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POWER DISTRIBUTION AND REACTIVITY CALCULATIONS
FOR THE MH-1A REACTOR

G.E. Edison and M.L. Winton

RELEASED FOR ANNOUNCEMENT
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POWER DISTRIBUTION AND REACTIVITY CALCULATIONS FOR THE MH-1A REACTOR

G. E. Edison and M. L. Winton

ABSTRACT

The power distribution and initial reactivity were calculated for the MH-1A reactor reference design and for several design variations. For the reference design, the power peaking and reactivity results were in good agreement with values previously calculated by the Martin Company and with the experimentally determined initial reactivity.

Removal of boron from the control rod followers increased the power peaking by about 30%. Replacement of the twelve stainless steel dummy rods with 0.9 w/o boron-stainless steel shim rods did not change the power peaking appreciably. The dummy rods had only a localized effect on the power distribution.

Estimated power margin values for the MH-1A in the steady-state operating condition were acceptable for all the design variations studied. However, removal of boron from the followers brought the power margin for transient operation close to the specified limit of 1.2.

INTRODUCTION

The MH-1A^{1,2} is a mobile 10 Mw(e) nuclear power plant mounted in a barge and is designed to provide the United States Army with a power source at any site accessible by waterways. The reactor has a design power of 45 Mw(t), utilizes low enriched UO₂ fuel, and is cooled and moderated with pressurized water at 490°F. The power plant is being designed and constructed by the Martin Company under contract to the U.S. Army. It will be initially operated at Fort Belvoir, Virginia and is expected to first achieve criticality during the latter part of 1966.

The two-zone reactor core has 16 fuel elements in each zone with an initial ²³⁵U enrichment of 4.07 w/o in the inner zone and 4.65 w/o in the outer zone. Each fuel element consists of a lattice of 104 stainless steel clad fuel pins of 0.507-in. OD on a 0.654-in. square pitch. The core data are summarized in Appendix A.

The design lifetime of the MH-1A core is one full-power year. At the end of core life, the 12 control rods will be replaced with new ones. Also, the 16 inner fuel elements will be replaced with the 16 outer elements, and 16 fresh fuel elements with 4.65 w/o ^{235}U will be placed in the outer zone. The out-in fuel reshuffling is expected to improve the power distribution and increase the fuel burnup. Additional power flattening will result from the burnable poison in the followers of the control rods.

Oak Ridge National Laboratory has provided technical assistance to the U.S. Army Corps of Engineers on several aspects of the MH-1A project. Recently, the laboratory was requested by U.S. Army representatives (Nuclear Power Field Office, Fort Belvoir) to investigate two potential problem areas. First, because a high degree of power peaking exists in the initial core and no experimental power mapping was planned, a detailed calculation of power distribution was desired. Second, as part of an effort to extend control rod life, the Army was interested in the effect of burnable poison depletion on power peaking.

A program of nuclear calculations to investigate power peaking and associated reactivity effects was initiated and carried out at ORNL. Power distribution and initial reactivity calculations were made for the cold clean reference design core and for the reactor at operating conditions with all control rods inserted 14.9 inches. An indirect verification of the calculational model was obtained by comparing the ORNL results with those of the Martin Company.¹ Additional calculations were then made for: (a) a case in which all boron had been removed from the control rod followers, and (b) a case with no boron in the followers and the 12 stainless steel dummy rods replaced with 12 boron-stainless steel shim rods.

ANALYTICAL TECHNIQUES

Cross Sections

Three thermal neutron groups having upper energy limits of 0.08, 0.55 and 1.86 eV were used in this study. The THERMOS³ integral transport code was used to generate the broad group thermal cross sections using the one-dimensional fuel-pin cell geometry shown in Fig. 1. The basic THERMOS

ORNL DWG 66-10190

Fig. 1. MH-1A Fuel-Pin Cell

cross section library has been used successfully in previous studies and is described elsewhere.⁴ The heavy scatterer region of Fig. 1 was used to obtain isotropic return of neutrons at the outer boundary of the moderator; this boundary condition has been shown⁵ to be superior to a reflection condition in small cylindrical cells. The 2.25 mil He gap between the fuel and cladding was homogenized with the cladding. Broad group cross sections (Appendix B) averaged over space and energy were determined for an enrichment of 4.36 w/o ^{235}U , which is the average enrichment of the inner and outer zones of the initial core. Fuel-pin cell results from reference 1 indicated a slight difference in the ratio of fuel flux to cell flux (below 0.6 eV) corresponding to enrichments of 4.07 and 4.65%. As the neutron energy increases above 0.6 eV, the difference is expected to vanish. The error in reactivity and power distribution associated with the use of cross sections at an average enrichment is expected to be much less than 1% for the reference design enrichments. The fuel-pin cell concentrations at 68°F and 490°F are given in Table C.1 of Appendix C.

In the two-dimensional calculations in R-Z geometry, boron-stainless steel control rods and followers were homogenized with the core. Therefore, it was necessary to multiply the cross sections of the boron by the ratio $(\bar{\Phi}_{\text{control rod}} / \bar{\Phi}_{\text{fuel-moderator}})$ to account for space and energy self-shielding. The stainless steel in the control rod followers was exposed to approximately the average fuel cell flux; disadvantage factors were not applied to this material. The THERMOS code was used to determine energy-dependent thermal disadvantage factors for the control rods and the inner and outer followers at 68°F and 490°F. The slab geometry shown in Fig. 2 was used for this calculation. Values obtained for disadvantage factors are given in Table D.1 of Appendix D.

The fast 6-group cross sections were obtained using a modified form of the GAM-I^{4,6} code. The 6-group fast constants were calculated using the B_1 approximation to the solution of the Boltzmann equation. Self-shielding in the epithermal range was treated using resonance parameters on the library tape. The upper energy limits of the 6 fast groups were (in eV) 35, 450, 5×10^3 , 6×10^4 , 8.21×10^5 and 1×10^7 .

Fast disadvantage factors for the boron in the control rods and followers were obtained from curves of disadvantage factor vs energy. The

ORNL DWG 66-10191

Fig. 2. MH-1A Control Rod Follower Cell.

curves were generated using THERMOS in the thermal range and previous S_n results⁷ in the fast range.

Reactor Representation

The power distribution and reactivity were calculated using the ASSAULT code.⁸ The nine-group diffusion equations were solved in two dimensions using X-Y and R-Z geometry. Radial power peaking was obtained using X-Y geometry while the axial power distribution was calculated with R-Z geometry. Figure 3 shows the geometrical model used for calculations in X-Y geometry with 4-fold symmetry. One quarter of the reactor was divided into as many as 76 regions using a 60 x 61 mesh, many of the regions having the same composition. The homogenized fuel region consisted of the fuel, stainless steel, and water from the pin cell calculation. The outer reflector regions were either water or a homogenized stainless steel-water mixture. The cladding and absorber sections of the control rod followers were homogenized on a volume basis.

All calculations in X-Y geometry were made with control rods withdrawn; the followers and their adjacent water gaps were treated explicitly using internal mesh points and diffusion theory. Subsequent analysis indicated that the neutron flux distribution within the followers calculated by ASSAULT was in agreement with the flux distributions obtained using transport theory. The poison shim rods were also treated with internal mesh points and diffusion theory. Because of the significant flux perturbation caused by the poison shim rods, this method probably does not give accurate results for the flux distribution within or near the poison shim rods. However, the effect on radial power peaking away from the shim rods should be calculated fairly accurately.

The X-Y power distribution calculations involved a direct search on leakage until the reactor was just critical. This was accomplished by using absorptions in a fictitious nuclide to represent leakage losses. In order to represent the leakage energy spectrum reasonably well, the broad group absorption cross sections of the fictitious nuclide were made proportional to the group diffusion coefficients obtained from the GAM-THERMOS calculations. The ASSAULT code then treated the search nuclide concentration as the eigenvalue of the problem.

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1. Po-Be source
2. Homogenized UO_2 + stainless steel + water, inner zone
3. Homogenized UO_2 + stainless steel + water, outer zone
4. Inner control rod or follower
5. Outer control rod or follower
6. Inner control rod or follower water gap
7. Outer control rod or follower water gap
8. Stainless steel insert
9. Insert water
10. Dummy rod
11. Homogenized water + stainless steel
12. Reflector water
13. Homogenized water + stainless steel
14. Homogenized water + stainless steel

Fig. 3. X-Y Geometrical Model.

The cold clean X-Y reactivity calculation required an energy-dependent axial leakage as input. The broad group leakages were obtained from a two-dimensional R-Z geometry calculation and are tabulated in Appendix C.

The R-Z geometrical model of the reactor with all control rods inserted 14.9 in. is shown in Fig. 4. Sixty-nine regions were used with a 44 x 59 mesh. The core was divided into 8 regions and represented by a homogenized mixture of UO_2 , stainless steel and water. The only part of the core represented explicitly was the source element and its different segments. The source element, primarily of stainless steel, had a 6-in. long Po-Be source capsule at the core mid-plane and a 6-in. length of 0.14 w/o boron-stainless steel immediately below the source.

For the R-Z calculation, the control rods and followers were included in the core homogenization. The outermost annular regions of the core contained no boron. The four annular regions of the core had the following compositions, proceeding outwards from the center of the core.

Region	Volume Fraction in Core	Fuel Elements	CR or Followers
A (inner)	1/8	4 inner	2 inner
B	3/8	12 inner	2 inner and 4 outer
C	1/4	8 outer	4 outer
D (outer)	1/4	8 outer	_____

The core barrel and outer reflector regions including the pressure vessel were represented explicitly. Inside the core barrel, the water and steel do not have a circular shape; the core shroud, inner thermal shields and water were cylindricalized with volumes conserved.

Some effort was made to accurately represent the axial reflectors immediately above and below the core. The first region below the core was 1-in. thick and made up of the fuel pin end caps, water and burnable poison (with control rods inserted). The first region above the core was about 1-in. thick and was made up of stainless steel, control rod absorber and water. Additional regions above and below the core consisted of structural stainless steel, water, and in some cases boron.

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1. Po-Be source
2. Homogenized UO_2 + stainless steel + water + 14.9-in. of 2 inner control rods
3. Homogenized UO_2 + stainless steel + water + 14.9-in. of 2 inner and 4 outer control rods
4. Homogenized UO_2 + stainless steel + water + 14.9-in. of 4 outer control rods
5. Homogenized UO_2 + stainless steel + water
6. Homogenized UO_2 + stainless steel + water + 21.1-in. of 2 inner followers
7. Homogenized UO_2 + stainless steel + water + 21.1-in. of 2 inner and 4 outer followers
8. Homogenized UO_2 + stainless steel + water + 21.1-in. of 4 outer followers
9. Homogenized stainless steel + water
10. Water
11. Stainless steel
12. Homogenized helium + stainless steel + water + control rods
13. Homogenized stainless steel + water + followers

Fig. 4. R-Z Geometrical Model.

RESULTS AND DISCUSSION

Reactivity

The effective multiplication factor k of the cold clean core was calculated using the ASSAULT code with X-Y and R-Z geometry. The values obtained compared favorably with both the value calculated by the Martin Company using the PDQ code and the value measured in a zero power experiment. The cold clean reactivity ρ was reported by the Martin Company; the value of k was inferred from the relation $\rho = (k - 1)/k$.

Values of the multiplication factor for the reference design MH-1A reactor at 68°F are given in Table 1.

Table 1. Values of Multiplication Factor of the Cold Clean MH-1A Reactor Obtained by ORNL and the Martin Company

Geometry		k	
		Calculated	Measured
ORNL	R-Z	1.134	
ORNL	X-Y	1.136	
Martin	X-Y	1.136	
Martin			1.140

The maximum insertion of the 12 rod control rod bank for full power operation was specified in the final design report¹ as 14.9 inches. This control rod position is expected to be reached after about 3-6 days of operation. The multiplication factor calculated for this rod insertion was 1.03 for the hot clean reactor without xenon. After about 3-6 days of operation, the buildup of xenon and other fission products combined with burnup of fuel is expected to reduce k to about unity for the 12 rod bank insertion of 14.9 in. Thus, the control rod bank worth corresponding to an insertion of 14.9 in. seems to be in fair agreement with that obtained by Martin Company.

The reactivity worth of the natural boron in the followers was calculated for both the hot and the cold clean core. ASSAULT calculations were made using X-Y geometry with boron in the followers. Because X-Y geometry precludes a detailed description of the core in the axial direction, the calculation corresponds to the presence of burnable poison in the full 36-in. length of the follower; actually, the boron exists only in the upper 27 in. of the follower. The necessary correction factor has been calculated by the Martin Company and was used by ORNL after verification (Appendix E). The boron in 27 in. of follower was found to have a worth equivalent to 87% of the worth of 36 in. of boron with all control rods withdrawn.

The reactivity worth of the burnable poison was approximately the same for the hot and cold cases with control rods out; a value of 2.5% $\Delta\rho$ was obtained for both the hot clean core and the cold clean core. This value was determined by multiplying the fractional neutron loss in the boron by 0.87, renormalizing to unit losses and dividing by the resultant k . For the cold clean core with rods out, the 87% poison-length correction caused k to increase from 1.131 to 1.136. In R-Z geometry, with the control rod bank inserted 14.9-in., the burnable poison reactivity worth was 2.6% $\Delta\rho$ for the hot clean core.

The 3-group relative thermal fluxes in the control rods and in the followers were calculated using the THERMOS transport code; the results after reduction to 1 group ($0 < E < 1.86$ ev) are plotted in Fig. 5. The thermal flux peaks in the water channel between the follower and the fuel, higher peaking occurring with lower boron concentrations and lower temperatures. The greater absorption of the control rod prevents flux peaking.

The design loadings of natural boron in the inner and outer followers were 0.16 w/o and 0.06 w/o, respectively; the loadings in the followers as built were 0.181 w/o and 0.030 w/o for the inner and outer followers, respectively. The four inner followers were brought to an effective loading of 0.16 w/o boron by decreasing the thickness of the absorbing material from 0.250-in. to 0.221-in. The follower was shimmed to the required thickness with 0.029-in. of stainless steel.

Because of the effectiveness of the inner followers in preventing power peaking, calculations were performed which would point out any

Fig. 5. Relative Thermal Flux Distributions in an MH-1A Control Rod and Follower Cell

differences between the as-built and the reference design inner followers with respect to resultant power distribution. The calculated thermal flux distributions are shown in Fig. 6. The different boron loadings result in identical thermal flux distributions in the fuel. Thus, the design and as-built inner followers are equivalent in their influence on the power distribution.

Provision has been made to shim the reactivity of the core, if necessary, with 12 stainless steel (0.9 w/o natural boron) shim rods. The total reactivity worth of the 12 rods was calculated to be 0.5%; an identical value was reported by the Martin Company.

A neutron balance for the cold clean core ($k = 1.136$) is given in Table 2. "Excess" represents control poison to make the reactor critical.

Table 2. Fractional Neutron Losses in Reference
Design MH-1A Reactor - 68°F,
Control Rods Withdrawn

Hydrogen	.0450
Boron in inner followers	.0158
Boron in outer followers	.0095
Uranium 235	.4874
Uranium 238	.1750
Oxygen	.0021
Stainless steel	.1145
Axial leakage from core	.0298
Radial leakage from pressure vessel	.0011
Excess	.1198
	<hr/> 1.0000 <hr/>

Power Distribution

Macroscopic radial power distributions at 490°F are shown in Fig. 7. Values of normalized power density averaged over a fuel element are presented, except in the outer elements where the average is over two elements

Fig. 6. Thermal Flux Distribution in (a) Reference Design Follower (0.16 w/o Boron and (b) As-Built Follower (0.181 w/o Boron)

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Fig. 7. MH-1A X-Y Relative Power Density Distribution - All Control Rods Withdrawn, 490°F

as indicated. All power densities in X-Y geometry are normalized to the average power density in the fuel-moderator region of the core.

Results for the initial design are in good agreement with those of the Martin Company.¹ Removal of burnable poison from the followers is seen to increase the macroscopic power peaking by about 15%. Insertion of the poisoned shim rods had only a localized effect and did not change the sub-assembly average power densities significantly.

Local peaking effects are shown in Fig. 8. Normalized power density is plotted, going radially outward from the center of the core. For the initial core, the radial peaking reaches a maximum near the source element at the center of the core. This is seen to be a localized effect that occurs because of the low neutron absorption in the source capsule. A calculation below the source indicates that the 0.14 w/o boron-stainless steel slug (Martin Company's design) is effective in removing the radial power peak from the core location of highest overall peaking without much change in the overall power distribution. A higher boron content in this slug would probably effect a further reduction of power peaking.

The burnable poison in the inner control rod followers contributes a great deal towards power flattening. However, removal of the boron from all of the followers did not cause much change in the local peaking near the outer followers, suggesting that the poison in the outer followers may be ineffective. Additional evidence for this suggestion came from the disadvantage factor calculations, which indicated that the thermal flux in the outer followers was only 5-10% lower than in the fuel region.

Although the effect of burnup on power distribution was not studied, it is expected that the power peaking will move radially outwards as operation continues through a fuel loading; the peaking is not expected to exceed the power peak in the center of the core at the beginning of life. A potential power peaking location is at that tip of the outer followers which is closest to the center of the core. The large water gap at the follower tip contributes to power peaking at this point. If the burnable poison is to be removed from all or some of the followers, the possibility of a power peak at the above location at the beginning of and throughout the core lifetime should be investigated.

Fig. 8. Relative Power Density vs Radius for MH-1A Reactor (490°F)
at Core Mid-Height, Control Rods Out

The localization of the power reduction caused by inserting poisoned shim rods is evident. The influence of the dummy rods extends about 2-in. from the point of insertion. When the poisoned shim rods were replaced with pure stainless steel dummy rods, there was practically no local peaking near them. Collectively, the poisoned shim rods caused about 1-2% increase in the macroscopic radial power peaking.

The power generation in the fuel pins protruding into the radial reflector was below core average in most cases. Power peaking in these areas does not appear to be a problem with the present design.

Relative power density through the center of 3 fuel subassemblies is plotted in Fig. 9. The curves represent X-Y calculations with or without the source element or poison dummy rods since local peaking effects from the source element or dummy rods do not extend very far into the fuel elements. Only the local peaking from control rod followers is evident in this graph which gives a general picture of the overall power distribution. Again, it seems that the burnable poison in the outer followers has little effect on the local power distribution.

The axial power distribution for the hot clean core with all control rods banked at 14.9 in. is shown in Fig. 10. The ORNL result was obtained from an R-Z calculation by plotting normalized power density in the axial direction at that radius at which maximum power generation occurred in the core. Power density was normalized to the average core power density. A peak-to-average value of 1.91 was obtained with all control rods inserted 14.9 in. The ORNL result is about 4% higher than that of the Martin Company, which is also shown in the figure. This difference is probably due in part to different calculational models and in part to the absence of xenon in the ORNL calculation.

The location of peak power generation was 6 in. below the core mid-plane at a radius of about 1.8 in. This is at a height corresponding to the center of the 6-in. boron-stainless steel slug in the source element. The radius of 1.8 in. is in agreement with the X-Y result in Fig. 8. The effect of the boron extends upwards about 2 in. so that the radial peaking occurs adjacent to the source capsule at a radius of about 0.25 in. and a height about 1 in. below the core midplane. Three inches below the mid-plane, at the bottom of the source capsule, the radial peak is at a radius of 1.8 in.

Fig. 9. Relative Power Density vs Radius for MH-1A Reactor (490°F)
at Core Mid-Height, Control Rods Out

Fig. 10. MH-1A Axial Power Distributions

No calculations of axial power distribution were made with the boron removed from the followers or with the poison shim rods inserted.

For the reference design core, the radial and axial peaking factors were 1.53 and 1.91, respectively, giving a total peaking factor of 2.92.

In the design with boron removed from the followers, a calculation at the reactor midplane gave a radial peaking factor of 1.94. The radial peaking factor at the point of maximum power density (below the midplane) was estimated from Fig. 8 with the aid of the reference design results to be 1.85-1.90. The axial peaking factor is known with less certainty. From the control rod bank worth curves of Martin Company,¹ a 12 rod insertion of about 18-19 in. would be required to control the reactivity gain of 2.6% $\Delta\rho$ caused by removal of boron from the followers. This additional insertion was estimated from Fig. 10 to cause at least a 0.1 increase in the axial peaking factor, raising this factor to at least 2.01. Thus the total peaking would be a minimum of 3.72-3.82, an increase of about 30% over the reference design. It should be mentioned that it may not be necessary to use a 12 rod bank to control the reactivity. Some alternate control rod programming scheme might be used which would give a lower axial peaking factor (for example, a 10 rod bank with 2 rods fully inserted).

For the case with boron removed from the followers and the poison shim rods inserted, a calculation at the reactor midplane gave a radial peaking factor of 1.97. The radial peaking factor at the point of maximum power density was estimated from Fig. 8 to be 1.87-1.92. The reactivity gain to be made up by control rod insertion was only about 2.1% for this case, since the poison shim rods were worth about 0.5%. This leads to a control rod bank insertion of about 18-in. which, from Fig. 10, gives an estimated axial peaking factor of at least 2.0. The total peaking is then a minimum of 3.74-3.84. These results are tabulated in Table 3. None of the values include a calculational uncertainty, which is estimated to be less than $\pm 5\%$.

In all cases with the control rods banked at 14.9 in., the overall power peak is expected to be at a core radius of about 1.8 in. (at the tip of the inner followers) and 24-26 in. below the top of the core.

Table 3. Power Peaking Factors in the MH-1A Reactor

	Reference Design ^a	No Boron in Followers	No Boron in Followers, Poison Shim Rods Inserted
Radial, at midplane	1.71 (1.73)	1.94	1.97
Radial, at point of peak power density	1.53 (1.68)	1.85	1.87
Axial	1.91 (1.83)	2.01 ^b	2.0 ^b
Total	2.92 (3.07)	3.72 ^b	3.74 ^b

^aValues in parentheses were calculated by the Martin Company. None of the values in the table include calculational uncertainty.

^bThese are minimum estimates; the true values may be as much as 5% higher. These values assume a 12 rod bank insertion of more than 14.9 inches for reactivity compensation.

Power Margin

An important design criterion for the MH-1A was that departure from nucleate boiling (DNB) should not occur during steady-state, normal power transients or credible accidents. In order to ensure that DNB would not occur, the power margin to DNB (PM) was limited to 1.5 during steady-state operation and 1.2 during transients. The power margin to DNB is defined as

$$PM = \frac{\text{reactor power at which DNB occurs}}{\text{reactor power at design conditions}} \quad (1)$$

It is generally accepted that DNB may occur through 2 different mechanisms, one operating in the sub-cooled region and the other in the quality region. The first mechanism (sub-cooled region) involves the formation of a vapor film on the channel wall; the film acts as a heat transfer barrier, the effectiveness of which is controlled by the local surface heat flux. The second mechanism is associated with the occurrence of dry areas on the wall resulting from bulk boiling and 2-phase flow; the total heat input to the coolant controls the effectiveness of the heat transfer barrier represented by the dry areas.

Both mechanisms should be analyzed in the MH-1A in order to determine which will give the lowest power margin. The effect of power peaking on the PM is considered below for each of the mechanisms. The treatment of the sub-cooled system was the simplest and is discussed first.

Assuming that in the sub-cooled region the DNB heat flux for a given configuration (case 1) is the same as in the reference design calculations of Martin Company (case 2), the maximum power density in the hot channel (same geometry) will not change.

$$P_{\max,1} = P_{\max,2} \quad (2)$$

If the peaking factor, $PF = P_{\max}/\bar{P}$ is independent of power level, then equation 2 may be written as

$$(PF)_1 \bar{P}_{\text{DNB},1} = (PF)_2 \bar{P}_{\text{DNB},2} \quad (3)$$

Thus, the reactor power at which DNB (sub-cooled) occurs for a given configuration is determined in terms of the Martin reference design results and the ORNL-calculated power peaking. The power margin is then determined from equations 1 and 3 to be inversely proportional to the peaking factor:

$$(PM)_1 = \frac{(PF)_2}{(PF)_1} (PM)_2 \quad (4)$$

In the quality region, the assumption made was that the total power input to the hot channel up to the point (Z^0) at which DNB occurs was the same for cases 1 and 2 above. Then,

$$\int_0^{Z_1^0} P_1(Z) dZ = \int_0^{Z_2^0} P_2(Z) dZ \quad (5)$$

Defining $(\overline{PF})_r$ as the average radial peaking factor along the hot channel up to the point of DNB, and P_a as the ratio of power to average power axially along the hot channel, equation 5 may be rewritten as

$$(\overline{PF})_{r,1} \overline{P}_{DNB,1} \int_0^{Z_1^0} P_{a,1}(Z) dZ = (\overline{PF})_{r,2} \overline{P}_{DNB,2} \int_0^{Z_2^0} P_{a,2}(Z) dZ \quad (6)$$

Equation 6 has the same form as equation 3 so that one may write

$$(PM)_1 = \frac{(\overline{PF})_{r,2} \int_0^{Z_2^0} P_{a,2}(Z) dZ}{(\overline{PF})_{r,1} \int_0^{Z_1^0} P_{a,1}(Z) dZ} (PM)_2 \quad (7)$$

The power margin in the quality region is thus inversely proportional to the product of the average radial peaking factor in the hot channel and the integral of the axial relative power density in the channel up to the point at which DNB occurs.

Although the values of Z^0 were not known for either the cases of interest or the reference design, enough information was available to indicate the sensitivity of the ratio of integrals in Eq. 7 to changes in Z^0 . It is expected that if DNB in the quality region occurs, it will occur near the core outlet. A 1000 Mwe PWR study showed⁹ that the minimum DNB ratio in the quality region occurred at a distance from the outlet which was about 8-1/2% of the channel length. If we assume that this value applies to the MH-1A, then $Z_1^0 = 0.925 (36) = 33.3$ in. In order to compare the ORNL and Martin Company reference design calculations, it was assumed that the axial power distributions were the same. It is evident from Fig. 10 that even if Z_2^0 is taken as 24 in. instead of 33.3 in., the error in the ratio of integrals in Eq. 7 is only about 5%. The ratio of the integrals was assumed to be unity in making PM estimates, which consequently include an uncertainty of about 5%.

In the cases where the control rod followers did not contain boron, axial power distributions were not calculated. However, if one compares these cases with the reference design case and assumes that the ratio of

the integrals in equation 7 is approximately unity, a rough estimate of the power margin can be made for these cases also.

A reference design steady-state PM value of 2.06 corresponding to radial and axial peaking factors of 1.79 and 1.92 (including calculational uncertainty) was reported by the Martin Company. This correspondence between PM and power peaking was used in conjunction with the peaking factors of Table 3 to arrive at steady-state values of PM for the 3 core configurations in Table 3. The maximum radial peaking factors (occurring at the core midplane) were used for the quality regime. In the case of transients resulting from operation or a credible accident such as loss of flow, an analysis similar to that described above was made of the ORNL power peaking data. The reference design value of PM = 1.35 obtained by the Martin Company¹⁰ for transient operation was used as a basis for determining the power margin from ORNL power distribution data.

The power margin estimates are listed in Table 4. The values should be taken to represent a rough assessment of PM variation caused by power

Table 4. Power Margins in the MH-1A Reactor

	Reference Design ^a	No Boron in Followers	No Boron in Followers, Poison Shim Rods Inserted
Sub-Cooled			
Steady-state	2.43 (2.06)	1.91 ^b	1.90 ^b
Transient	1.59 (1.35)	1.25 ^b	1.24 ^b
Quality			
Steady-state	2.16 (2.06)	1.90 ^b	1.87 ^b
Transient	1.41 (1.35)	1.25 ^b	1.23 ^b

^aValues in parentheses were calculated by the Martin Company and include a calculational uncertainty of 5% in radial power peaking as well as in axial peaking. None of the ORNL values in the table include calculational uncertainty.

^bIn addition to calculational uncertainty, an uncertainty of about $\pm 5\%$ is associated with these values because of the assumptions used.

peaking changes for the cases listed in the table. Although the results are for both sub-cooled and bulk boiling burnout, it is suspected that the Martin Company power margin data are for burnout due to bulk boiling. If this is the case, the sub-cooled DNB power margins are probably not too important but should be re-calculated using the Martin data for sub-cooled DNB as a basis. Because of the higher power peaking associated with removing boron from the followers, it is possible that the DNB mechanism could change from bulk boiling to vapor film formation in the sub-cooled system.

SUMMARY AND CONCLUSIONS

The power distribution in the reference design of the MH-1A reactor was calculated and found to be in fair agreement with that reported by Martin Company. The power peaking factor was 2.92 compared with 3.07 reported by the Martin Company. The location of maximum power density was 24 in. below the top of the core at a radius of about 1.8 in., corresponding to the tip of the inner followers; a similar finding was reported by The Martin Company. No significant power peaking was observed near the twelve steel dummy rods or in the protruding fuel pins at the core perimeter.

Removal of boron from the control rod followers increased the power peaking by 25-30%, primarily by changing the radial distribution. Most of the increase resulted from removing the boron from the inner followers.

Replacement of the twelve steel dummy rods with 0.9 w/o boron-steel rods did not change the power peaking appreciably. The poisoned shim rods had only a localized effect on the power distribution.

The source element had considerable local effect on the power distribution. The power peaking could be reduced by either replacing the source capsule with steel or increasing the boron concentration in the 6-in. slug immediately below the source capsule.

Calculations of k-effective for the cold clean reference core gave values of 1.136 in X-Y geometry and 1.134 in R-Z geometry, in good agreement with the experimentally measured value of 1.140 and the value of 1.136 calculated by the Martin Company.

A calculation with the reactor at operating temperature (490°F) and all control rods inserted 14.9-in. indicated fair agreement with the control rod worth predicted by the Martin Company.

Power margin (PM) estimates based on the original Martin Company calculations but using ORNL power peaking factors indicate that the MH-1A reactor has a PM well above 1.5 in the steady-state operating condition for all the configurations investigated. Under transient operating conditions, the application of ORNL peaking factors to Martin Company data resulted in a PM significantly above 1.2 for the reference design, and in the neighborhood of 1.2 for the calculations without burnable poison in the followers. Insertion of the poison shim rods did not change the PM significantly.

RECOMMENDATIONS

Nuclear calculations made at ORNL indicate that the power distribution and reactivity of the reference design MH-1A reactor are close to the design predictions of Martin Company. No changes in nuclear design are considered necessary in order to obtain a satisfactory power distribution and initial reactivity.

Power distributions calculated with no boron in the followers resulted in power margin estimates close to the limit of 1.2 specified for transient operation. It is recommended that detailed attention be given to the calculational model for transient operation used by Martin Company in their power margin calculations. It may be possible to remove the burnable poison from all of the followers. However, we think that some power flattening device (possibly an alternate control rod programming scheme) will be necessary before this can be done.

It is further recommended that some attention be given to the possibility of removing the boron from only the outer followers. We suggest that a power distribution calculation be made for a case with the design boron loading in the 4 inner followers and no boron in the 8 outer followers. Since the power peaking will move radially outward during the core lifetime, the large H_2O gap at the tip of the outer followers nearest

the center of the core is a potential source of power peaking. Thus, the calculation should be made for different burnups.

An additional suggestion is that some thought be given to placing the source capsule in a different location — where the power peaking is less severe. Perhaps one of the 12 poison shim rod locations might be suitable. Questions concerning adequate source strength and detection are relevant to such a design change.

A final recommendation concerns the optimization of the core lifetime. By increasing the enrichment and making use of the poisoned dummy fuel rods for power flattening and reactivity control, it may be possible to increase the core lifetime from one year to two years. A comprehensive study involving reactivity lifetime and power distribution calculations would be required. It is recommended that a preliminary study be made to determine whether it would be worthwhile to optimize the MH-1A core life.

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APPENDICES

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APPENDIX A

Core Description

A summary of the nuclear and physical design data of the MH-1A reactor is given in the following table. Burnup characteristics are not given since the core life was not investigated.

Table A.1. MH-1A Core Description

Core nuclear data	
Design power level (Mwt)	45
Core cycle lifetime (yr)	1
Initial core loadings (kg U)	
Inner region	1465 (4.07 w/o ^{235}U)
Outer region	1465 (4.65 w/o ^{235}U)
Core physical data	
Equivalent diameter (in.)	45.2
Active height (in.)	36.0
Fuel element data	
Number of fuel elements	32
Fuel pins per fuel element	104
Fuel pin pitch (in.)	0.654
Fuel pin OD (in.)	0.507
Fuel cladding material	Type 348 SS
Fuel cladding thickness (in.)	0.023
UO_2 pellet diameter (in.)	0.4565
Control rod data	
Number of control rods	12
Shape	cruciform
Blade width (in.)	
Inner 4 rods	10.78
Outer 8 rods	10.20
Absorber composition	2.1 w/o B in SS
Enrichment of ^{10}B in the boron, a/o	92
Absorber thickness (in.)	0.250
Cladding material	Type 348 SS
Cladding thickness (in.)	0.050
Absorber length (in.)	36.75

Table A.1 (Cont.)

Core physical data (cont.)

Control rod followers

Blade width (in.)

Inner 4 rods	10.78
--------------	-------

Outer 8 rods	10.20
--------------	-------

Poisoned section length (in.)	27.0
-------------------------------	------

Unpoisoned section length (in.)	14.9
---------------------------------	------

Poison section composition	Natural B in SS
----------------------------	-----------------

As designed

Inner 4 rods	0.16 w/o B _{nat}
--------------	---------------------------

Outer 8 rods	0.06 w/o B _{nat}
--------------	---------------------------

As built

Inner 4 rods	0.181 w/o B _{nat} 0.221" thick 0.029" SS skin
--------------	---

Outer 8 rods	16.0 in. of 0.039 w/o B _{nat} , 3.0 in. of 0.181 w/o B _{nat} , 8.0 in. of 0.039 w/o B _{nat} ,
--------------	--

Unpoisoned section composition	Type 348 SS
--------------------------------	-------------

Dummy shim rods

Number	12
--------	----

Diameter (in.)	0.507
----------------	-------

Composition	0.90 w/o natural B in SS
-------------	--------------------------

Source element data

Number	1
--------	---

Diameter	0.507
----------	-------

Source capsule

Length (in.)	6
--------------	---

Curies (Po-Be)	200
----------------	-----

Position	Core midplane
----------	---------------

Poison slug

Length (in.)	6
--------------	---

Composition	0.14 w/o natural B in SS
-------------	--------------------------

Position	Below source capsule
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APPENDIX B

Broad Group Microscopic Cross Sections

Table B.1. Broad Group Microscopic Cross Sections in Barns, Reactor Temperature = 68°F

Group	Energy Range, ev	Hydrogen		Oxygen		Boron ^a		Stainless Steel	
		σ_a	σ_{tr}	σ_a	σ_{tr}	σ_a	σ_{tr}	σ_a	σ_{tr}
1	8.21×10^5 – 1×10^7	3.8456×10^{-5}	1.6107	9.2145×10^{-3}	1.8813	8.5584×10^{-2}	1.6910	3.6261×10^{-3}	2.1634
2	6.0×10^4 – 8.21×10^5	1.0381×10^{-4}	2.7376	0	3.8410	0.22917	2.8825	6.4133×10^{-3}	2.9106
3	5.0×10^3 – 6.0×10^4	3.9269×10^{-4}	4.5753	0	3.6291	1.1477	4.8263	9.0651×10^{-3}	6.3082
4	450–5000	1.4047×10^{-3}	5.8670	0	3.6574	3.2009	6.9185	1.4101×10^{-2}	7.4816
5	35–450	4.8416×10^{-3}	5.7250	0	3.6512	11.086	14.830	3.9263×10^{-2}	10.882
6	1.86–35	1.9860×10^{-2}	6.2689	0	3.6521	44.876	51.229	0.15707	11.049
7	0.55–1.86	5.4569×10^{-2}	9.8317	2.8593×10^{-5}	3.4234	121.66	46.649	0.45964	10.098
8	0.08–0.55	0.13443	17.064	6.6507×10^{-5}	3.4102	285.37	109.42	1.0644	9.8146
9	0.005–0.08	0.34817	42.815	1.5320×10^{-4}	3.4339	668.78	256.44	2.3928	9.3999

^aSpace and energy weighting are not included in the cross sections of boron.

Table B.1 (Cont.)

Group	Energy Range, ev	Uranium 235				Uranium 238			
		σ_a	σ_{tr}	σ_f	ν	σ_a	σ_{tr}	σ_f	ν
1	8.21×10^5 – 1×10^7	1.3260	4.8085	1.2609	2.7085	0.46675	5.0330	4.0550×10^{-1}	2.7677
2	6.0×10^4 – 8.21×10^5	1.6983	7.7774	1.3864	2.4639	0.18173	6.8918	4.6346×10^{-4}	2.4994
3	5.0×10^3 – 6.0×10^4	4.0650	14.037	2.9280	2.4324	0.44563	12.966	0	0
4	450 – 5.0×10^3	11.253	21.485	7.8289	2.4303	0.90893	16.798	0	0
5	35 – 450	42.873	54.433	27.918	2.4300	1.4878	27.037	0	0
6	1.86 – 35	76.836	84.756	42.252	2.4300	3.4069	25.372	0	0
7	0.55 – 1.86	56.997	29.745	47.235	2.4260	0.42525	7.8640	0	0
8	0.08 – 0.55	204.25	85.466	171.76	2.4260	0.92802	7.2173	0	0
9	0.005 – 0.08	447.40	177.66	380.60	2.4260	1.8243	6.1599	0	0

Table B.2. Broad Group Microscopic Cross Sections in Barns, Reactor Temperature = 490°F

Group	Energy Range, ev	Hydrogen		Oxygen		Boron ^a		Stainless Steel	
		σ_a	σ_{tr}	σ_a	σ_{tr}	σ_a	σ_{tr}	σ_a	σ_{tr}
1	$8.21 \times 10^5 - 1 \times 10^7$	3.8665×10^{-5}	1.6389	8.9083×10^{-3}	1.9061	8.5123×10^{-2}	1.6967	3.5920×10^{-3}	2.1697
2	$6.0 \times 10^4 - 8.21 \times 10^5$	1.0399×10^{-4}	2.8138	0	3.8323	0.22989	2.8864	6.4168×10^{-3}	2.9128
3	$5.0 \times 10^3 - 6.0 \times 10^4$	3.9240×10^{-4}	4.5694	0	3.6304	1.1471	4.8289	9.0636×10^{-3}	6.2626
4	$450 - 5.0 \times 10^3$	1.4010×10^{-3}	5.7814	0	3.6604	3.1925	6.9091	1.4082×10^{-2}	7.4636
5	$35 - 450$	4.8254×10^{-3}	5.5749	0	3.6532	11.049	14.811	3.9141×10^{-2}	10.884
6	$1.86 - 35$	1.9803×10^{-2}	6.1620	0	3.6555	44.750	51.292	0.15663	11.053
7	$0.55 - 1.86$	5.4996×10^{-2}	9.9929	2.8098×10^{-5}	3.3471	123.19	47.236	0.46379	10.118
8	$0.08 - 0.55$	0.13511	17.624	6.1679×10^{-5}	3.1815	289.20	110.89	1.0778	9.8632
9	$0.005 - 0.08$	0.31434	42.722	1.1390×10^{-4}	2.9310	618.17	237.03	2.2386	9.5870

^aSpace and energy weighting are not included in the cross sections of boron.

Table B.2 (Cont.)

Group	Energy Range, ev	Uranium 235				Uranium 238			
		σ_a	σ_{tr}	σ_f	ν	σ_a	σ_{tr}	σ_f	ν
1	$8.21 \times 10^5 - 1 \times 10^7$	1.3262	4.8321	1.2604	2.7045	0.46200	5.0599	0.39981	2.7655
2	$6.0 \times 10^4 - 8.21 \times 10^5$	1.7001	7.7914	1.3874	2.4638	0.18063	6.9061	4.5988×10^{-4}	2.4994
3	$5.0 \times 10^3 - 6.0 \times 10^4$	4.0635	14.042	2.9269	2.4324	0.44660	12.970	0	0
4	$450 - 5.0 \times 10^3$	11.216	21.430	7.8049	2.4303	1.0744	16.943	0	0
5	35-450	42.725	54.411	27.826	2.4300	1.7407	26.647	0	0
6	1.86-35	77.033	84.645	42.342	2.4300	3.2801	24.163	0	0
7	0.55-1.86	57.828	30.046	47.983	2.4260	0.42779	7.8504	0	0
8	0.08-0.55	207.18	86.616	174.01	2.4260	0.93905	7.2399	0	0
9	0.005-0.08	419.64	167.20	356.71	2.4260	1.7341	6.3374	0	0

APPENDIX C

Nuclide Concentrations and Core Axial Leakage

The nuclide concentrations used to get the thermal and fast cross sections are given in Tables C.1 and C.2. Table C.3 lists the poison concentrations used in the 2-dimensional calculations.

The broad group leakages for the cold clean eigenvalue calculation in X-Y geometry were obtained from a cold clean R-Z geometry calculation with control rods out by adding the absorptions in the regions above and below the core. Radial leakage from these regions was negligible.

Table C.1. THERMOS Fuel-Pin Cell Nuclide Concentrations
(atoms/barn-cm of region)

Nuclide	68°F	490°F
^{235}U	1.01895×10^{-3}	1.01895×10^{-3}
^{238}U	2.2070×10^{-2}	2.2070×10^{-2}
^{16}O (fuel)	4.6175×10^{-2}	4.6175×10^{-2}
Stainless steel	7.9846×10^{-2}	7.9846×10^{-2}
Hydrogen	6.6730×10^{-2}	5.3250×10^{-2}
^{16}O (coolant)	3.3365×10^{-2}	2.6625×10^{-2}
Heavy scatterer	1.0	1.0

Table C.2. Homogeneous Nuclide Concentrations for GAM
Spectrum Calculations (atoms/barn-cm of core)

Nuclide	68°F	490°F
^{235}U	3.4410×10^{-4}	3.4410×10^{-4}
^{238}U	7.4530×10^{-3}	7.4530×10^{-3}
^{16}O (fuel)	1.5594×10^{-2}	1.5594×10^{-2}
Stainless steel	1.1417×10^{-2}	1.1417×10^{-2}
Hydrogen	3.4950×10^{-2}	2.7890×10^{-2}
^{16}O (coolant)	1.7475×10^{-2}	1.3945×10^{-2}
Beryllium	2.0941×10^{-6}	2.0941×10^{-6}
Boron, inner followers	7.0151×10^{-6}	7.0151×10^{-6}
Boron, outer followers	4.9709×10^{-6}	4.9709×10^{-6}

Table C.3. Nuclide Concentrations for Control Rods
and Reference Design Followers
(atoms/barn-cm of region)

<u>Control rods</u>	
Poison region	
Boron	9.2692×10^{-3}
Stainless steel	8.5447×10^{-2}
Cladding	8.7250×10^{-2}
<u>Inner followers</u>	
Poison region	
Boron	7.1097×10^{-4}
Stainless steel	8.6820×10^{-2}
Cladding	8.7250×10^{-2}
<u>Outer followers</u>	
Poison region	
Boron	2.6667×10^{-4}
Stainless steel	8.6810×10^{-2}
Cladding	8.7250×10^{-2}

Table C.4. MH-1A Core Axial Leakage, 68°F

Group	Leakage, $\text{DB}^2, \text{cm}^{-1}$
1	2.28861×10^{-3}
2	1.30219×10^{-3}
3	7.18110×10^{-4}
4	5.40783×10^{-4}
5	3.77403×10^{-4}
6	2.47335×10^{-4}
7	2.93548×10^{-4}
8	-1.66293×10^{-4}
9	-4.76483×10^{-4}

APPENDIX D

Disadvantage Factors for Control Rods and Followers

For homogenized regions in which an energy-dependent "region flux" exists, the correct reaction rate in an individual nuclide was obtained by weighting the cross section with a disadvantage factor, defined as

$$\frac{\bar{\phi}_{\text{nuclide}}}{\bar{\phi}_{\text{region}}} .$$

In this study the control rods and followers were homogenized with the fuel, cladding, and moderator in R-Z geometry. The thermal disadvantage factors for the control rods and followers were determined from THERMOS. The epithermal disadvantage factors may be obtained by use of the Carlson S_n , Monte Carlo, or some equivalent method of calculation. For the MH-1A reactor, a previous study¹ had used the S_n method to calculate 4-group disadvantage factors for the reference control rod and fuel-lattice design with a slightly higher fuel enrichment. These results were combined with the THERMOS results to plot disadvantage factor vs energy for the control rods and followers at 490° and 68°F. Disadvantage factors for the various energy groups were then taken from these curves and used in the R-Z calculations. The uncertainty in these factors was estimated to be about 3% in groups 1-4, 10-15% in groups 5 and 6, and 5% in groups 7-9. A tabulation of disadvantage factors used in this study is given in Table D.1.

¹E. E. Gross, M. L. Winton, "Nuclear Analysis of the MH-1A Reactor," USAEC Report ORNL-TM-714, Oak Ridge National Laboratory, April 1964.

Table D.1. MH-1A Disadvantage Factors, $\bar{\phi}/\phi_{\text{Fuel-Moderator}}$, for Control Rods and Followers

Group	Energy Range, ev	Control Rods ^a		Outer Followers ^a		Inner Followers ^a	
		490°F	68°F	490°F	68°F	490°F	68°F
1	0.821 x 10 ⁶ –1 x 10 ⁷	0.95	0.93	0.88	0.84	0.87	0.88
2	6 x 10 ⁴ –0.821 x 10 ⁶	0.87	0.86	0.91	0.89	0.91	0.91
3	5 x 10 ³ –6 x 10 ⁴	0.80	0.80	0.95	0.93	0.94	0.94
4	450–5 x 10 ³	0.72	0.72	1.00	0.97	0.98	0.98
5	35–450	0.60	0.57	1.05	1.02	1.01	1.00
6	1.86–35	0.320	0.275	0.99	1.00	0.95	0.93
7	0.55–1.86	0.1100	0.1132	0.9026	0.9079	0.8486	0.8536
8	0.08–0.55	0.04250	0.04404	0.9562	0.9190	0.7968	0.7790
9	0.005–0.08	0.01765	0.01706	0.9305	0.9444	0.6748	0.6708

^aControl rods: 2.1 w/o B (92 a/o B¹⁰) in stainless steel.

Inner followers: 0.16 w/o B_{nat} in stainless steel.

Outer followers: 0.06 w/o B_{nat} in stainless steel.

APPENDIX E

Poison-Length Correction

The ratio of the reactivity worth of the actual poisoned length (27 in.) to the reactivity worth that would exist if the entire 36-in. length of follower were poisoned is estimated below. This correction factor was used in X-Y geometry with control rods withdrawn.

With control rods out, the axial neutron flux across the core height should be very nearly in a chopped cosine distribution, corresponding to the solution of the wave equation

$$\nabla^2 \phi + B^2 \phi = 0 .$$

Taking $B^2 = (\frac{\pi}{H + 2\delta})^2$, where $\delta \approx 0.06H$ and ignoring spectrum effects, flux perturbations, and other details, the reactivity worth of a perturbation in boron cross section $\delta\Sigma_a$ of the lower 9 in. of the core relative to the worth of 36 in. of boron is approximately,

$$\frac{\int_{H/4}^{H/2} \delta\Sigma_a \cos^2 \frac{\pi x}{1.12H} dx}{\int_{-H/2}^{H/2} \Sigma_a \cos^2 \frac{\pi x}{1.12H} dx} .$$

Setting $\delta\Sigma_a = \Sigma_a$ and taking Σ_a out of the integrals, the reactivity worth of 27 in. of poison relative to the worth of 36 in. is then

$$1 - \frac{\int_{H/4}^{H/2} \cos^2 \frac{\pi x}{1.12H} dx}{\int_{-H/2}^{H/2} \cos^2 \frac{\pi x}{1.12H} dx} = \frac{\int_{-H/2}^{H/4} \cos^2 \frac{\pi x}{1.12H} dx}{\int_{-H/2}^{H/2} \cos^2 \frac{\pi x}{1.12H} dx} = 0.88 ,$$

which is in good agreement with the value of 0.87 calculated by Martin Company. Further verification was obtained from calculations in R-Z geometry with control rods out which indicated an approximate cosine flux shape. Graphical integration of a plot of $(\text{flux})^2$ vs axial distance for the various broad group fluxes gave values for the length correction which were close to 0.87.

It should be noted that the core reactivity is only weakly dependent on the value of this correction factor; a 10% error in the correction factor of 0.87 causes a change in k of only about 0.002. An accurate calculation of the length correction factor does not warrant much effort.

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