05576		
Mn		0.00049	0.001738		
B		0.000003			
Al	Glass Mockup			0.0165	
O				0.0435	0.00089
Na				0.0078	
Be					0.1214
Sm ¹⁴⁹				0.00002

INTERVAL	RADIUS (cm)	INTERVAL	HEIGHT (cm)
1 15	10 2210	1 3	3 8100
16-18	11 3487	4-5	6 3500
19	11 4300	6-7	8 2106
20	11 5824	8	8 8900
21 27	13 2153	9 16	19 0500
28 30	14 9907	17	20 0025
31 33	16 3903	18 24	28 8925
34	16 7110	25	29 8450
35 41	18 3147	26-33	40 0050
42	18 5188	34	41 1302
43-48	21 1722		
49	21 7553		

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Figure 12. R, Z Dimensions and Mesh Spacing

INTERVAL	RADIUS (cm)	INTERVAL	ANGLE (°)
1-15	10.2210	1-21	63
16-18	11.3487	22	65
19	11.4300	23	69
20	11.5824	24-31	90
21-45	19.5199		

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Figure 13. R, θ Dimensions and Mesh Spacing

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