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SHAPED THERMAL NEUTRON FLUX FILTERS FOR AN IN-PILE TEST CAPSULE

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16. Abstract

Flux tailoring filters are necessary to achieve uniform, flat reaction rates for configurations of test capsules to be irradiated in high thermal flux test reactors. The shaping of filters has been studied by an experimental method using (α, n) neutron sources in water media. The design objective was to achieve acceptably flat reaction rates along the axes of the test capsules when the unperturbed flux has a steep gradient. The flat filtered reaction rates finally attained were only slightly lower than those due to the lowest thermal flux level present before the tailoring filters were introduced.

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SUMMARY

An experimental method is employed for designing thermal flux flattening filters to be used with test capsules in reflector regions of high thermal neutron flux test reactors. The procedure for determining the shape of the filters involved using an americium-beryllium neutron source in water to approximate the unperturbed thermal neutron flux gradient in the test region. The thermal neutron absorptivity of materials in the test capsules and the filters was simulated by mylar tape containing boron.

Using a series of flux mapping experiments together with a flux transmission estimate allowed a satisfactorily shaped filter to be evolved that provided acceptably flat reaction rates along the axes of the test capsules. The flat filtered reaction rates finally attained were only slightly lower than those due to the lowest thermal flux level present before the tailoring filters were introduced.

INTRODUCTION

The NASA Plum Brook Reactor (PBR) is used for experiments such as burnup and radiation effects on fuel elements. Such experiments to study fuel elements for use in fast spectrum reactors of space-power generating systems pose special problems for the thermal flux facilities of the PBR. Conducting burnup and radiation effects experiments on fast spectrum reactor fuel elements using the thermal spectrum reactor, PBR, tacitly assumes that test fuel pins are affected in the same manner whether fission occurs from fast or thermal neutrons. Fuel pins considered in this report are for such fast-spectrum reactor systems.

One special problem with using PBR as the test facility for fast spectrum reactor test fuel pins is that such pins must be only slightly enriched in uranium-235. This limitation is necessary to keep self-shielding low and to help achieve more uniform power distribution throughout the test fuel pin volume.

Although actual fast spectrum reactor fuel pins may be quite long, it is expedient to test three small segments of these long fuel pins in one test hole of PBR at one time. Reference 1 shows the configuration of these test fuel pins.

Since the burnup will be quite uniform over any small segment of an actual space power fast spectrum reactor fuel pin, the neutron flux for the test fuel pins also must be quite uniform or flat. This poses another special problem with using PBR. Unperturbed thermal neutron flux in some test holes of PBR is not flat but has a large gradient. In addition, fueled or absorptive experiments depress the available flux and usually cause an even larger flux gradient. Therefore, shaped filters are required to flatten the flux around the test fuel pins and to reduce the perturbed gradients. Some of these problems and methods for alleviating them are discussed in references 1 and 2.

In the present report, an experimental method for determining the shape and thickness of thermal neutron filters required to reduce a flux gradient is studied. A thermal neutron flux gradient is first generated using an (α, n) neutron source in water. The thermal neutron absorptivity of the test fuel pins are simulated by layers of boron-mylar tape wrapped around mandrils. Finally, the shaped filters are also simulated by layers of boron tape.

Although performing flux tailoring experiments in actual or mockup irradiation facilities is desirable (see ref. 1), the task of distributing and shaping thermal neutron filters is complex. Therefore, the present experiments have been performed to guide and formulate procedures for achieving flat reaction rates using simulated test capsules in a thermal flux gradient in water generated by a single neutron source.

EXPERIMENT DESCRIPTION

In the actual irradiation at PBR some terminology definitions have evolved that will be adhered to in this report. A test capsule is composed of a fuel pin (fuel and cladding) in a stainless steel container. Several test capsules are positioned in a test capsule holder and irradiated in a test hole.

Figure 1 shows mockup test capsules relative to a 54 curie (2×10^{12} disintegrations/sec; 1.3×10^{8} neutrons/sec) americium-beryllium neutron source in water. The test capsule holder contains three simulated cylindrical test capsules arranged as shown. (Details of the simulation of the test capsules are discussed later in this section.) To approximate the thermal neutron flux gradient found in the PBR, unperturbed components of the flux gradient in the y- and x-directions were required to be roughly 2 to 1 over the axial length of the simulated fueled region of the test capsules and across the diameter of the test capsule holder at the center of the simulated fueled region.

The orientation of the test capsule holder relative to the source shown in figure 1 was determined after measuring the spatial distribution of thermal neutrons using dysprosium-aluminum (Dy-Al) foils (0.32 cm diam by 0.0127 cm thick and 5 percent Dy by weight). The measured distribution is shown in figure 2. It is the reaction rate indicated by these Dy-Al foils that is used as a measure of the effectiveness of the filters used. Two design points are located in this figure that were chosen to provide an unperturbed flux ratio of 2 to 1 axially and still have as high an absolute flux as possible over a length of the simulated fuel region. In addition, at the center of the simulated fuel region, a flux ratio as large as possible across the diameter of the test capsule holder is provided. The orientation shown in figure 1 provides the unperturbed 2 to 1 flux ratio needed for the flux simulation. The radius vectors R locate the simulated fuel region to correspond to the design points of figure 2.

Figure 3(a) shows the configuration of the mockup fuel pin test capsule holder. Two rods and a tube made of aluminum were used to approximate the water-flow baffles in the actual fuel pin test capsule holder (ref. 1). Figures 3(b) and (c), in which D and D/2 are the designations for full- and half-size fuel spins, respectively, show two of the three mockup fuel pins. The third fuel pin is identical to the small one. The heights of the cladding and the fuel regions were made approximately the same as those in the actual fuel pins.

The macroscopic thermal neutron absorptivity is $\Sigma_a V$, where Σ_a is the macroscopic cross section and V, the volume. The $\Sigma_a V$ of the materials in the test capsule and later the shaped filters were simulated using boron-mylar tape, similar in construction to magnetic tape. The boron was uniformly deposited on 5.08-centimeter-wide mylar tape with a $\Sigma_a t$ of 0.074 where t is one thickness of tape. It is convenient to cut, roll, or stack the tape into any desired shape. The appendix lists the cross sections, dimensions, and amounts of boron tape used in mocking-up the test capsules.

To mockup the macroscopic thermal absorptivity of the fuel and the cladding, rectangular pieces of boron tape were used such that

$$(\Sigma_a V)_{boron} = (\Sigma_a V)_{fuel} + (\Sigma_a V)_{cladding}$$

The boron tape to simulate the fuel was wound around an aluminum mandril whose diameter was close to that of the fuel pin. Since it was desired to mount Dy-Al foils between the simulated fuel and the cladding and since the actual fuel pin is clad with tungsten and T-111 contained in a stainless steel container, an additional volume of boron tape was used to mockup T-111 and tungsten. Boron tape was not used to mockup stainless steel since stainless steel also was used as the mockup pin container. This boron tape was rolled and then allowed to spring out to the inside diameter of the mockup stainless steel container as shown in figures 3(b) and (c). T-111 and tungsten on the ends of the actual test capsules were also simulated by disks of boron tape. The orientation of the test capsules in the test capsule holder with respect to the source is indicated in figure 3(a).

To position the mockup test capsule holder accurately with respect to the source as indicated in figure 3(a), a Lucite tube was used as shown in figure 1. The large Lucite tube contains a smaller Lucite cup. The inside diameter of the cup admits the test capsule holder. Each component has either a pin or a notch such that the test capsules could be placed at the same position with respect to the source each time a flux mapping experiment was run. The filters used to approach a flattened flux were taped around the outside of the large Lucite tube and for some cases, the mockup test capsules also had individual filters.

The thermal flux mapping measurements were made by spacing the Dy-Al foils along vertical traverses parallel to the axis of the cylindrical fuel pins. The six radial positions of these vertical traverses are shown in figure 3(a) and lettered A, B, C, E, F, and G. These six radial positions with assigned plotting symbols will appear again in figure 9. Figure 3(b) shows a typical foil layout for any one of the traverses. Five foils were used in the A and B traverses while only three foils were used in each of the others.

RESULTS AND DISCUSSION

This section discusses the succession of filters used to evolve a flat dysprosium reaction rate in the test capsule. Figures 4 to 8 show the arrangement and shape of the filters as they evolved after each of the flux mapping experiments. The axial distributions of saturated foil count rates at each of the various radial positions (A, B, C, E, F, and G) in the test capsules are shown in figure 9 for each filter configuration. Abscissa positions 11 to 13 span a 5.08-centimeter distance corresponding to the length of the fueled region of an actual test capsule in a typical position in the PBR.

All the data from all the flux mapping experiments are shown in figure 9 in order that the spatial reaction rates of the successive filter configurations can be seen easily. Table I lists the data plotted in figure 9. Saturated activities and errors listed in table I are computed as described in reference 3, in which similar flux traversing experiments were performed. The experiment run numbers in table I and figures 4 to 9 correspond.

The shape of the perturbed flux around the test capsule holder with no filter was measured first. The results of this no filter case shown in figure 9, run 1, indicate a large fall off in reaction rate along the axis of the capsule holder. Note that the presence of the test capsules increases the flux gradient from the unperturbed ratio of 2 to 1. The results of a base filter case shown in figure 9, run 2, were obtained using a filter (fig. 5) similar in thermal neutron absorptivity, size, and position as a hafnium filter used with fueled test capsules in the Plum Brook mockup reactor. These first two runs had two purposes: (1) The data obtained in the first run showed that we could approximate the flux gradient in a test hole of the PBR using a 54 curie neutron source in water. (2) A simple transmission computation using the data obtained from the A traverse of run 2 showed that about 11 thicknesses of boron tape were necessary to bring the reaction rate level at the nearest point down to the reaction rate level of the point farthest from the source. However, it was obvious from figure 9, run 2, that less filter was required far from the source than near to it. Therefore, the graded filter of figure 6 was made. In figure 9, run 3, some improvement is seen at positions 12 and 13 in both the upper and lower graphs, but at position 11 the flux is high.

Results of changes made in the boron filter to improve the flux flattening can be seen by comparing figure 7 to figure 6. The maximum height of the contour lines are generally higher to remove the slight rise in the data at position 13, run 3, figure 9, traverse A. An extra thickness of boron tape near position 11 plus the disks at the bottom of the fuel pins were intended to reduce further the reaction rate in the vicinity of position 11. Also, the slight contour peaks of the filters which were placed near the D/2 pins were intended to reduce the reaction rate level near these pins at position 11 and 12. Indeed, a look at figure 9, run 4, shows that some of the desired effects were obtained. The slight contour change in the filter near the D/2 pins decreased the reaction rate at position 11 for the D/2 pins, but the disk filters at the bottom had little effect because they were about 2.5 centimeters away from the foil at position 11. At this distance the flux depression due to the disks is down to less than 10 percent effective. The next modification used small half cylinder filters around the bottom of the individual pins below the foils as shown in figure 8. In figure 9, when run 5 is compared to 4, the improved flux flattening is seen at position 11. Thus, the absorber filters of run 5 control thermal neutrons in two ways: (1) broad control by absorption in outer filters that are shaped and surround the capsule, and (2) local control by filters that suppress the flux near the simulated fuel pins.

Inspection of the distributions of the saturated Dy-Al foil counts in successive filtered configurations shown in figure 9 shows that the reaction rates in the filtered thermal fluxes can be flattened to an axial variation of less than 35 percent. In this process, the magnitude of the flat filtered reaction rate finally attained was only slightly lower than that with the lowest thermal flux level present before the tailoring filters were introduced.

CONCLUSIONS

A method for designing a configuration of shaped filters to flatten the reaction rates around irradiation test capsules located in a flux gradient was evolved. Boron was used to mockup the thermal neutron absorptivity of the test fuel pin capsules and an americium-beryllium (α, n) neutron source in water was used to mockup the flux gradients in the test regions. Using successive dysprosium-aluminum foil flux mapping experiments and a flux transmission estimate produced a final filter which showed it was possible to obtain less than 35 percent variation axially in the reaction rate distribution in the particular array of three simulated test fuel pin capsules studied. The flat filtered reaction rates finally attained were only slightly lower than those due to the lowest thermal flux level before the tailoring filters were introduced.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 28, 1970,
129-02.

APPENDIX - MACROSCOPIC CROSS-SECTION CALCULATIONS

Table II shows the calculated macroscopic cross sections of the various materials used in a test fuel pin capsule. Table III shows the working dimensions of a certain size fuel pin, D, and an approximately half-size fuel pin, D/2. Table III also shows the amounts of boron tape used in the mockup fuel pin capsules. Boron tape was not used to mockup stainless steel since the jacket of each pin was made of stainless steel. The boron tape quantities and dimensions in table III are indicated in two ways: (1) as length and width of boron tape, and (2) as number of thicknesses on either a cylinder or a disk. In the case of fuel mockup the boron tape wraps around the mandril an integral number of times. In the case of cladding, the thicknesses are not integral.

The equations used to calculate the cross sections of the various elements and molecules were

Elements
$$(\Sigma_a)_{th} = \sum_{i=1}^{n} \frac{b_i \rho_i N_0}{A_i} (\sigma_a)_i$$

Molecules
$$(\Sigma_a)_{th} = \frac{w \rho N_0}{M} \sum_{i=1}^{n} b_i \nu_i (\sigma_a)_i$$

where

$(\Sigma_a)_{th}$	macroscopic thermal absorption cross section, cm^{-1}
b	weight fraction
ρ	density, g/cm^3
N_0	Avogadro's number, atoms/g-at
A	atomic weight, g/g-at
σ_a	microscopic thermal absorption cross section, cm^2
w	fraction of theoretical density
M	molecular weight, atoms/g-molecule
ν	number of atoms per molecule

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1. Stein, Ralph; Homyak, Len; and DeFayette, Robert: Experiment Design Studies for Fuel Pin Development. National Symposium on Developments in Irradiation Testing Technology. AEC Rep. CONF-690910, 1969, pp. 210-220.
2. Anderson, John L.: Design Guides for Irradiation Experiments with Fast Spectrum Reactor Fuel Elements in Thermal Test Reactors. NASA TM X-2012, 1970.
3. Fieno, Daniel; Alexander, Roger L.; and Ford, C. Hubbard: Tests of Evaluated Beryllium (n, 2n) Cross Sections by Analysis of 1.4-eV Flux in Water for an Americium-Beryllium Source Enclosed in Beryllium Spheres. NASA TN D-5995, 1970.

TABLE I. - DYSPROSIUM-ALUMINUM FOIL THERMAL NEUTRON FLUX MAPPING DATA

Position number	Saturated foil count rate (counts/min) and standard error					
	Traverses and figure 9 plot symbols					
	A-□	B-○	C-△	E-◻	F-D	G-Ʊ
Run 1						
11.0	636±13	440±13	443±5	553±9	492±8	505±14
11.5	463±10	359±22	------	------	------	------
12.0	360±12	248±10	264±17	315±4	297±6	------
12.5	295±9	195±11	------	------	------	------
13.0	263±16	192±3	192±22	223±12	215±8	216±8
Run 2						
11.0	254±11	215±10	224±8	251±1	310±17	255±11
11.5	146±10	178±18	------	------	------	------
12.0	133±4	121±4	150±8	220±5	239±9	170±6
12.5	197±11	134±7	------	------	------	------
13.0	208±11	133±20	146±9	181±11	178±16	156±14
Run 3						
11.0	265±22	214±8	220±9	252±6	246±7	248±6
11.5	189±13	158±13	------	------	------	------
12.0	186±4	136±8	205±30	207±6	183±9	176±7
12.5	182±4	139±5	------	------	------	------
13.0	203±13	140±8	162±3	188±6	180±10	171±10
Run 4						
11.0	230±11	163±33	191±26	225±9	210±37	215±8
11.5	170±25	144±24	------	------	------	------
12.0	163±19	140±15	223±46	164±26	187±11	164±30
12.5	180±21	142±11	------	------	------	------
13.0	190±10	115±28	156±9	185±21	180±21	173±7
Run 5						
11.0	205±5	180±5	169±12	232±11	228±1	217±19
11.5	190±10	153±8	------	------	------	------
12.0	169±20	147±10	157±6	206±13	196±8	262±39
12.5	206±37	127±14	------	------	------	------
13.0	193±2	138±7	185±9	188±17	185±15	198±11

TABLE II. - MACROSCOPIC CROSS SECTIONS AND RELATED PARAMETERS OF MATERIALS

USED IN TEST FUEL ELEMENT PIN CAPSULES

Material		Weight fraction, b	Atoms/ molecule, ν	Density, ρ, g/cm^3	Fraction theor. density, w	Atomic weight, A, g/g-at	Molecular weight, M, atoms/ g-molecule	Micro-scopic cross section, σ_a, cm^2	Macro-scopic cross section, $(\Sigma_a)_i$, cm^{-1}	$\sum_{i=1}^{n} (\Sigma_a)_i$, cm^{-1}
N		-----	--	-----	----	-----	------	1.9	-----	-----
W		1.000	1	18.9	----	184	------	19.2	1.187	1.187
T-111	0.08W	.08	--	18.9	----	184	------	19.2	.095	1.233
	0.9Ta	.9	--	16.6	----	181	------	21	1.044	
	0.02Hf	.02	--	13.3	----	178.5	------	105	.094	
D	^{235}UN	.056	1	14.22	0.96	-----	249.22	638	-----	1.321
	^{238}UN	.944	1	14.22	.96	-----	252.22	2.7	-----	
D/2	^{235}UN	.082	1	14.22	.96	-----	249.22	638	-----	1.866
	^{238}UN	.918	1	14.22	.96	-----	252.22	2.7	-----	
Boron tape $\Sigma_a t$ for one thickness										0.074

TABLE III. - WORKING DIMENSIONS AND BORON MOCKUP INFORMATION FOR

D AND D/2 SIZE TEST FUEL ELEMENT PIN CAPSULES

Fuel pin working dimensions								Fuel pin boron mockup dimensions						
Pin	Material	Radius, cm			Height or thickness, cm			Radius			Height, cm	Length of boron tape, cm	Thicknesses of boron tape	
		Ends	Cylinder		Ends		Cylinder	Mandril, cm	Disk, cm	SS cylinder, cm			Mandril	Disk
			Outside	Inside	Top	Bottom								
D	S.S.	1.01	1.21	1.02	0.64	0.30	9.83	----	1.01	1.02	9.83	-----	--	--
(5.6% ^{235}U)	T-111	0.95	0.95	0.81	0.28	0.28	6.42	----	0.94	----	6.35	13.3 } 14.4	--	6
	W	.81	.81	.79	.033	.033	6.35					1.1		
	Fuel	----	0.79	0.25	-----	-----	5.72	0.74	----	----	5.72	31.6	7	--
D/2	S.S.	0.54	0.74	0.54	0.64	0.30	9.83	----	0.54	0.54	9.83	-----	--	--
(8.2% ^{235}U)	T-111	0.46	0.46	0.39	0.28	0.28	6.42	----	0.47	----	6.35	3.4 } 3.7	--	6
	W	.39	.39	.38	.033	.033	6.35					.32		
	Fuel	----	0.38	0.13	-----	-----	5.72	0.35	----	----	5.72	11.0	5	--

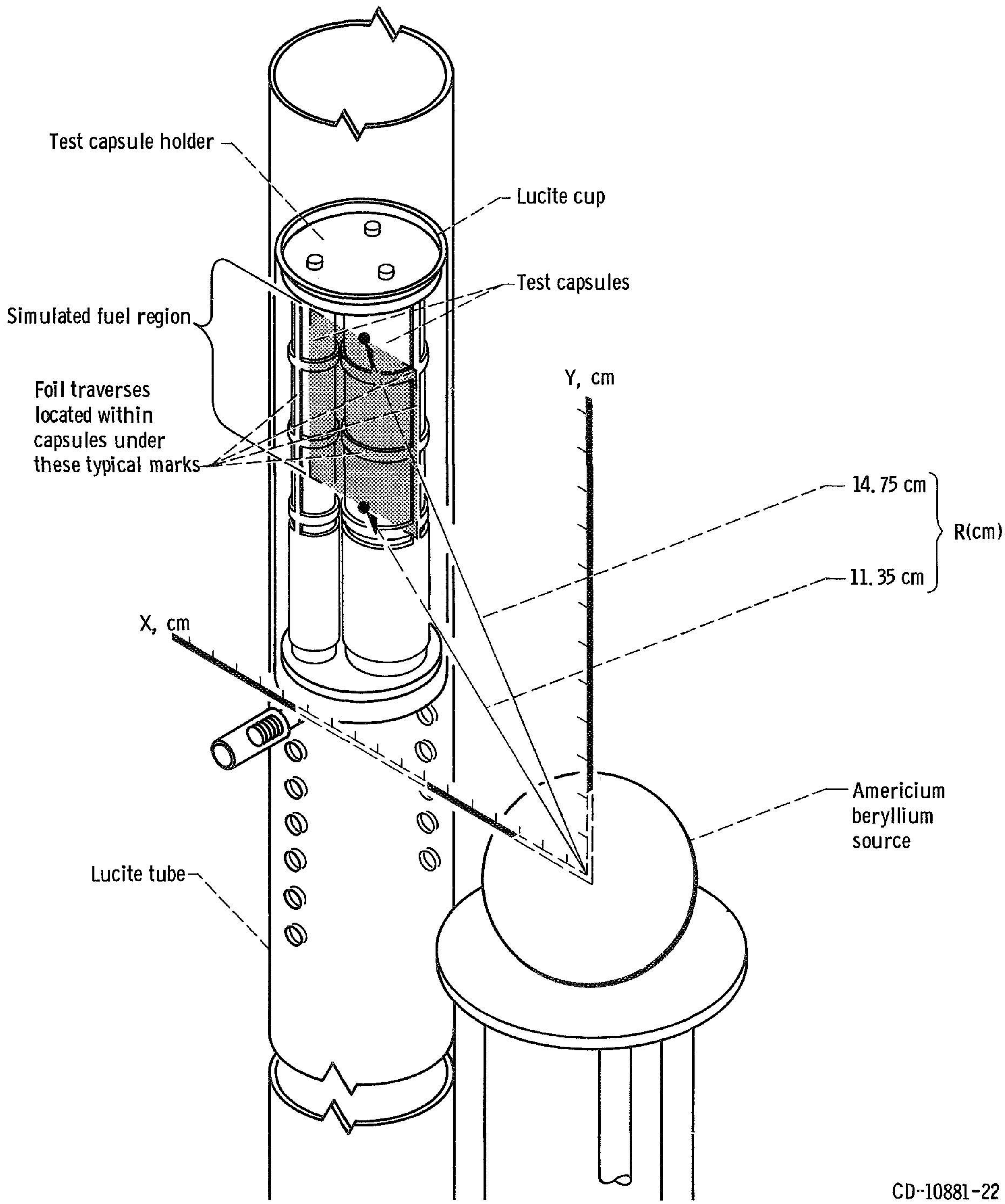


Figure 1. - Configuration of mockup test capsules in a simulated capsule holder and orientation of source to holder.

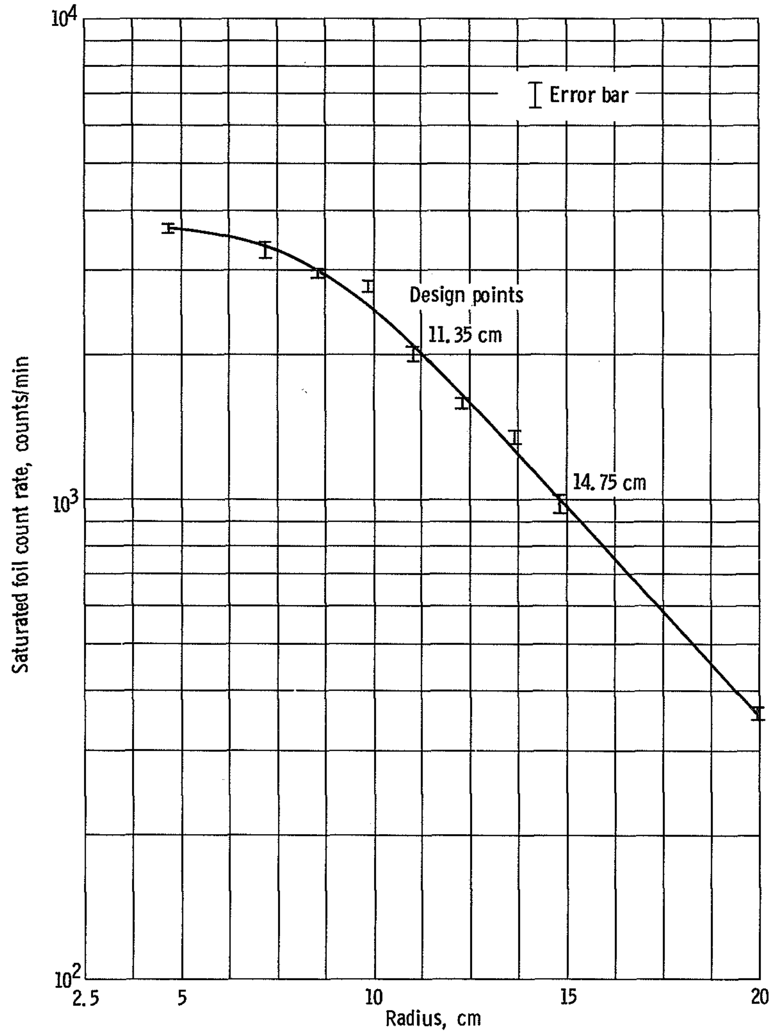
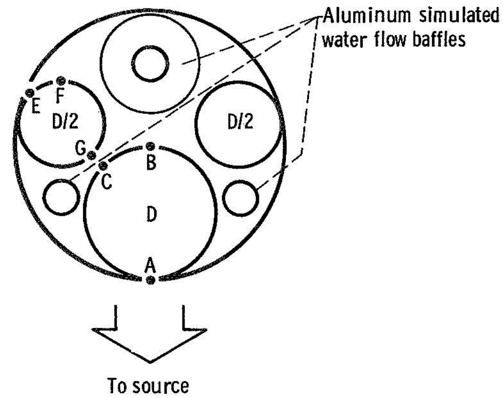
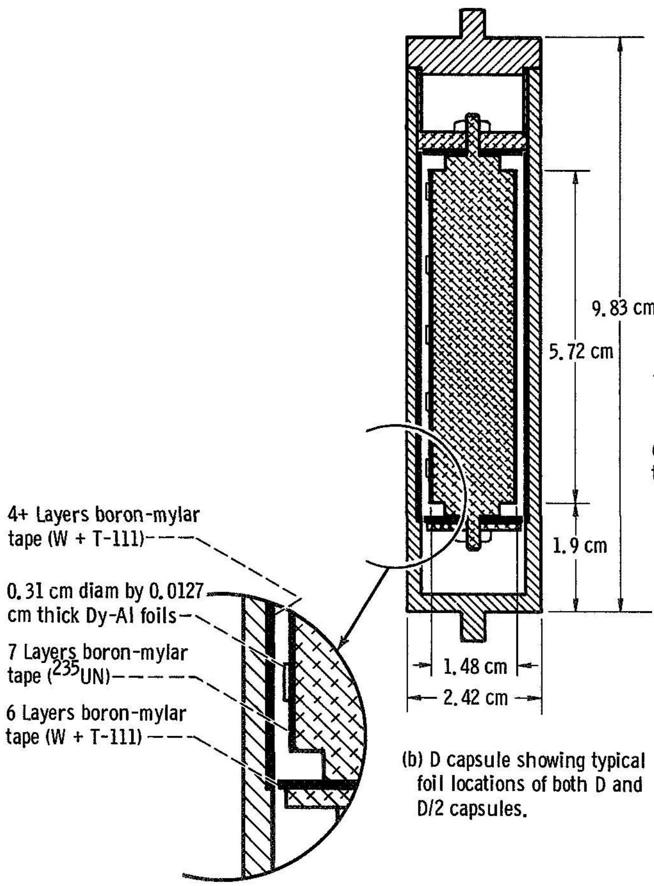


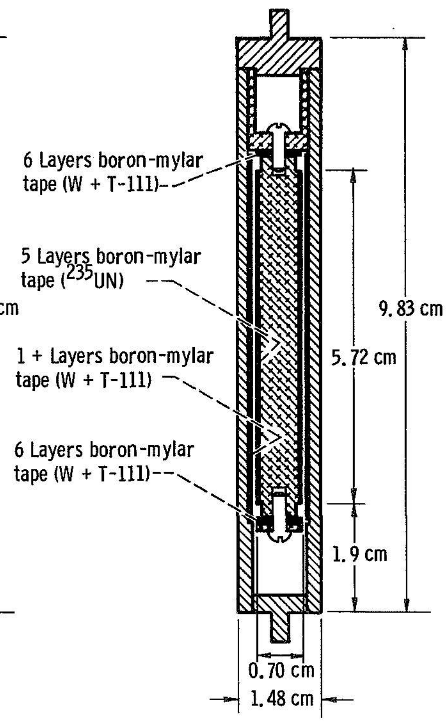
Figure 2. - Unperturbed thermal neutron flux distribution from an americium-beryllium neutron source in water obtained with 0.32 centimeter diameter by 0.0127 centimeter thick dysprosium-aluminum foils (5 percent Dy by weight).



(a) Holder configuration showing source orientation.



(b) D capsule showing typical foil locations of both D and D/2 capsules.



(c) D/2 capsule.

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Figure 3. - Boron mockup test fuel pin capsules and test capsule holder configuration showing source orientation.

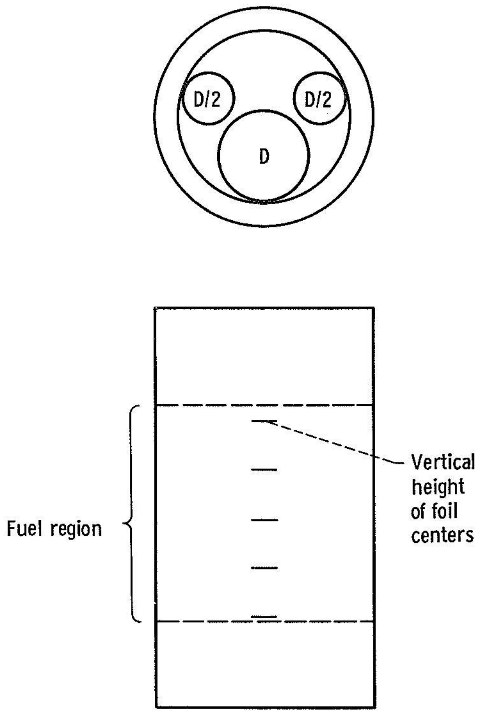

Figure 4. - Test fuel pin capsule holder in position for unfiltered case. Run 1.

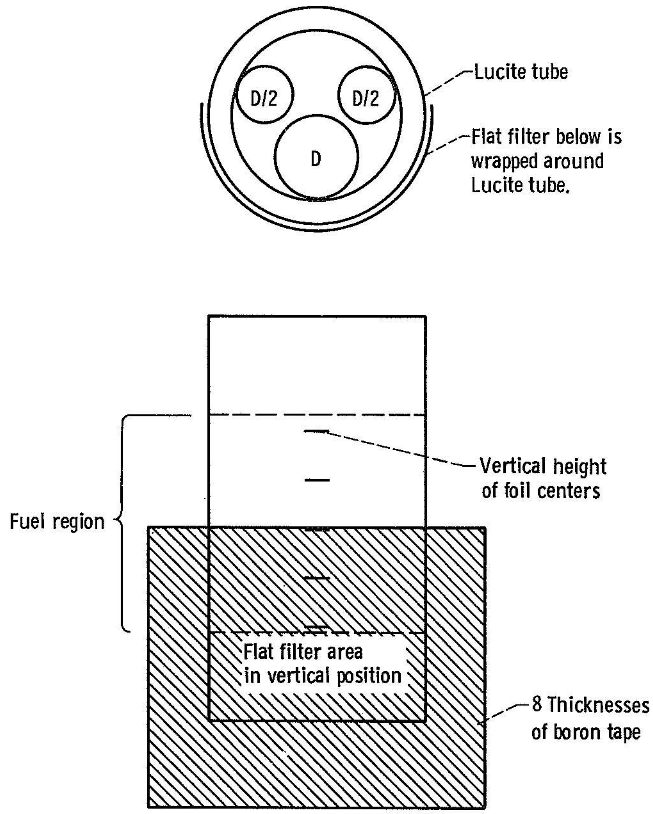

Figure 5. - Configuration for base filtered case. Run 2.

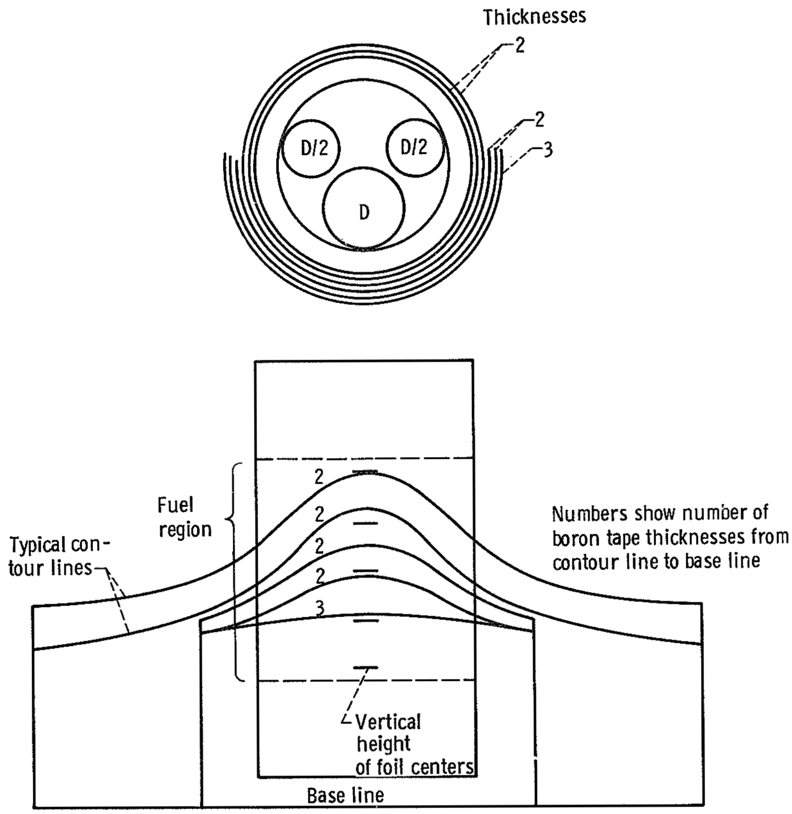

Figure 6. - Graded filter 1. Run 3.

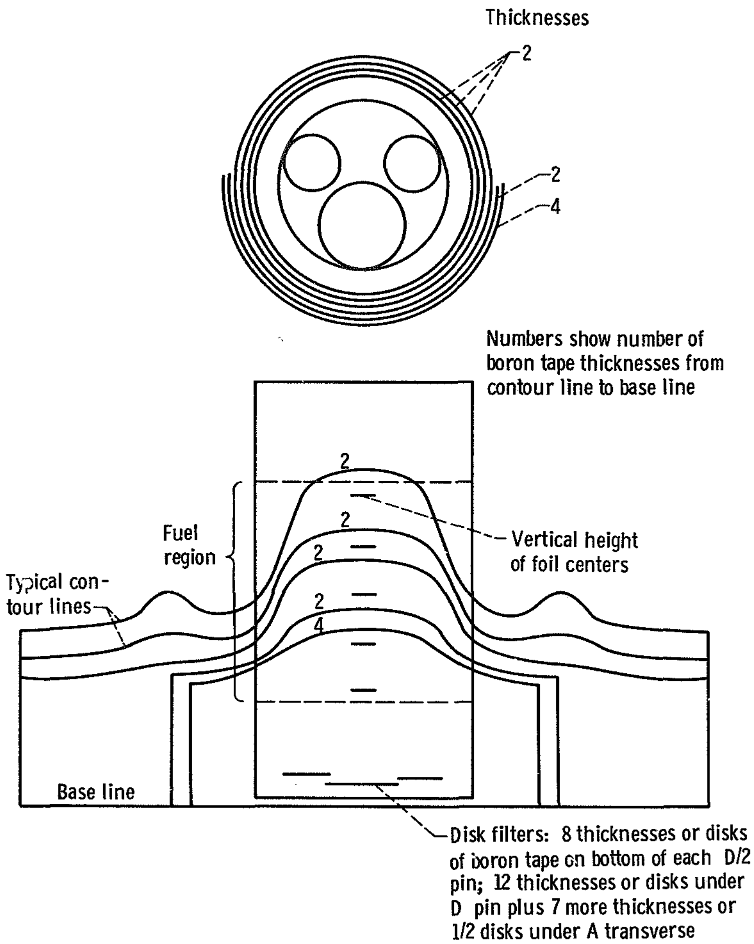

Figure 7. - Graded filter 2 with disk filters. Run 4.

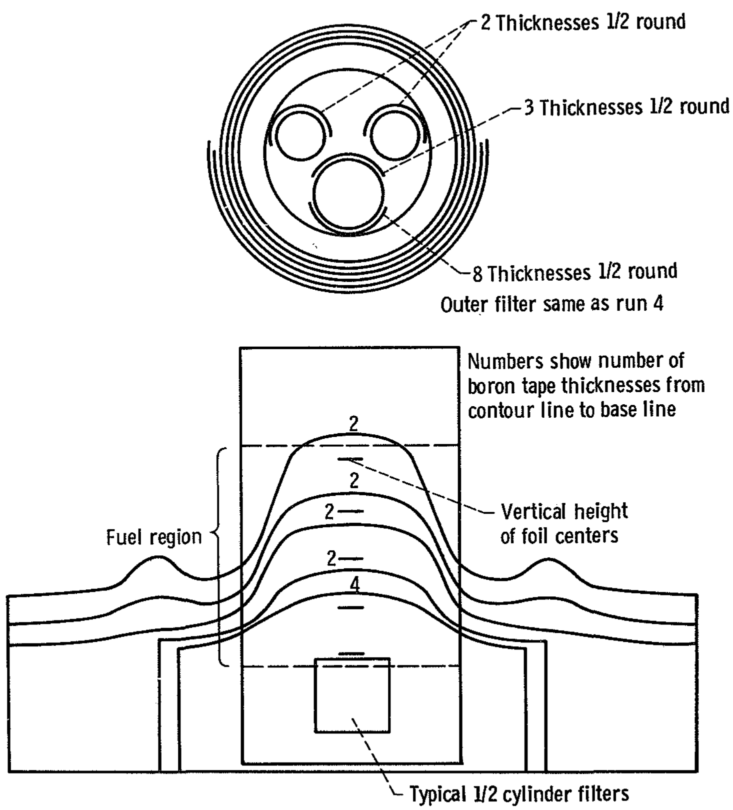

Figure 8. - Graded filter 2 with half-cylinder filters close to lower foils. Run 5.

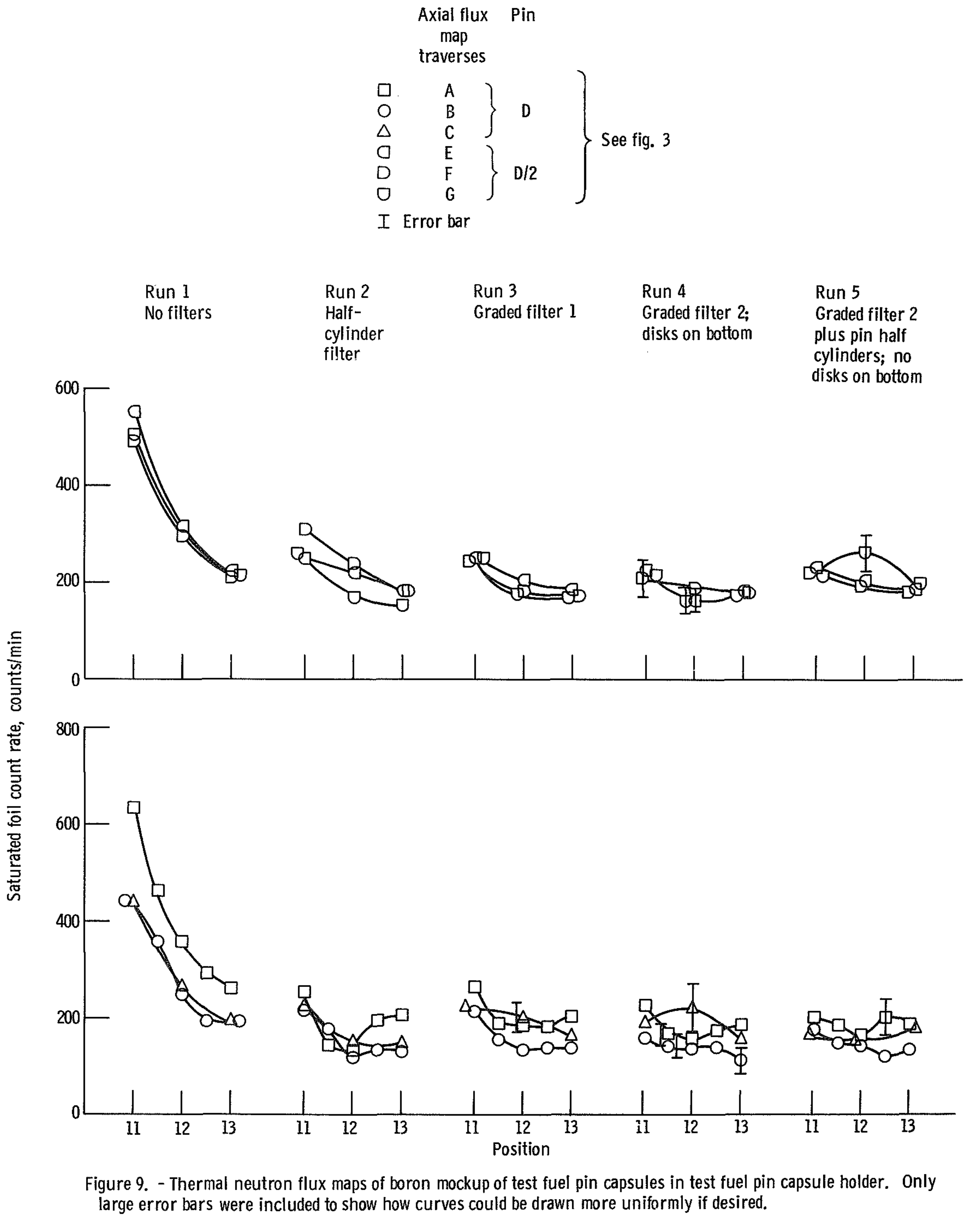

Figure 9. - Thermal neutron flux maps of boron mockup of test fuel pin capsules in test fuel pin capsule holder. Only large error bars were included to show how curves could be drawn more uniformly if desired.

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