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ORNL - TM - 189

COPY NO. - 79

DATE - May 10, 1962

REACTIVITY CALIBRATIONS AND FISSION-RATE DISTRIBUTIONS IN AN UNMODERATED, UNREFLECTED URANIUM-MOLYBDENUM ALLOY RESEARCH REACTOR

J. T. Mihalczo

Abstract

Zero-power critical experiments with an unmoderated, unreflected research reactor constructed of 90 wt% uranium (93.2 wt% U^{235} enriched), 10 wt% molybdenum alloy and designed to produce bursts of fast neutrons have been completed. The assembly is essentially a 20.32-cm-dia by 23-cm-high cylinder of the alloy and contains 96.6 kg of U^{235}. The reactivity of the assembly and its movable parts have been calibrated. The temperature coefficient of reactivity is 0.31 cents/°C. Measured fission-rate distributions are compared to those calculated using an S_n transport theory code, TDC, in the S_4 approximation.

Introduction

A series of zero-power critical experiments with the ORNL Health Physics Research Reactor (previously known as the Fast Burst Reactor) have been completed at the ORNL Critical Experiments Facility.[1,2,3] Although of the same general type as the Godiva reactors, an unmoderated and unreflected uranium metal assembly, this reactor embodies a number of differences; the most significant is the use of a cast and machined uranium-molybdenum alloy as fuel rather than the unalloyed uranium of the earlier reactors. This report describes the zero-power critical experiments which determined the critical size, fission-rate distributions, reactivity calibrations of its movable parts, the temperature coefficient of reactivity, and the reactivity effects of the presence of neutron-reflecting materials adjacent to the reactor.

Description of Reactor

The ORNL Health Physics Research Reactor (HPRR) is basically an unreflected and unmoderated right cylinder of uranium-molybdenum alloy. The alloy contains 90 wt% uranium, enriched to 93.2 wt% U^{235}, and 10 wt% molybdenum. By alloying uranium with molybdenum difficulties with phase changes characteristic of pure uranium during thermal cycling are removed, the tensile strength becomes twice that of uranium, and the yield strength is increased by a factor of four. These improved physical properties will allow the production of neutron bursts of greater than 10^{17} fissions, about an order of magnitude larger than those obtained from Godiva II, while reactor operating lifetime will be increased owing to the better dimensional stability of the alloy during thermal cycling. In addition to its burst capabilities, the HPRR is designed to operate under steady-state conditions at a power level of 1 kw with natural convection cooling or at 10 kw with forced-air cooling for 10 minutes. Tensile strength, yield strength, elongation, and moduli of elasticity of typical alloy specimens are tabulated in the Appendix.

1. G. Breidenbach et al., Preliminary Design of the ORNL Fast Burst Reactor, NDA-2136-1 (July 30, 1960).
2. T. F. Wimett et al., Nucl. Sci. and Eng. 8, 691 (1960).
3. W. E. Kinney and J. T. Mihalczo, Oak Ridge National Laboratory Fast Burst Reactor: Critical Experiments and Calculations, ORNL-CF-61-8-71 (August 24, 1961).

Figure 1 shows a drawing of the reactor. It consists of a 20.3-cm-dia outer annulus made up of uranium-molybdenum disks of several thicknesses held together by nine 1.9-cm-dia uranium-molybdenum bolts. Each bolt has a removable axial plug of the same material or of stainless steel. The outer annulus has a 5.1-cm-dia cylindrical steel core which is movable and supported magnetically. To the lower section of this core is attached the safety block, an 8.9-cm-dia fuel annulus. The reactor contains three movable fuel rods having diameters of 1.59, 1.91, and 2.54 cm, which are used to adjust the reactivity to delayed critical and to provide excess reactivity for burst generation. A vertical, ~23-cm-deep, 0.673-cm-dia "glory hole" is eccentrically positioned for specimen irradiations. Two thermocouples, shown in Fig. 1, provide temperature measurements.

It was necessary to increase the height of the reactor somewhat over that determined by the preliminary critical assembly with uranium-molybdenum alloy,[3] due to the introduction of about a 5% void volume in the reactor, stemming from the large clearance around the safety block, clearances at bolts and control rods, etc. The final height is 23.0 cm, and the entire assembly contains 96.6 kg of U^{235}.

The core parts were nickel plated by different methods which accounts for the variation in appearance evident in the photographs of Figs. 2 and 3. The control rods and the safety block were also flashed with chromium for wear resistance. The crash pipe bolted to the bottom of the reactor prevents the safety block from being pushed into the core if the reactor should fall. The weight of uranium in each of the core pieces is tabulated in the Appendix.

Results

Fuel Reactivity Effects

With all the bolt inserts, irradiation hole plug, and all control rods in the core, the reactor has about 152 cents excess reactivity. The reactivity worths of various movable fuel parts have been evaluated and are given in Table 1.

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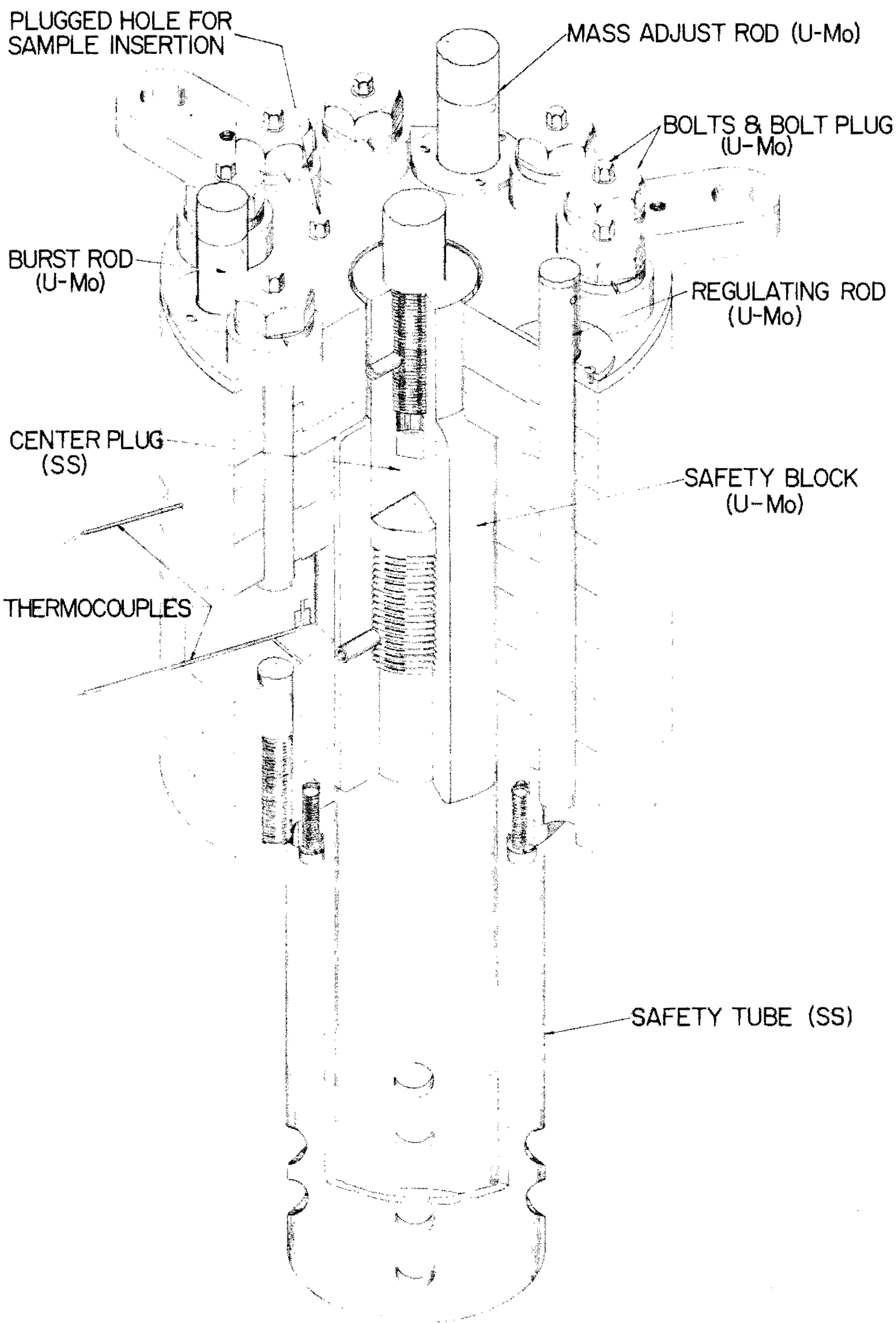

Fig. 1. ORNL Health Physics Research Reactor.

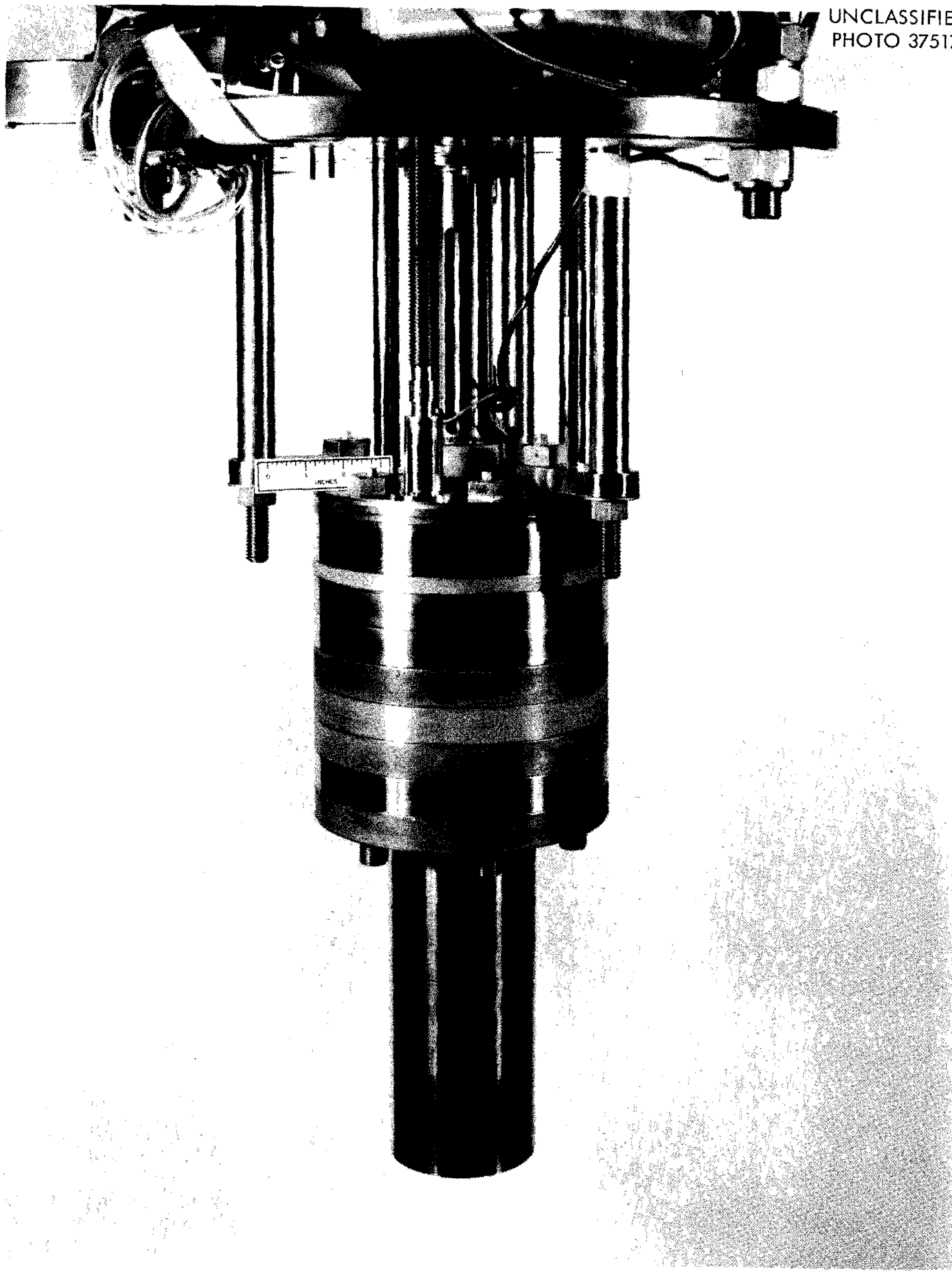

Fig. 2. The ORNL Health Physics Research Reactor

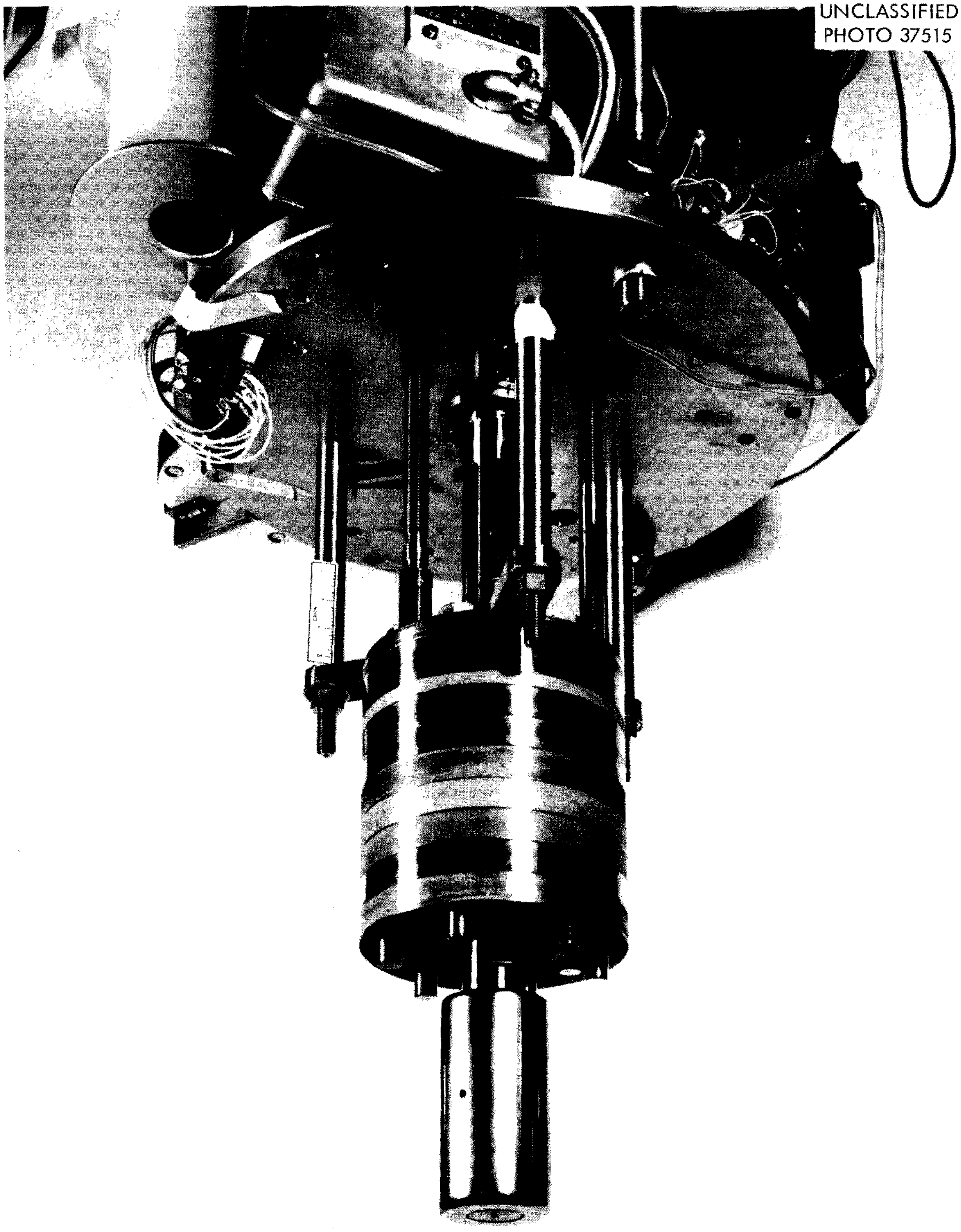

Fig. 3. The ORNL Health Physics Research Reactor. In this photograph the crash pipe has been removed to show the safety block withdrawn.

Table 1. Reactivity Worth of Movable Uranium-Molybdenum Alloy Parts of the HPRR

Part	Uranium Mass (g)	Reactivity Worth (dollars)
Bolt Insert Plug*	120	0.16
"Glory Hole" Plug	130	0.20
Burst Rod	965	1.15
Regulating Rod	658	0.83
Mass Adjustment Rod	1,746	1.95
Safety Block	10,109	20.0

*The values shown are for one plug; there are nine identical and equivalently located plugs in the complete assembly.

The removal of all bolt insert plugs and the "glory hole" plug decreases the reactivity of the system 164 cents. Increased reactivity caused by reflecting materials placed near the reactor during experiments will be compensated for by removal of a suitable number of these plugs and by control rod adjustment. The worth of the three fuel rods as a function of position is shown in Fig. 4. Burst production will be obtained by partial insertion of the 1.91-cm-dia rod into the slightly supercritical reactor.

The negative reactivity of the assembly as a function of safety block position after scram is shown in Fig. 5. The first 2.5 cm of safety block withdrawal decreases the reactivity two dollars. The reactivity is a linear function of block position in this region and has a sensitivity of 80 cents/cm. Figure 5 also shows the reactivity as a function of time after the application of a simulated scram signal in the magnet amplifier. The release time of the magnet is about 4 msec. It is noted that the reactivity of the reactor has decreased one dollar 38 msec after the application of this signal. The large negative reactivity of the safety block was determined by a method in which the leakage flux from the reactor is monitored by a BF_3 ionization chamber. The response of the chamber serves as input data for a small, special-purpose analogue computer (loaned by Brookhaven National Laboratory)

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ROD WORTH VALUES FROM LINEAR PORTION OF CURVES

	DIA (cm)	WORTH (cents/cm)
MASS ADJUSTMENT ROD	2.54	13.3
BURST ROD	1.91	7.7
REGULATING ROD	1.59	4.1

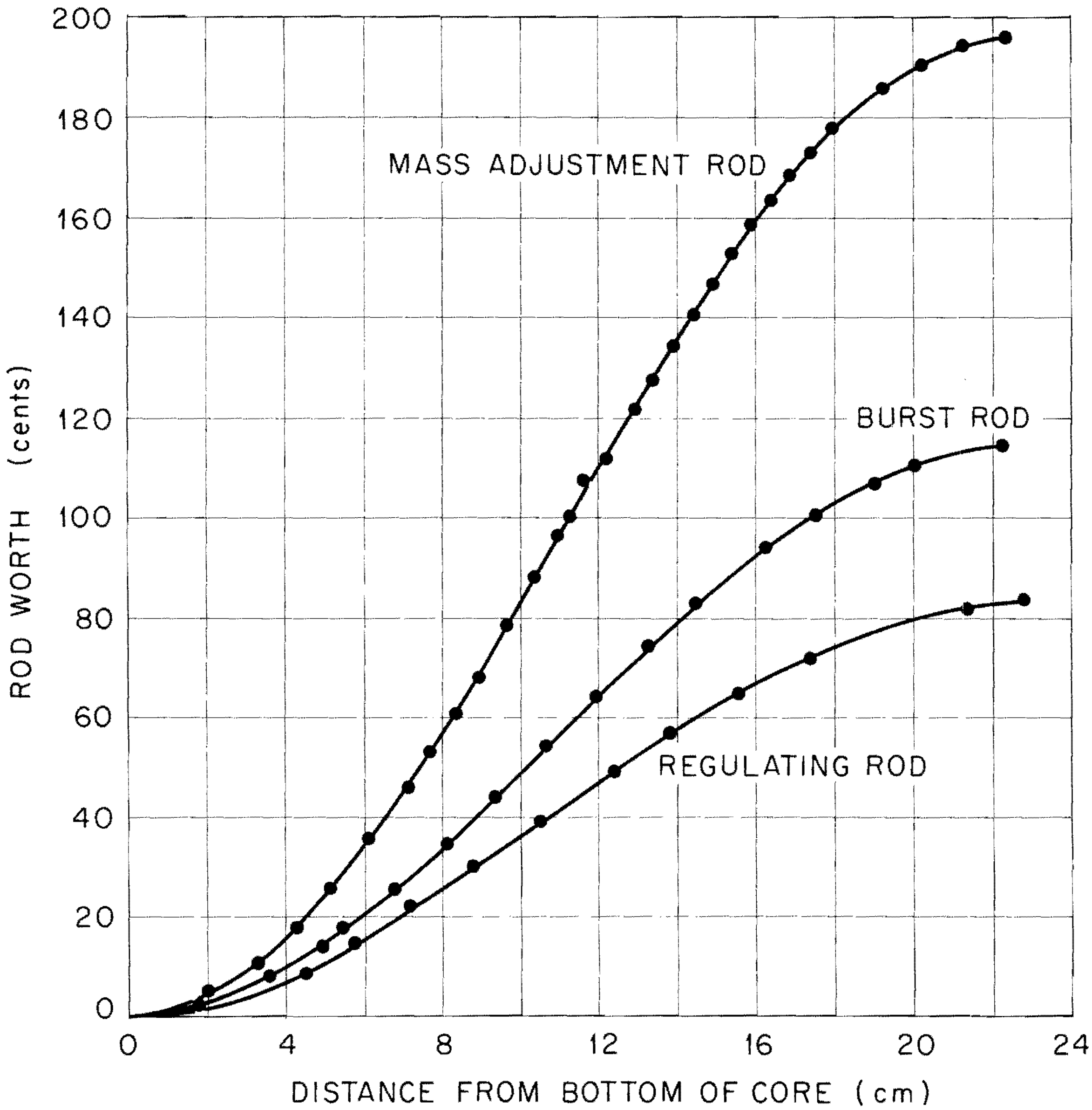

Fig. 4. Rod Worth as a Function of Position for HPRR Control Rods

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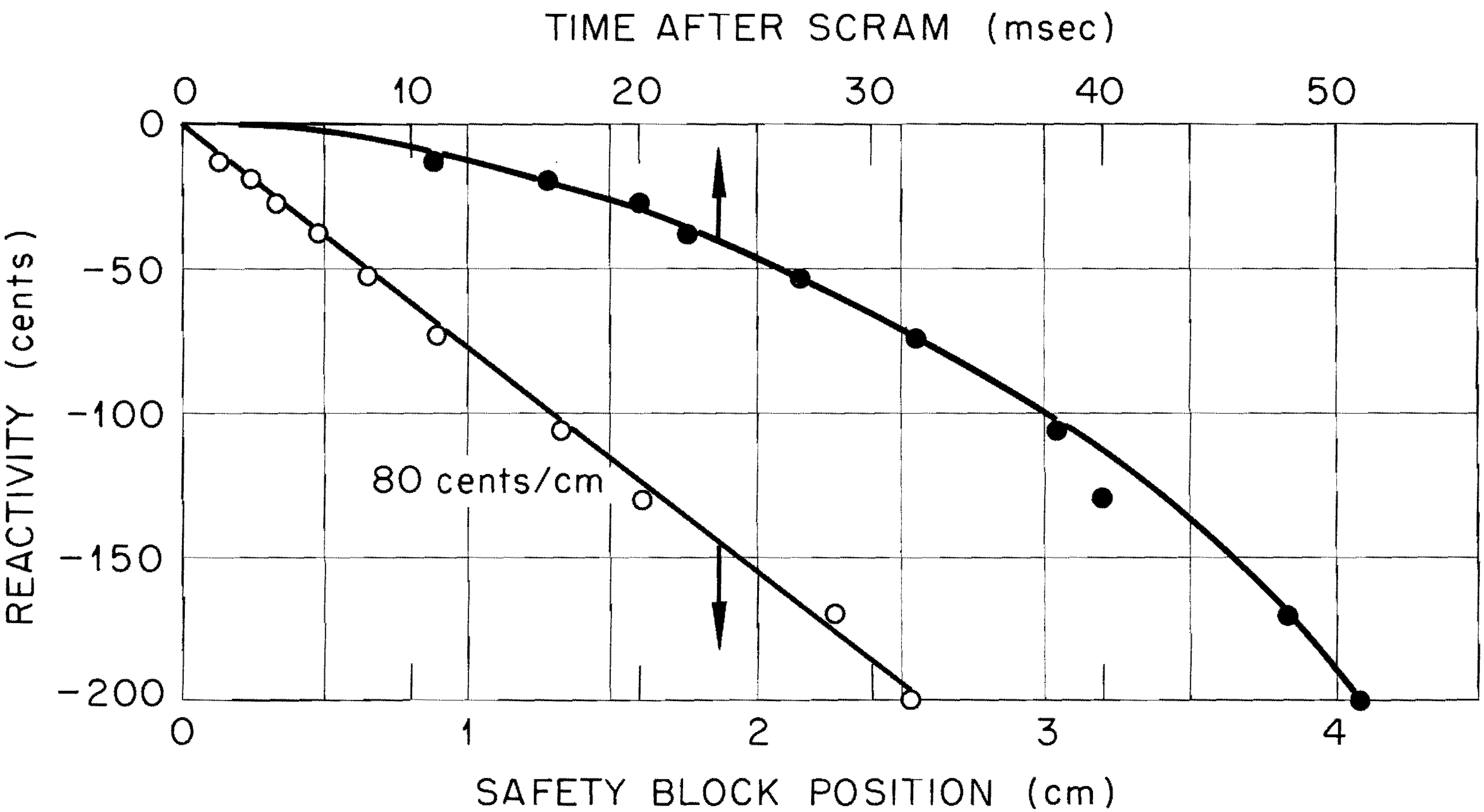

Fig. 5. Reactivity Worth of the HPRR Safety Block as a Function of Its Position and the Time After Scram

which contains the delayed neutron equations for U^{235} systems. The analog computer indicates the reactivity changes from the changes in power level sensed by the ionization chamber.[4]

Reflection Effects

Previously reported experiments[3] with uranium-molybdenum alloy reflected with a methacrylate plastic (Plexiglas) having a hydrogen content of 5.8×10^{22} atoms/cc indicated that the HPRR in the shutdown condition can be made critical with about 1 in. of hydrogenous reflector on all outer surfaces. To further evaluate the effect of reflection, the reactivity effect of a 20- by 20- by 2.5-cm piece of Plexiglas having the same radius of curvature as the core surface was measured as a function of distance from the core surface. The results are shown in Fig. 6. The lack of agreement in values measured at the core surface results from the perturbation of the flux distribution in the core by the Plexiglas reflector. This difference illustrates the dependence of the rod calibrations on the presence of neutron reflectors near the core and emphasizes the caution with which rod calibration curves must be used.

During the present series of experiments the core was located above a 122- by 152-cm steel table 1.9 cm thick. The bottom of the core was 81.3 cm above the steel table, which in turn was 37.6 cm above the concrete floor. So that reflection effects due to the table and floor could be evaluated, measurements were made with the core raised 127 cm from its original position. A decrease of 5 cents in reactivity was observed.

Temperature Coefficient Measurements

The static temperature coefficient of reactivity of the HPRR was measured over the range $20^{o}C-135^{o}C$ and found to be 0.31 ¢/^{o}C, without measurable dependence on temperature. The temperatures were achieved by radiant heating of the assembly which, incidentally, caused peeling of the plating on the threads of one of the bolts.

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4. K. Downes and C. Sastre, Trans. Amer. Nucl. Soc. 3, 423 (1960).

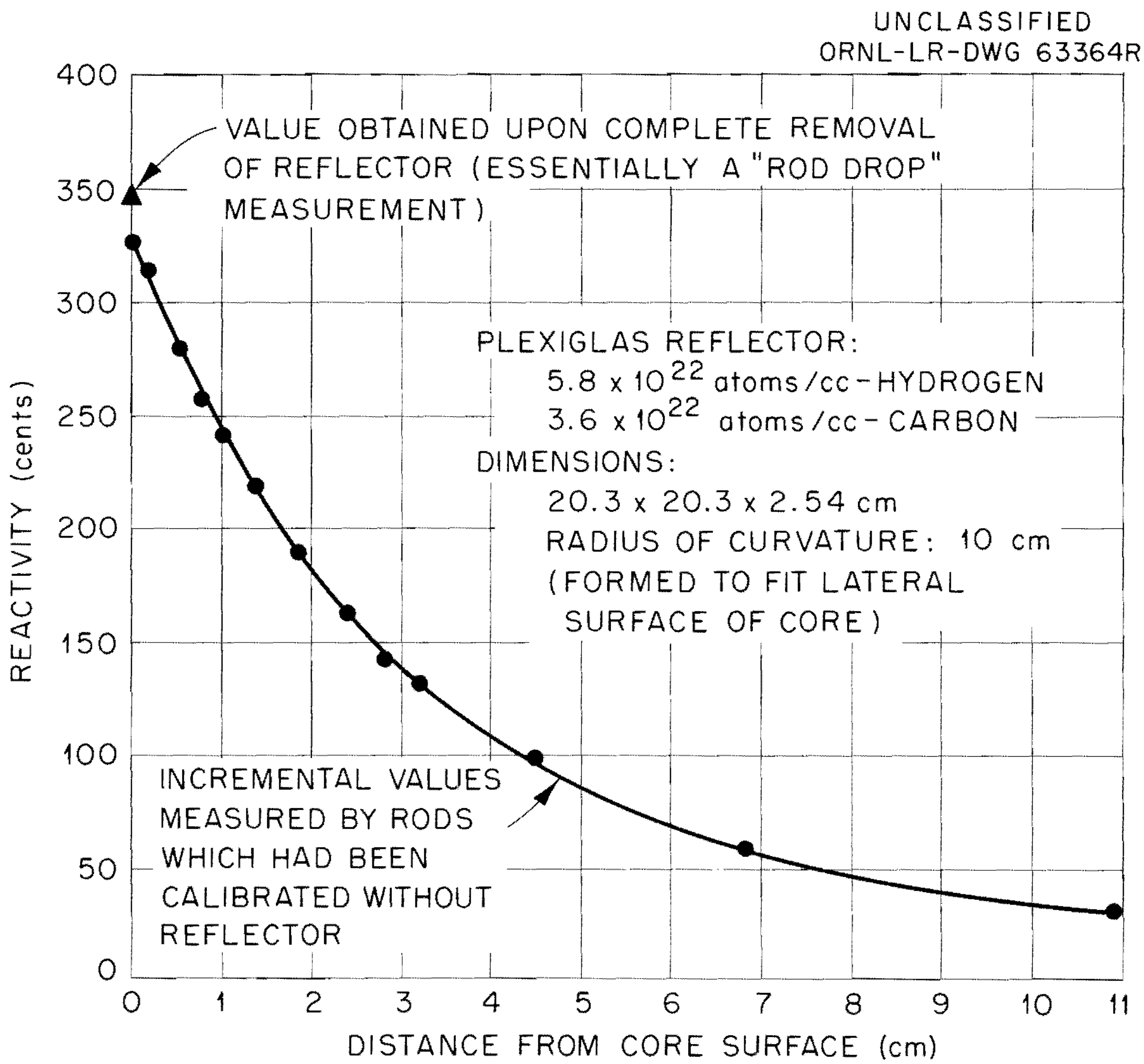

Fig. 6. Reactivity Worth of a Plexiglas Reflector as a Function of Separation Distance from the HPRR

Fission-Rate Distribution

The vertical fission density distribution within the "glory hole" was obtained from the fission-product activity produced in cylindrical uranium-molybdenum pellets, 0.16 cm long and 0.75 cm in diameter. The results are compared in Fig. 7 to a fission distribution calculated by the S_n transport theory code TDC (Ref. 5), using the S_4 approximation. The radial fission density in the safety block was similarly measured, using pellets 0.16 cm thick and 0.62 cm in diameter, and is compared to TDC calculations in Fig. 8. The group structure and cross sections for the calculations are those given in Ref. 3 and a diagram of the geometrical model used in the calculation is shown as Fig. 9. It may be noted that in the geometrical model all voids were treated as a homogeneous reduction in the material density.

Calculated Prompt-Neutron Lifetime

The prompt-neutron lifetime in the HPRR was calculated, using perturbation theory, to be 1.04×10^{-8} sec (Ref. 3).

Acknowledgements

Coworkers in the performance of the experiments are L. W. Gilley and J. J. Lynn. Transport theory calculations were performed by W. E. Kinney of ORNL with the assistance of E. Whitesides of ORGDP. The work of C. Sastre in setting up the analog computer to measure the large reactivities at the ORNL Critical Experiments Facility is acknowledged.

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5. B. Carlson and G. I. Bell, Solution of the Transport Equation by the S_n Method, P/2386, Proc. U.N. Intern. Conf. Peaceful Uses Atomic Energy, 2nd, Geneva, 1958.

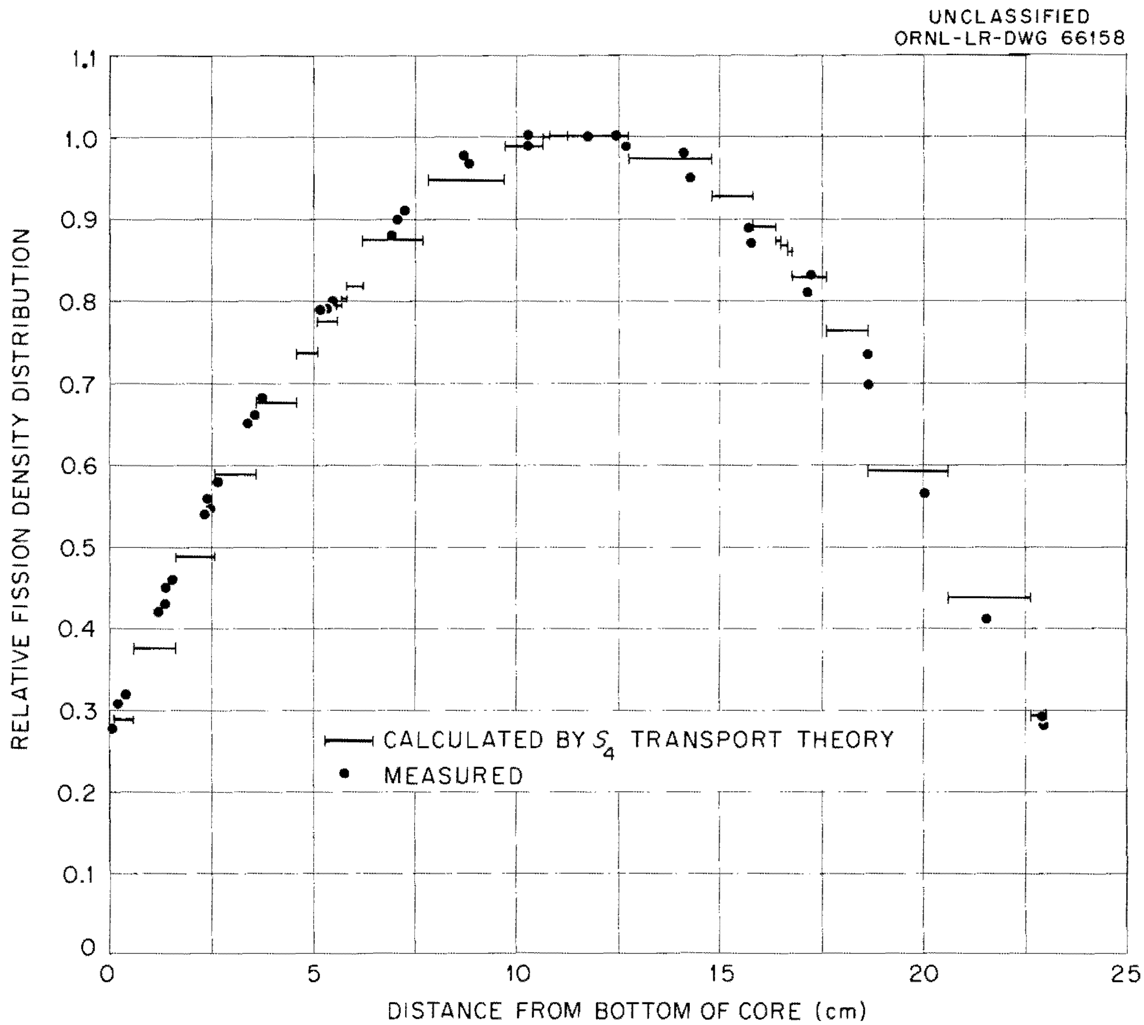

Fig. 7. Vertical Fission Density Distribution in the Irradiation Hole of the HPRR

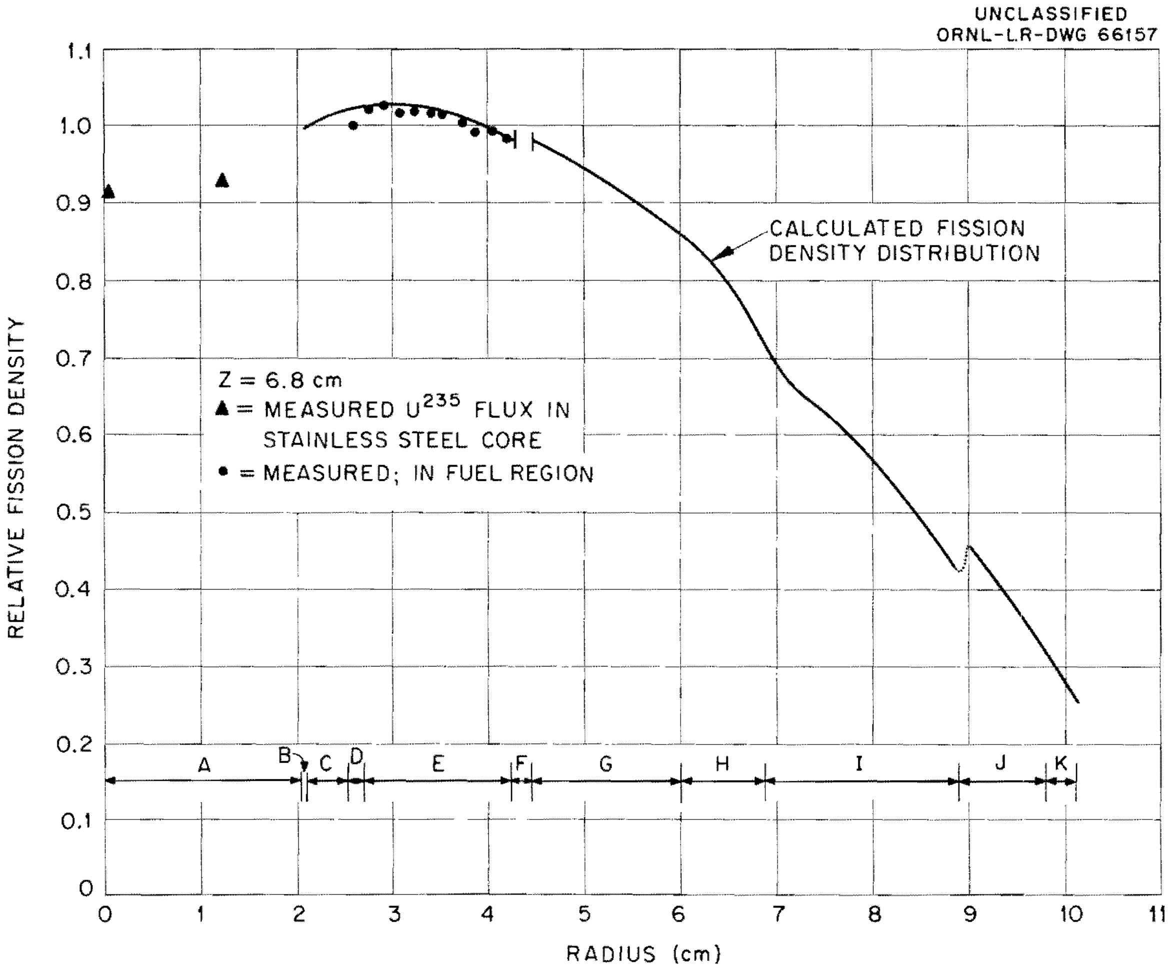

Fig. 8. Radial Fission Density Distribution in a Plane 6.8 cm Above the Bottom of the HPRR

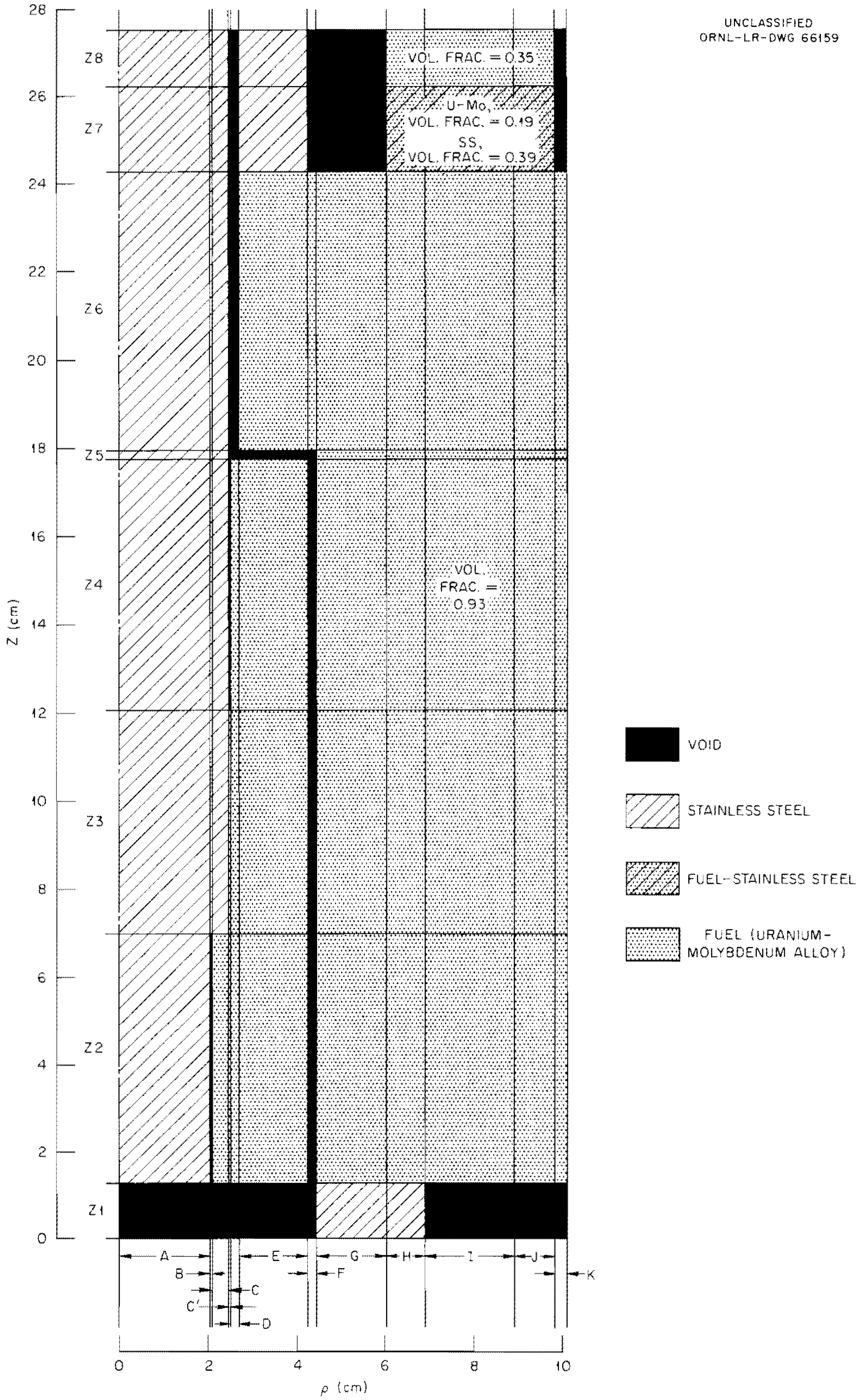

Fig. 9. Geometrical Model Used for HPRR TDC Calculations

Appendix

Some pertinent mechanical properties of the uranium-molybdenum alloy used in the HPRR are shown in Tables A-1 and A-2, and Table B-1 shows the uranium content of the various parts of the reactor. It should be noted that here and in Table 1 of the text the weights are those of the uranium. The U^{235} content would be 93.2% of these numbers.

The data shown as Tables A-1 and A-2 were obtained by W. H. Martin and M. I. Lundin of ORNL.

Table A-1. Some Mechanical Properties of Selected Samples of 10 wt% Molybdenum - 90 wt% Uranium Alloy at Room Temperature (22°C)

Sample Number	Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)	Modulus of Elasticity (psi)
				(x 10^6)
1	130,150	126,800	16.0	12.4
2	133,800	127,300	16.0	12.6
3	135,400	130,850	11.0	12.4
4	134,600	125,300	17.0	13.2
5	135,400	130,850	11.0	12.4
6	134,600	125,300	17.0	13.2
7*	135,350	131,000	7.5	12.9
8*	138,000	134,000	5.5	12.7
9	133,200	126,100	13.0	12.9
10	130,150	126,800	16.0	12.4
11	133,200	128,850	14.5	12.9
12	133,900	127,800	15.5	12.2
13	133,400	125,800	20.0	13.7
14	130,950	126,500	14.5	12.6

*Small tensile bars were made from fragments of larger pulled bars. This probably accounts for the evident higher strength and lesser elongation.

Table A-2. Tensile and Yield Strengths of Selected Samples of 10 wt% Molybdenum - 90 wt% Uranium Alloy at Elevated Temperatures

Sample Number	Temperature (°C)	Tensile Strength (psi)	Yield Strength (psi)
1	24	126,110	125,305
2	24	128,735	128,735
3	24	131,140	131,140
4	94	110,350	110,350
5	94	117,905	117,905
6	205	100,060	100,060
7	205	87,830	87,830
8	205	97,455	97,455
9	316	76,200	73,190
10	316	79,223	76,800
11	316	73,565	72,655
12	316	78,205	76,200
13	316	78,805	78,205
14	316	79,005	77,800
15	316	75,395	73,190
16	316	81,610	81,610
17	316	77,600	76,600
18	316	77,405	77,000
19	316	78,415	77,605
20	427	73,590	68,200
21	427	74,575	66,695
22	427	74,395	71,485
23	538	54,340	54,340
24	538	73,360	69,525

Table B-1. Uranium Inventory in the Oak Ridge Health Physics Research Reactor

Part Description	Mass of Uranium (g)
Safety block	10,109
Regulating rod	658
Burst rod	965
Mass adjustment rod	1,746
Glory hole plug	130
9 bolt inserts	1,079
Nine 1.9-cm bolts	1,025
	1,022
	1,018
	1,016
	1,024
	1,024
	1,025
	1,033
	1,036
Seven lower sections	8,162
	7,971
	8,034
	7,932
	8,009
	7,846
	7,856
Two upper sections	4,247
	4,395
Thick upper section	13,212
Top plate	2,146
	103,720

Internal Distribution

1. J. L. Anderson
2. J. A. Auxier
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5. C. J. Borkowski
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120. C. Sastre; Brookhaven National Laboratory, Upton, Long Island, New York.