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NUCLEAR ANALYSIS OF THE MH-1A REACTOR

E. E. Gross
M. L. Winton

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NUCLEAR ANALYSIS OF THE MH-1A REACTOR

E. E. Gross M. L. Winton

Reactor Division

APRIL 1964

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ABSTRACT

A nuclear analysis of the conceptual design of the MH-1A nuclear reactor was made using machine codes and methods previously shown to give good agreement with experimental measurements for a similar core. The cold clean reactivity worth of all 12 control rods and the most important control rod was calculated to be $\Delta k = 0.20$ and $\Delta k = 0.035$ respectively. This indicates that the reactor can be adequately shut down with one rod stuck in the fully-withdrawn position. A radial peak-to-average power ratio of 1.63 was calculated for the case with followers in the core. The reactivity lifetime of the core was calculated to be 11 months for the initial core. Additional calculations showed that the first fuel "shuffling" gave a core with the same lifetime.

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NUCLEAR ANALYSIS OF THE MH-1A REACTOR

E. E. Gross M. L. Winton

1. INTRODUCTION

The MH-1A[1] is a barge-mounted pressurized-water nuclear power plant which has an output of 45 Mwt and 10 Mwe. It is designed to serve the United States Army as a mobile source of power at any site accessible by waterways. It is expected that construction of the MH-1A will be completed early in 1965.

The U.S. Army Corps of Engineers has engaged the Oak Ridge National Laboratory to review the reactor core analysis, as well as certain other aspects of the design. This report covers the nuclear analysis of the conceptual design core performed by ORNL.

2. DESCRIPTION OF THE CORE

The core is a heterogeneous low enrichment, light water moderated and cooled, two zone core. It is designed for partial fuel replacement and shuffling after a one-year life at full power. A quadrant of the geometrical model of the core on which this analysis is based is shown in Fig. 1 and the geometrical model of a fuel element is shown in Fig. 2. The core has not yet been completely designed.

The core is similar to the N.S. SAVANNAH[2] core I but smaller, and it does not have fuel-element containers. It is controlled by 12 cruciform, boron stainless steel control rods which contain 2 wt % boron enriched to 93 wt % B-10. A follower is attached to the bottom of each control rod, and the four innermost followers have 0.07 wt % natural boron in the stainless steel. The core has an equivalent diameter of 45.2 in. and an active length of 36 in. There are 32 fuel elements with 104 fuel pins per element. The fuel is in the form of UO_2 pellets with a 0.4565 in. diameter. The pin cladding is 0.507 in. O.D. x 0.023 in. wall tubing of type 304 stainless steel containing 600 ppm natural boron. The inner and outer fuel zones have U-235 enrichments of 5.0 wt % and 5.4 wt % respectively. Core volume fractions are given in Appendix A.

Regions

1. Homogenized fuel, inner zone
2. Homogenized fuel, inner zone
3. Homogenized fuel, inner zone
4. Homogenized fuel, outer zone
5. Homogenized fuel, outer zone
6. Follower of control rod
7. Water around follower or rod
8. Follower or control rod
9. Water around follower or rod
10. Shroud support
11. Shroud support water
12. Locking shaft
13. Locking shaft
14. Locking shaft
15. Source
16. Shroud
17. Reflector water
18. First thermal shield
19. Second thermal shield
20. Steel-water mixture

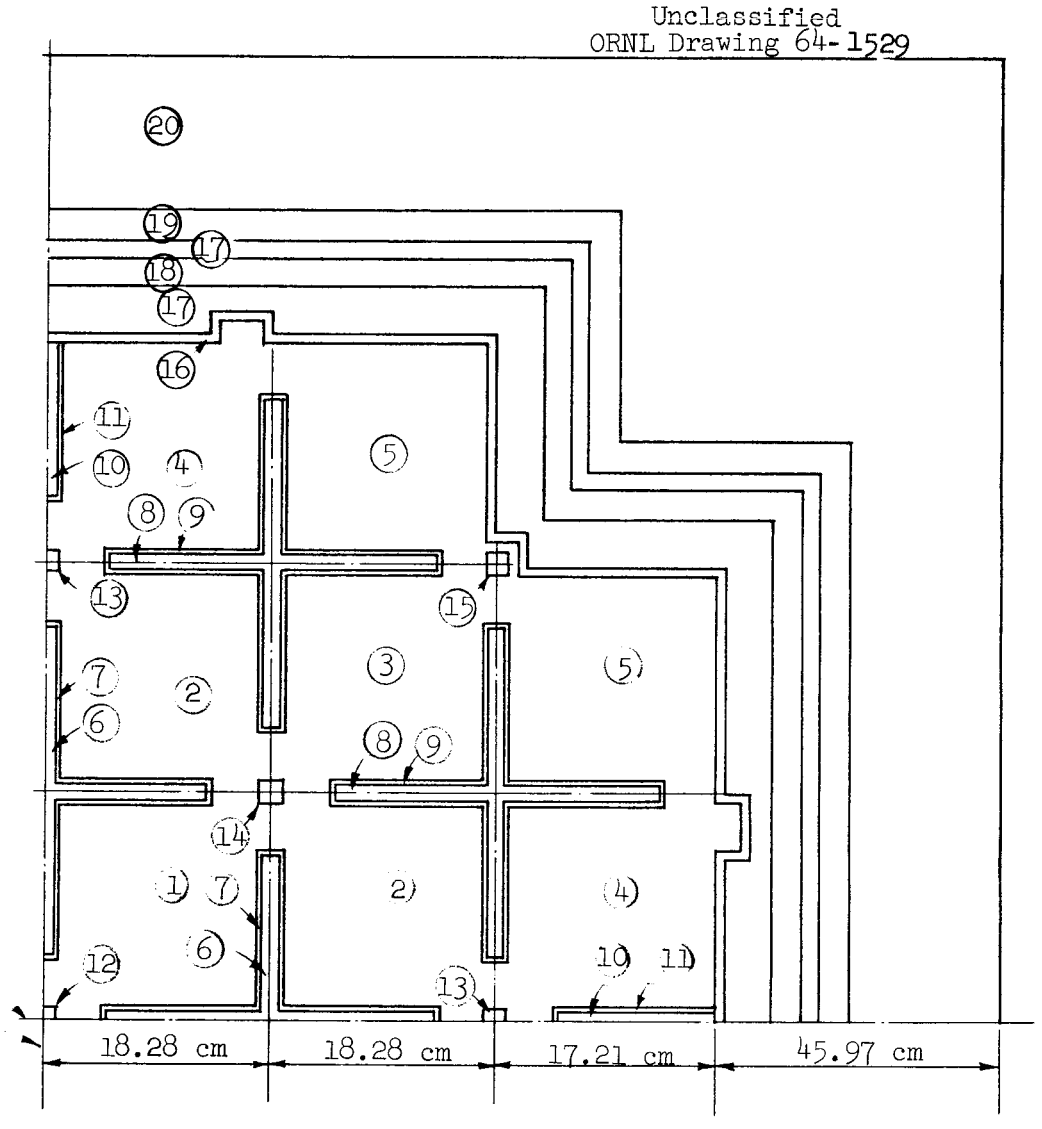

Fig. 1. Geometrical Model of One Quadrant of MH-1A Core.

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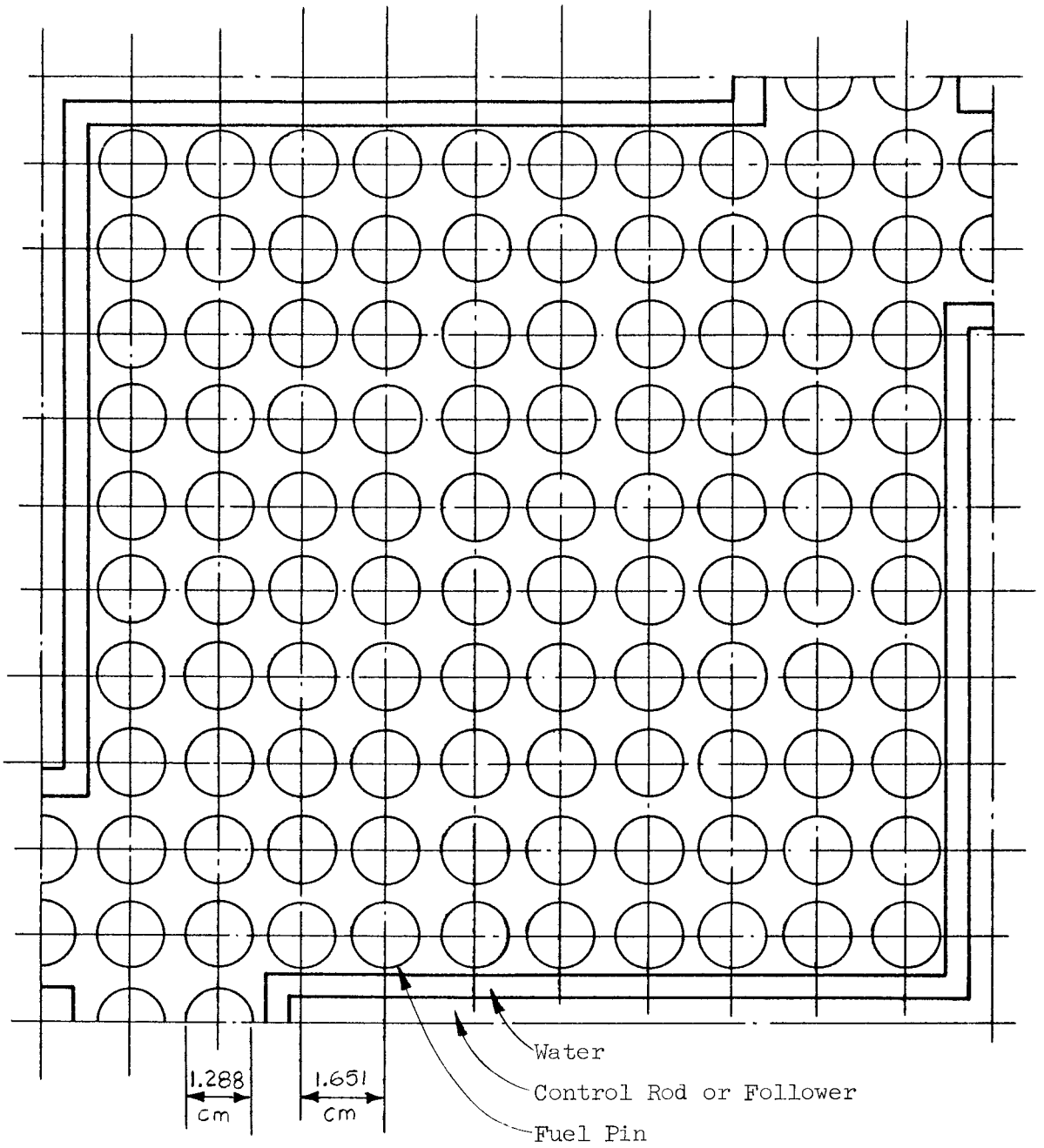


Fig. 2. Geometrical Model of the MH-1A Fuel Element.

3. ANALYTICAL MODEL

Thermal Cross-Sections

The analytical model used in this study differs from that used in the nuclear analysis of the N.S. SAVANNAH reactor[2] only in the treatment of the thermal flux. Since the MH-1A has a higher enrichment of the fuel and a burnable poison in the cladding, the treatment of the thermal flux followed that of reference 3. It is evident from Figs. 1 and 2 that the most of the core is composed of fuel-pin cells which may reasonably be approximated by the cylindrical geometry of Fig. 3. With trial thermal cross sections and a source for thermal neutrons in the water region only, transport theory flux distributions were determined throughout the geometry of Fig. 3 with the use of the SNG Code.[4,5] From these results flux- and volume-averaged atom densities for the individual isotopes of the materials indicated in Fig. 3 were obtained and used as input to a Wigner-Wilkins slowing down calculation using the SOFOCATE Code.[6] SOFOCATE provides energy-averaged microscopic thermal cross sections which were used in a further SNG calculation of pin-cell fluxes. The coupling of SNG and SOFOCATE has been automated,[7] and the calculation stops when the average absorption cross section for the pin-cell region computed from SNG and SOFOCATE agree to within the desired convergence criterion.

When the BAM[7] calculation converged the last SOFOCATE step was re-run with the high energy cutoff raised to six times the energy at which the flux was a maximum. The factor is somewhat arbitrary, but the thermal cutoff for a core at room temperature used in reference 2 was 0.15 ev which is six times 0.025 ev. Taking the thermal group cut-off at six times the energy at which the flux is maximum is an attempt to use approximately the same shape for the thermal flux energy distribution in this calculation as was used to obtain thermal cross sections in reference 2.

Cross sections used in these calculations were related to the cross sections of reference 2 by the following method. Thermal cross sections for the N.S. SAVANNAH Core I at 68° and 508°F were calculated using BAM as described above. The ratio of the cross sections of reference 2 to the BAM calculated cross sections were then multiplied by the BAM

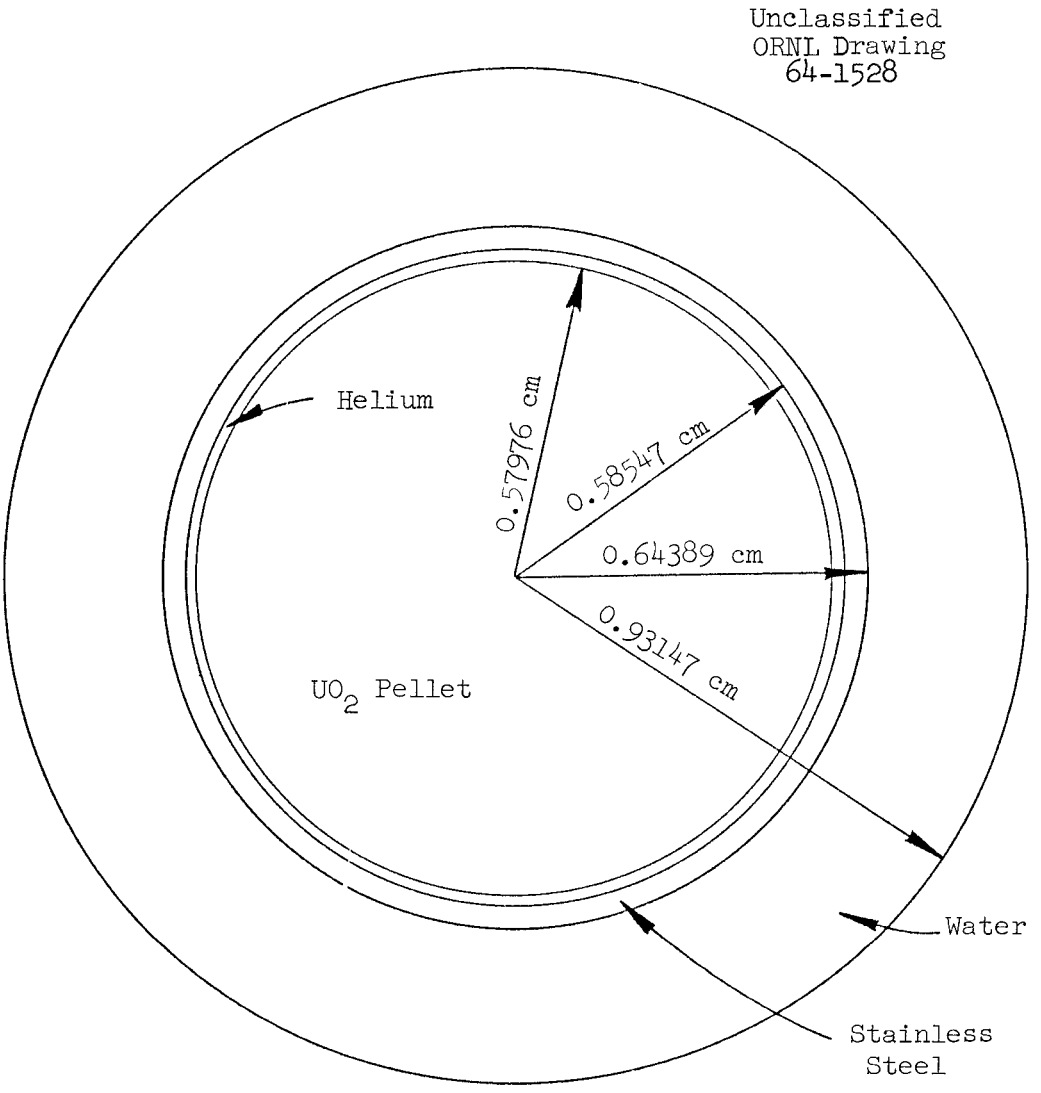


Fig. 3. Geometrical Model of the MH-1A Fuel-Pin Cell.

calculated MH-1A cross sections to obtain the values which were used. The resulting cross sections are thus normalized to those of reference 2 and are given in Tables B1-B4 in Appendix B.

Four-Group Cross-Sections

The geometrical model used here was much the same as used in reference 2. The SNG code was used to calculate four group average cross sections using the geometry of Fig. 3. This gave the fuel cross sections to be used in a slab fuel element cell with a control rod and also in the full core. The S-5 approximation of the S_n method was used to determine the constant C_g, the current per unit flux. Cross sections are given in Appendix B, Tables B5, B6, B7 and B8. Current per unit flux values are shown in Table B9 in Appendix B.

Full Core Model

With these calculated cross sections and control rod boundary conditions the full size core was represented by the geometry of Fig. 1. When control rods were present in regions 6 and 8, current-per-unit-of-flux boundary conditions were used on the control rod surface. Cross sections for the outer zone homogenized 5.4 wt %-enriched fuel and the boron stainless steel followers of the inner four control rods are given in Tables B10 and B11 of Appendix B.

The axial leakage of neutrons was initially accounted for by assuming that the axial reflector savings of the MH-1A was the same as in the SAVANNAH core I. The results of x-y geometry calculations with the assumed axial buckling allowed the core to be homogenized and treated in two dimensional r-z geometry which accounted for the leakage from all sides of the core.

4. RESULTS OF FULL CORE CALCULATIONS

The two dimensional full core calculations using the PDQ Code[8] gave the multiplication factors and the control rod worth of the MH-1A. With all control rods inserted, the reactor is safely shut down with a margin of about 10% Δk at 68°F.

Calculations were also made to determine the worth of one rod. The calculations showed that the worth of the rods depends on the rod pattern. For example if the eight outer rods are inserted the multiplication falls from 1.108 to 1.046 when the reactor is at 68°F. These eight rods are evidently worth 0.062 Δk, and the four inner rods must be worth 0.140 Δk. However, if the four inner rods are inserted first, their worth appears to be 0.076 Δk, and the eight outer rods must then be worth 0.126 Δk. Taking the maximum worth of the four inner rods to be 0.140 Δk, and assuming that they are of equal worth gives 0.035 Δk for the maximum worth of one rod at 68°F. The insertion of two of the central control rods as shown in Fig. 4 makes the reactor subcritical at 490°F. The calculated static multiplication factors and rod worths for clean cores are given in the following tabulation.

Rod Pattern	Multiplication Factor, k		Rod Worth, Δk	
	68°F	490°F	68°F	490°F
No rods in	1.108	1.040		
All rods in	0.906	0.816		
Worth of all rods			0.202	0.224
8 outer rods in	1.046			
Worth of 8 outer rods			0.062	
Worth of 4 inner rods			0.140	
4 inner rods in	1.032			
Worth of 4 inner rods			0.076	
Worth of 8 outer rods			0.126	
2 opposite central rods in	1.047	0.980		
Worth of 1 rod, maximum			0.035	

The horizontal power distribution shown in Fig. 5 represents the calculated local-to-average power ratio along the centerline of a row of pins nearest the followers. The ratio of peak-to-average power is 1.63, which is less than that calculated for the N.S. SAVANNAH Core I. This is due to the presence of B-10 in the MH-1A control-rod followers.

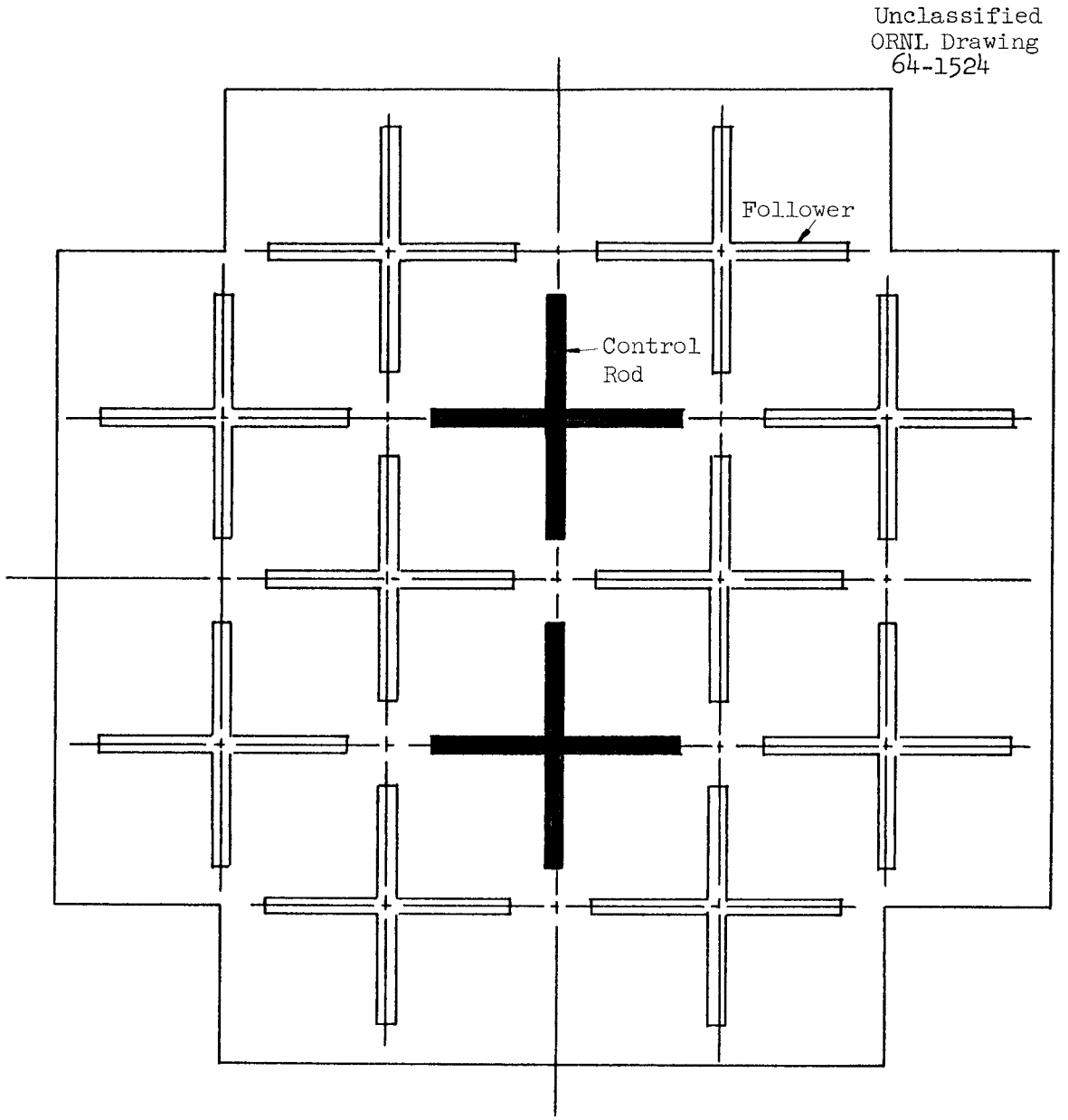


Fig. 4. Geometrical Model of the Full Core of the MH-1A with Two of the Central Control Rods Inserted.

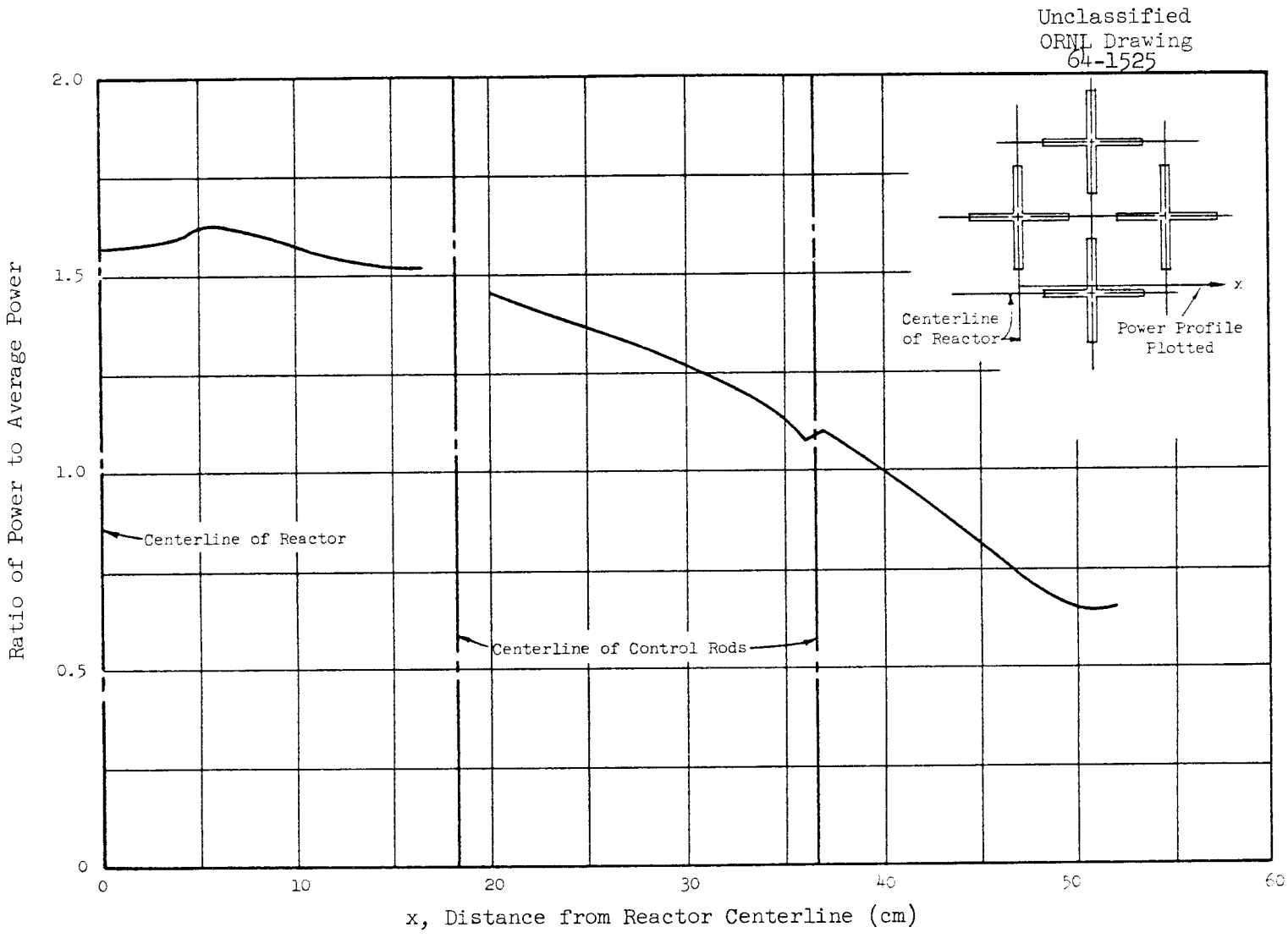
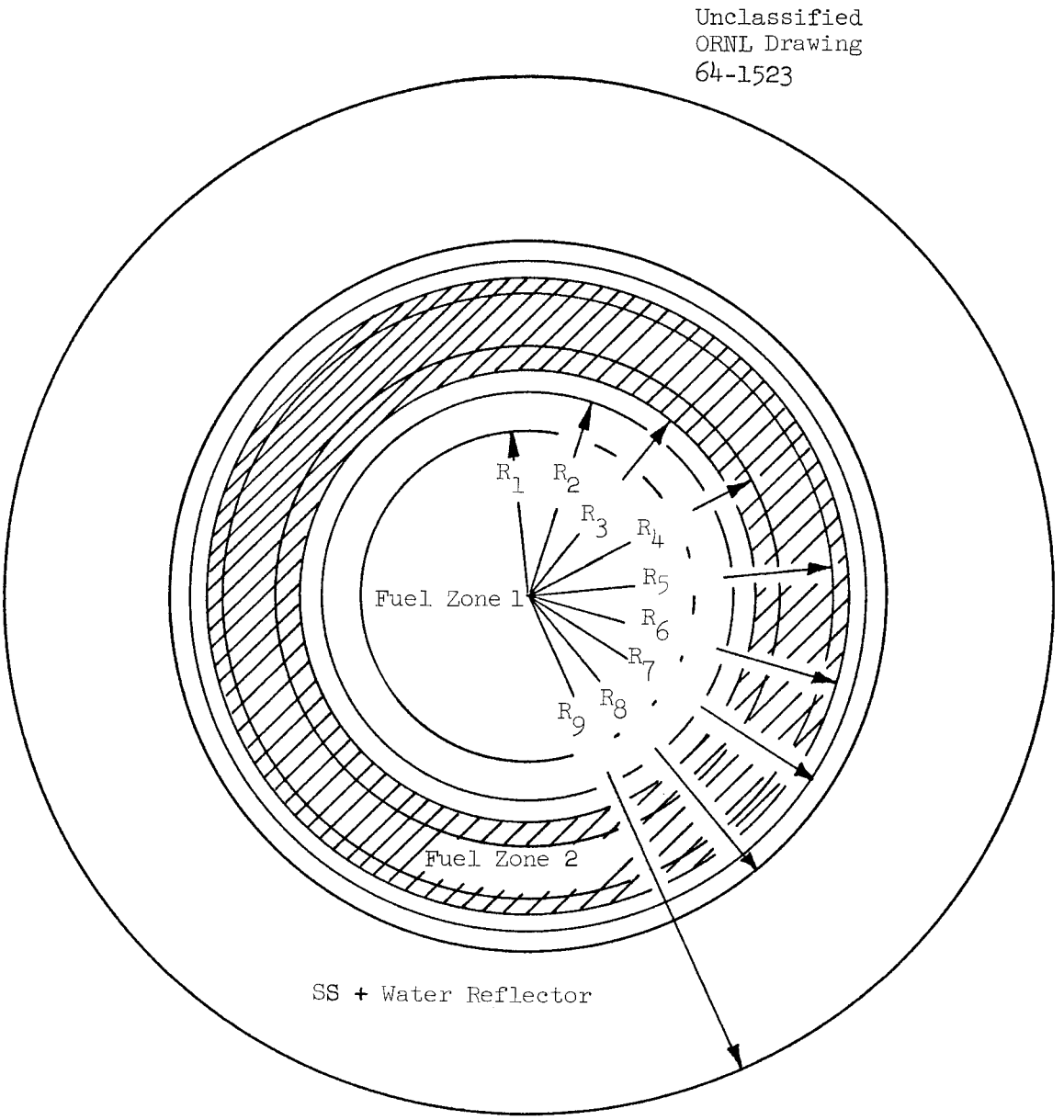


Fig. 5. Power Along a Row of Pins Nearest a Centerline of the MH-1A Core at 490°F.

5. LIFETIME CALCULATIONS

One dimensional burnup calculations were made using the CANDLE code[9] in the geometry of Fig. 6. The calculations are similar to those made for the N.S. SAVANNAH reactor.[10] Homogenized four group cross sections representing the core regions at the beginning of life were obtained from the full core, two dimensional calculations (in the geometry of Fig. 1 with followers present) and are given in Table B12 of Appendix B. Element E is a composite of those elements which do not burn up; two cross sections for element E are given, one for the inner zone and one for the outer zone. Also two different cross sections are given for boron since the boron in the fuel cladding is not exposed to the same flux as the boron in the followers. Plutonium and fission products were assumed to be exposed to the same flux levels as seen by the UO_2. The calculated reactivity lifetime is about 11 full power months, see Fig. 7. With no boron in the followers the reactivity lifetime is a month longer. The boron inventory in the core throughout core life is shown in Fig. 8. About one half of the boron in the fuel cladding remains at the end of core life.

Further calculations showed that if at the end of 11 months of full power operation the fuel of the inner zone (including fission products) is replaced by the burned fuel of the outer zone (including fission products), and fresh fuel of enrichment 5.4 wt % U-235 is placed in the outer zone, the additional reactivity lifetime is about 11 months.



R_1 = 30.000 cm	R_4 = 45.508 cm	R_7 = 61.492 cm
R_2 = 37.000 cm	R_5 = 55.284 cm	R_8 = 65.492 cm
R_3 = 41.254 cm	R_6 = 57.492 cm	R_9 = 95.492 cm

Fig. 6. Geometrical Model for Radial Burnup of the MH-1A Core.

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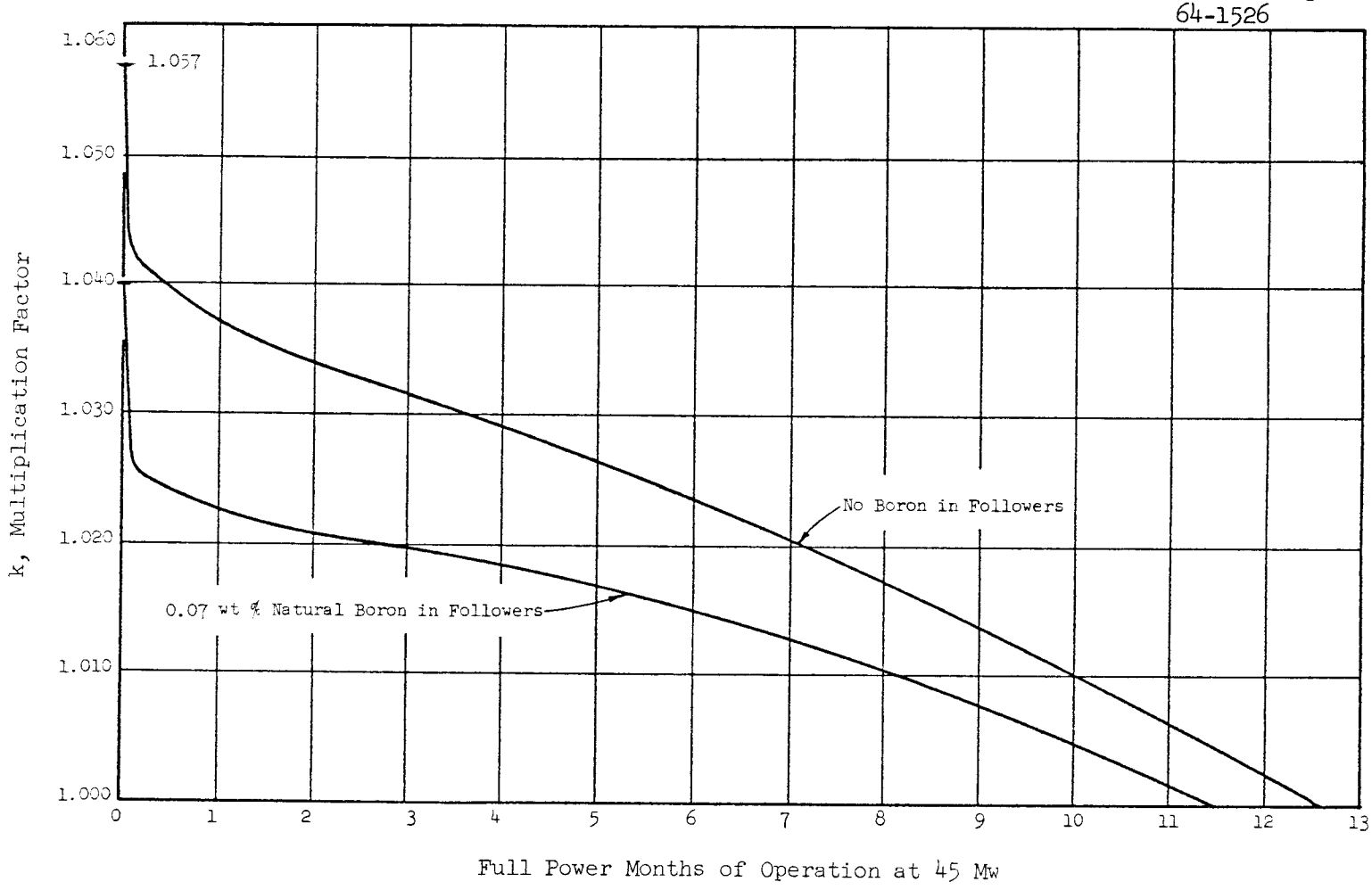

Fig. 7. Effect of Boron in the Four Inner Followers on Reactivity Lifetimes of the MH-1A Core.

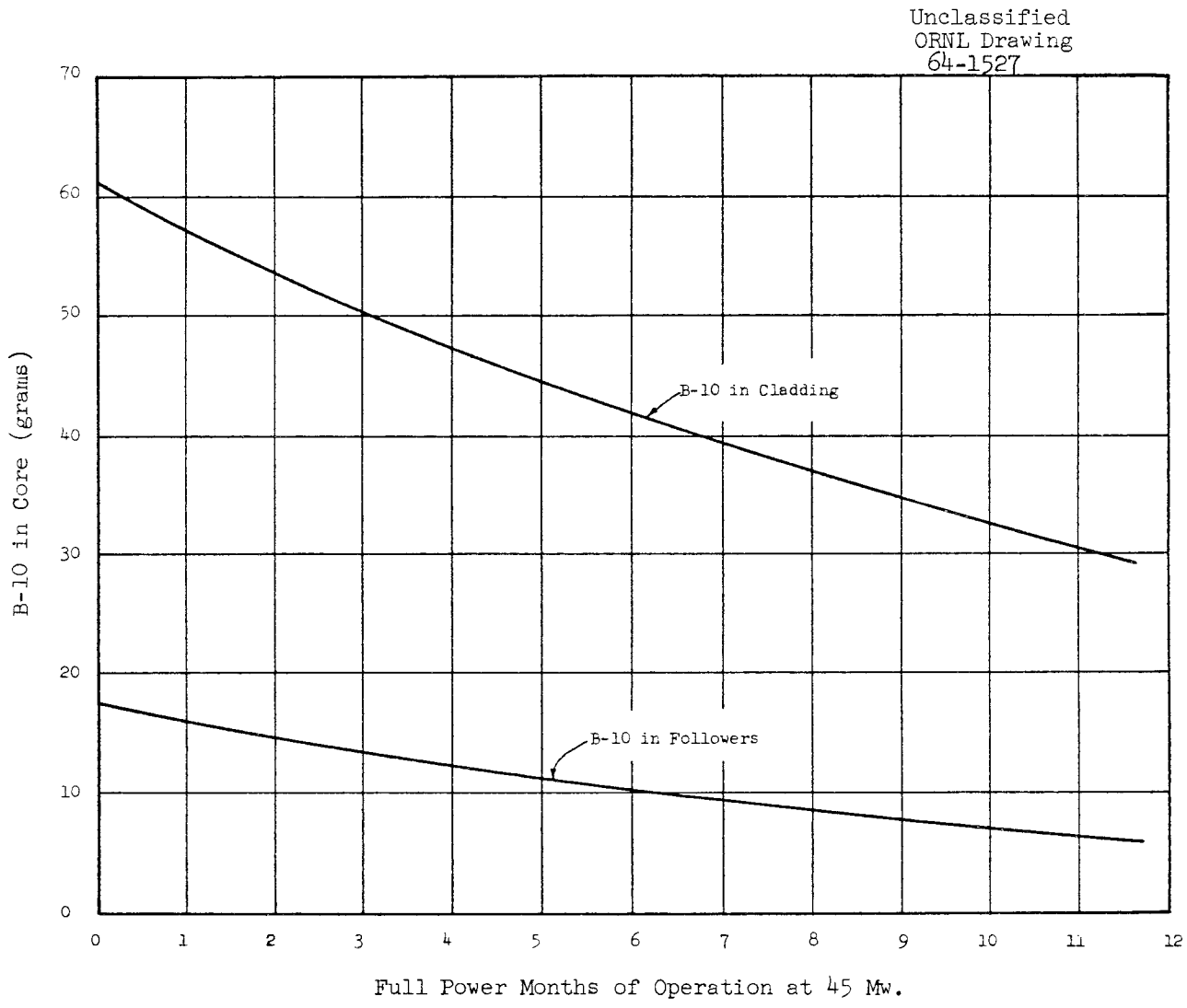

Fig. 8. Calculated Core Inventory of Born 10 in the MH-1A Core.

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APPENDICES

APPENDIX A – CORE VOLUME FRACTIONS

Water	0.522
UO_2	0.337
Fuel Cladding & Locking Rods	0.074
Control Rods	0.060
Helium Gap	0.007
	1.000

APPENDIX B – CALCULATED NUCLEAR DATA

Table B1. Hardened Thermal-Group Cross Sections at 68°F

Material	Microscopic Cross Section (barns)		
	σ_a	$\nu\sigma_f$	$\sigma_s(1 - \bar{\mu}_o)$
U^{235}	519.97	1076.45	14.96
U^{238}	2.152	0	8.28
Stainless steel	2.36	0	9.65
Hydrogen	0.258	0	30.03
Oxygen	0	0	4.025
B-10	3009.	0	3.76

Table B2. Well Moderated Thermal-Group Cross Sections at 68°F

Material	Microscopic Cross Section (barns)	
	σ_a	$\sigma_s(1 - \bar{\mu}_o)$
Hydrogen	0.293	32.93
Oxygen	0	4.025
Stainless steel	2.68	9.65

Table B3. Hardened Thermal-Group Cross Sections at 490°F

Material	Microscopic Cross Section (barns)		
	σ_a	$\nu\sigma_f$	$\sigma_s(1 - \bar{\mu}_o)$
U^{235}	383.19	789.30	14.96
U^{238}	1.608	0	8.28
Stainless steel	1.743	0	9.65
Hydrogen	0.193	0	21.03
Oxygen	0	0	4.025
B-10	2248.	0	3.76

Table B4. Well Moderated Thermal-Group Cross Sections at 490°F

Material	Microscopic Cross Section (barns)	
	σ_a	$\sigma_s(1 - \bar{\mu}_o)$
Hydrogen	0.213	24.26
Oxygen	0	4.025
Stainless steel	1.926	9.65

B5. Four Group Macroscopic Cross Sections for Pin Cell Materials at 68°F

		Macroscopic Cross Sections (cm^{-1})			
		5.0 wt % Enriched UO_2	5.4 wt % Enriched UO_2	Boron Stainless Steel	H_2O
Group 1	$\nu\Sigma_{f1}$	0.01539	0.01571	0	0
	Σ_{a1}	0.01082	0.01096	0.00588	0.00028
	Σ_{tr1}	0.22248	0.22248	0.25706	0.16170
	Σ_{12}	0.00146	0.00146	0.00010	0.07602
	Σ_{13}	0	0	0	0.00013
	Σ_{14}	0	0	0	0
Group 2	$\nu\Sigma_{f2}$	0.05057	0.05461	0	0
	Σ_{a2}	0.06616	0.07229	0.01624	0
	Σ_{tr2}	0.38109	0.38109	0.70658	0.56605
	Σ_{23}	0.00010	0.00010	0	0.18683
	Σ_{24}	0	0	0	0.00190
Group 3	$\nu\Sigma_{f3}$	0.18180	0.19634	0	0
	Σ_{a3}	0.13313	0.14435	0.05780	0.00211
	Σ_{tr3}	0.37127	0.37127	0.96006	0.58842
	Σ_{34}	0	0	0	0.26968
Group 4	$\nu\Sigma_{f4}$	1.25360	1.35385	0	0
	Σ_{a4}	0.65258	0.70076	0.36709	0.01722
	Σ_{tr_4}	0.38355	0.38394	0.83989	2.04209

Table B6. Four Group Macroscopic Cross Sections for Pin-Cell Materials at 490°F

		Macroscopic Cross Sections (cm^{-1})			
		5.0 wt %-Enriched UO_2	5.4 wt %-Enriched UO_2	Boron Stainless Steel	H_2O
Group 1	$\nu\Sigma_{f1}$	0.01508	0.01541	0	0
	Σ_{a1}	0.01067	0.01082	0.00581	0.00021
	Σ_{tr1}	0.22258	0.22258	0.25408	0.12986
	Σ_{12}	0.00147	0.00146	0.00010	0.06091
	Σ_{13}	0	0	0	0.00010
	Σ_{14}	0	0	0	0
Group 2	$\nu\Sigma_{f2}$	0.04943	0.05338	0	0
	Σ_{a2}	0.06842	0.07081	0.01615	0
	Σ_{tr2}	0.37890	0.37890	0.69477	0.44979
	Σ_{23}	0.00010	0.00010	0	0.14379
	Σ_{24}	0	0	0	0.00146
Group 3	$\nu\Sigma_{f3}$	0.17779	0.19200	0	0
	Σ_{a3}	0.13408	0.14204	0.05642	0.00164
	Σ_{tr3}	0.36894	0.36894	0.94844	0.46723
	Σ_{34}	0	0	0	0.20892
Group 4	$\nu\Sigma_{f4}$	0.91338	0.98639	0	0
	Σ_{a4}	0.47835	0.51362	0.26906	0.01022
	Σ_{tr4}	0.38112	0.38150	0.82954	1.22164

Table B7. Four Group Macroscopic Cross Sections for Homogenized 5.0 wt % Fuel, Stainless Steel and 2.0 wt % Boron (93 wt % B-10) Stainless Steel at 68°F

		Macroscopic Cross Section (cm^{-1})		
		Homogenized Fuel	Stainless Steel	Boron Steel
Group 1	$\nu\Sigma_{f1}$	0.00700	0	0
	Σ_{a1}	0.00553	0.00579	0.02006
	Σ_{tr1}	0.19598	0.25601	0.28520
	Σ_{12}	0.03521	0.00010	0.00010
	Σ_{13}	0.00006	0	0
	Σ_{14}	0	0	0
Group 2	$\nu\Sigma_{f2}$	0.01876	0	0
	Σ_{a2}	0.02726	0.01390	0.40010
	Σ_{tr2}	0.50475	0.70554	0.72447
	Σ_{23}	0.10066	0	0
	Σ_{24}	0.00102	0	0
Group 3	$\nu\Sigma_{f3}$	0.06426	0	0
	Σ_{a3}	0.05408	0.02951	4.69539
	Σ_{tr3}	0.53779	0.95907	0.97068
	Σ_{34}	0.15019	0	0
Group 4	$\nu\Sigma_{f4}$	0.36417	0	0
	Σ_{a4}	0.22930	0.20526	26.89090
	Σ_{tr4}	1.45111	0.83889	0.85543

Table B8. Four-Group Macroscopic Cross Sections for Homogenized 5.0 wt % Enriched Fuel, Stainless Steel and 2.0 wt % Boron (93 wt % B-10) Stainless Steel at 490°F

		Macroscopic Cross Section (cm^{-1})		
		Homogenized Fuel	Stainless Steel	Boron Steel
Group 1	$\nu\Sigma_{f1}$	0.00684	0	0
	Σ_{a1}	0.00542	0.00573	0.01990
	Σ_{tr1}	0.18116	0.25304	0.28188
	Σ_{12}	0.02845	0.00009	0.00009
	Σ_{13}	0.00005	0	0
	Σ_{14}	0	0	0
Group 2	$\nu\Sigma_{f2}$	0.01820	0	0
	Σ_{a2}	0.02654	0.01388	0.38829
	Σ_{tr2}	0.44054	0.69374	0.71249
	Σ_{23}	0.07788	0	0
	Σ_{24}	0.00079	0	0
Group 3	$\nu\Sigma_{f3}$	0.06197	0	0
	Σ_{a3}	0.05228	0.02880	4.58376
	Σ_{tr3}	0.46899	0.94746	0.95892
	Σ_{34}	0.11740	0	0
Group 4	$\nu\Sigma_{f4}$	0.27397	0	0
	Σ_{a4}	0.17136	0.14968	19.83749
	Σ_{tr4}	0.92934	0.82856	0.81817

Table B9. Current per Unit Flux Values at a Control Rod Surface at 68° and 490°F

Group	Energy Internal (ev)	J/Ø at Rod Surface	
		68°	490°
1	$9.1 \times 10^3 < E < 10^7$	0.0070	0.0071
2	$15.7 < E < 9.1 \times 10^3$	0.1068	0.1037
3	$0.15 < E < 15.7$	0.3732	0.3663
4	$0 < E < 0.15$	0.4305	0.4202

Table B10. Four Group Macroscopic Cross Sections for Homogenized 5.4 wt %-Enriched Fuel and 0.07 wt % Natural Boron Stainless Steel at 68°F

		Macroscopic Cross Section (cm^{-1})	
		5.4 wt % Homogenized Fuel	0.07 wt % Boron SS
Group 1	$\nu\Sigma_{f1}$	0.00715	0
	Σ_{a1}	0.00560	0.00587
	Σ_{tr1}	0.19597	0.25635
	Σ_{12}	0.03521	0.00010
	Σ_{13}	0.00006	0
	Σ_{14}	0	0
Group 2	$\nu\Sigma_{f2}$	0.02023	0
	Σ_{a2}	0.02812	0.01657
	Σ_{tr2}	0.50487	0.70431
	Σ_{23}	0.10077	0
	Σ_{24}	0.00102	0
Group 3	$\nu\Sigma_{f3}$	0.06905	0
	Σ_{a3}	0.05669	0.06229
	Σ_{tr3}	0.53817	0.95690
	Σ_{34}	0.15067	0
Group 4	$\nu\Sigma_{f4}$	0.38598	0
	Σ_{a4}	0.23959	0.39334
	Σ_{tr4}	1.46027	0.83988

Table B11. Four Group Macroscopic Cross Sections for Homogenized 5.4 wt %-Enriched Fuel and a 07 wt % Natural Boron Stainless Steel at 490°F

		Macroscopic Cross Section (cm^{-1})	
		5.4 wt % Homogenized Fuel	0.07 wt % Boron SS
Group 1	$\nu\Sigma_{f1}$	0.00698	0
	Σ_{a1}	0.00548	0.00588
	Σ_{tr1}	0.18116	0.25652
	Σ_{12}	0.02844	0.00009
	Σ_{13}	0.00005	0
	Σ_{14}	0	0
Group 2	$\nu\Sigma_{f2}$	0.01962	0
	Σ_{a2}	0.02737	0.01664
	Σ_{tr2}	0.44059	0.70115
	Σ_{23}	0.07798	0
	Σ_{24}	0.00079	0
Group 3	$\nu\Sigma_{f3}$	0.06654	0
	Σ_{a3}	0.05482	0.06115
	Σ_{tr3}	0.46918	0.95709
	Σ_{34}	0.11781	0
Group 4	$\nu\Sigma_{f4}$	0.29108	0
	Σ_{a4}	0.17949	0.28777
	Σ_{tr4}	0.93358	0.82856

Table B12. Flux Averaged Microscopic Cross Sections for Inner and Outer Zones of MH-1A at 490°F

Cross Section Calculated	Microscopic Cross Sections (barns)					
	U-235	U-238	B-10		E	
			Pin Cladding	Followers	Inner Zone	Outer Zone
σ_{tr1}	9.224	5.940	0	0	0.1331	0.1331
σ_{a1}	2.278	0.425	1.617	1.639	0.0010	0.0010
σ_{12}	0	0.0778	0	0	0.0284	0.0281
$\nu\sigma_{f1}$	4.660	0.551	0	0	0	0
σ_{tr2}	13.30	8.942	0	0	0.3869	0.3859
σ_{a2}	25.69	1.550	41.93	45.42	0.0020	0.0019
σ_{23}	0	0.0042	0	0	0.0782	0.0777
$\nu\sigma_{f2}$	39.57	0	0	0	0	0
σ_{tr3}	22.30	8.051	0	0	0.4282	0.4278
σ_{a3}	76.76	1.313	504.6	549.9	0.0052	0.0050
σ_{34}	0	0	0	0	0.1161	0.1157
$\nu\sigma_{f3}$	134.5	0	0	0	0	0
σ_{tr4}	69.01	6.480	0	0	0.9000	0.9022
σ_{a4}	288.7	1.212	2131.	2156.	0.0278	0.0279
$\nu\sigma_{f4}$	594.6	0	0	0	0	0

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