WCAP - 7113

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USE OF BURNABLE POISON PODS IN WESTINGHOUSE PRESSURIZED WATER REACTORS

October 1967

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USE OF BURNABLE POISON RODS IN WESTINGHOUSE PRESSURIZED WATER REACTORS

1. INTRODUCTION AND SUMMARY

Burnable poison rods will be added to the core to eliminate a positive moderator reactivity temperature coefficient at operating temperature conditions during the initial portion of the first fuel cycle. With the addition of the burnable poison rods the spatial power distribution will be stable with respect to azimuthal and diametral xenon oscillations, and moderator reactivity addition that could otherwise occur in the event of a loss of coolant or rod ejection accident during the early portion of the first core cycle will be eliminated lessening the severity of these accidents.

The burnable poison rods will be in the form of borated pyrex glass tubes clad in stainless steel. There will be approximately 1144 of these rods grouped in clusters which will be distributed throughout the core in vacant rod cluster control guide tubes. These rods will initially control about 7.2% $\frac{\Delta k}{k}$ of the installed excess reactivity and their addition will result in a reduction of the initial operating boron concentration in the coolant to 1200 ppm. The moderator coefficient is negative at this boron concentration with the burnable poison rods installed. The poison is depleted as the core accumulates burn up during operation. The poison depletion rate is sufficiently slow that the boron requirement in the coolant and hence the moderator temperature coefficient will be less than their initial values throughout the entire initial cycle. In succeeding cycles, the core boron requirement is less due to the partially depleted fuel loading and the poison rods are not required to maintain the moderator coefficient negative and will be removed.

The following paragraphs describe the evaluation and development of the preliminary design for the poison rods. The numerical calculations presented in Sections 3.1 and 3.2 were performed with initial enrichments of 2.25, 2.8, and 3.42 wt% U-235. Since these calculations were performed, the enrichments have been changed to 2.2, 2.7,and 3.2 wt% U-235 as a result of recent data from operating reactors. The effect of this change will be a 3% increase in flux level and a reduction of initial boron concentration from 1300 ppm to 1200 ppm which will make the moderator temperature coefficient 0.1×10^{-4}/°F more negative. The net result of this change should improve stability.

2. RESEARCH AND DEVELOPMENT

An evaluation of nuclear requirements and material properties for the burnable poison rods has been completed and borosilicate glass has been selected as the reference design burnable poison material.

A series of critical experiments has been performed at the Westinghouse Reactor Evaluation Center to evaluate the reactivity worth and effect on power distribution of borosilicate glass. The experiments were performed using 2.72% enriched UO_2 clad in Zircaloy. The reactivity worth was measured for solid glass rod and two thicknesses of glass tubing, for several ratios of glass to fuel. [redacted]e fuel element configuration with glass rods was simulated in the critical experiments and the power distribution measured.

These experiments are presently being evaluated to test the adequacy of calculational techniques. Each critical loading will be calculated using two dimensional diffusion theory with methods identical to those used in the core design. Preliminary results from the evaluation of the experiments indicate that the design methods predict the reactivity worth of the glass to within 0.1% Δk_{eff}.

The configuration and mechanical design of the poison rod has been selected. A program for in-pile testing two of the rods in the Saxton Reactor has been initiated to verify mechanical performance of the burnable poison material and rod configuration in a power reactor environment.

3 REACTOR

3.1 DESIGN BASIS

The function of the burnable poison rods is to absorb neutrons which would otherwise be absorbed by soluble poison in the coolant. In effect, the poison rods will "control" a portion of the excess reactivity normally "controlled" by the boric acid in the coolant and the boric acid requirement will be less. The result will be that changes in density of the coolant will have less effect on the density of poison and the moderator reactivity temperature coefficient will be reduced. The details of the quantity, com-position, location, and structure of the burnable poison rods will satisfy the following limits on the design.

a) The moderator temperature coefficient of reactivity will be negative at operating coolant temperature.

b) Induced aazimuthal and diametral xenon oscillations will be damped.

c) Power distribution, shutdown margin, fuel and clad temperature, and minimum DNB ratio will be within the design limits previously established.

d) Materials, construction, and support of the poison rods will insure integrity of the poison rods for both normal operating conditions, and accident conditions.

e) The poison rods will be held down in place by a spider assembly compressed beneath the upper core plate to ensure that they cannot be lifted out of the core by flow forces.

Table I summarizes design and operating characteristics of the burnable poison rods.

Xenon Oscillations in the X-Y Plane (Diametral and Azimuthal Oscillations)

Because the coolant flow is transverse to the X-Y plane, changes in the moderator temperature distribution influence the stability of the core to xenon oscillations in the X-Y plane. As the power shifts to one side of the core the average temperature in that side increases. If the moderator temperature coefficient of reactivity is negative this results in a negative feedback which tends to stabilize the power distribution. On the other hand, if the moderator temperature coefficient is positive, the feedback is destabilizing and the core is more subject to oscillations.

An extensive program sponsored by the AEC and Euratom (AEC Contract AT(30-1)-3680) has been initiated to develop methods for the control of xenon instabilities in large PWR's. Methods to incorporate the effects of coolant temperature distribution into a two dimensional calculation are being developed. As a survey tool a relatively simple one-dimensional method has been developed to investigate the effect of variables on stability. This one-dimensional model has been compared to two dimensional cases and gives a conservative result.

TABLE I

PRELIMINARY DESIGN AND OPERATING CHARACTERISTICS OF BURNABLE POISON ROD CORE

Mechanical Design	
Borosilicate Glass - Composition (wt%)	SiO_2-80.5, Al_2O_3-2.2, Na_2O-3.8, K_2O-0.5, B_2O_3-[redacted]
I.D.	[redacted]
O.D.	[redacted]
Length	[redacted]
External Clad	
I.D.	.4005
O.D.	.4395
Internal Support Clad	
I.D.	.2235
O.D.	.2365
Guide Thimble	
I.D.	.515
O.D.	.545
Total Number of Poison Rods	1128
Poison Rod Location (See Figs. 3-5 and 3-6)	
Poison Rods per Assembly	6, 12, 16
Nuclear Design	
Poison Rod Boron Content ([redacted]	[redacted]
Initial Worth of Poison Rods-hot full power (% Δk/k)	7.2
Initial worth of single poison rod (% Δk/k)	.007
Initial worth of single poison rod cluster (% Δk/k)	.11
Poison Rod Depletion Rate (See Fig. 3-9)	
Moderator Reactivity Temperature Coefficient (at power)	-0.5×10^{-4} to -3×10^{-4} °F^{-1}
Initial Moderator Boron Requirements	1200 ppm
First Cycle Enrichments (wt% U-235)	2.2, 2.7, 3.2

TABLE I (Cont'd)

Installed Reactivity	K_{eff} Without Poison Rods	K_{eff} With Poison Rods
Cold, No Power	1.291	1.225
Hot, No Power	1.244	1.172
Hot, Full Power	1.220	1.148
Hot, Full Power, Xe and Sm	1.178	1.106

Rod Thermal Design

Average B_{10} (n, α) reaction heating (kw/ft)	0.467
Peak B_{10} (n, α) reaction heating (kw/ft)	1.32
Average gamma heating (watts/gm)	1
Peak gamma heating (watts/gm)	3
Peak glass temperature (°F)	1190

Summary of Operating Clad Stress and Pressure for Burnable Poison Rods	Beginning of Life	End of Life
Primary Pressure Stress, psi	-24,870	2650
Secondary Pressure Stress, psi	±7610	±440
Maximum Pressure Stress, psi	-32,480	-3090
Thermal Stress, psi	1280	380
Operating Differential Pressure, psi	-2250	-240
Critical Buckling Differential Pressure, psi	-4650	-4650
Safety Factor Based on Buckling	2.07	11.34

The calculational method assumes a one dimensional slab core having the same physical width as the diameter of the actual core and with a fuel enrichment distribution to give a flattened power distribution. The flux and power distribution in the core is calculated using FAB-8, a two group diffusion theory code. The fuel temperature coefficient (doppler effect) is taken into account by adjusting the fast absorption cross section at each point in the mesh to correspond to the relative power at that point. The calculation is iterative with the Doppler correction recalculated until a convergent solution is obtained. Similarly, the effects of water density are taken into account by adjusting the nuclear constants at each point to correspond to the relative enthalpy at that point. The coolant density and effects of xenon-135 and iodine-135 are calculated at each mesh point.

To study the stability of the core, a perturbation is introduced at one side of the core by adding a fixed poison equivalent to one control rod and letting the perturbed core operate for 1 hour to redistribute the xenon. The perturbation is then removed and the power shape in the reactor is calculated at two or three hour time intervals, with the feedbacks from moderator temperature, xenon, and Doppler effects included. The results of the calculations with the two-three hour time steps are corrected back to a zero time step using the results of Poncelet, et. al.[1]

It is possible to adjust the moderator temperature coefficient in the calculation by adjusting the fixed absorption cross section of the core and letting the code search for a critical boron concentration.

The behavior of the diametral hot channel factor as a function of time after the perturbation is shown in Figure 3-1 for the case of a core with a positive moderator temperature coefficient ($\alpha_m = 0.10 \times 10^{-4}/°F$) and

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(1) Poncelet, C. G., Christie, A. M., "The Effect of Finite Time Step on Calculated Spatial Stability Characteristics," Trans. Am. Nuc. Soc., Vol. 10, No. 2, 1967.

in Figure 3-2 for the case of a negative moderator coefficient (α_m = -0.35 x 10^{-4}/°F) at 3250 Mwt. Note that the core with the negative coefficient shows convergent oscillations while the core with the positive coefficient shows divergent oscillations.

The damping factor is shown as a function of moderator temperature coefficient in Figure 3-3 for two power densities, 84.5 kw/liter equivalent to 2758 MWt and 99.6 kw/liter equivalent to 3250 MWt.

The threshold of stability is α_m = -0.07 x 10^{-4}/°F for the 3250 MWt power level and +0.4 x 10^{-4}/°F for the 2758 MWt power level.

The damping factor, b, is defined by the equation:

$$P(t) = P_o + Ae^{b(t-t_o)/T} \sin \omega(t-t_o)$$

where:

P_o = unperturbed $F_{\Delta h}$

$P(t) = F_{\Delta h}(t)$

T = period

ω = angular frequency

t = time

b is negative for convergent oscillations and positive for divergent oscillations.

The program to study the X-Y xenon oscillation problem is still in progress but the one dimensional result, demonstrates the dependence of the stability of the core to diameteral oscillations on the moderator reactivity temperature coefficient. Hence, the burnable poison rods will be incorporated in the core during the first cycle to improve stability.

The moderator coefficient of reactivity in the second and subsequent cycles is sufficiently negative to ensure stability.

3.2 REACTOR DESIGN

3.2.1 Nuclear Design and Evaluation

After a review of the elements available for use as burnable poison, it was concluded the boron was the most desirable for this application. Self-shielded Gadolinium was investigated as a possibility, but it was concluded that the rapid decrease of its cross section in the thermal region gives rise to a positive moderator coefficient contribution that more than offsets the improvement obtained by lowering shim boron concentration. The incorporation of boron or its compounds in the UO_2 fuel was investigated and found not to be practical with normal manufacturing practice. It was concluded that the most straightforward way of incorporating burnable poison in the core is to clad some boron containing material in rods and to introduce these rods into the RCC water holes not used by the RCC assemblies. Borosilicate (Pyrex) glass has been selected as the reference design burnable poison material.

A study was performed to select a boron loading which would provide a suitably negative moderator temperature coefficient with the number of burnable poison rods and the fuel cost penalty from residual poison as variables. A boron loading of 0.043 [redacted] length was selected as near optimum. The moderator temperature coefficient of reactivity for the initial core at 572.9°F was calculated as a function of the number of burnable poison rods in each of 96 fuel assemblies (a checkerboard pattern) and is shown in Figure 3-4. The coolant boron concentration was adjusted to keep the reactor just critical. Since the burnable poison rods act as leakage surfaces, the effect on the moderator temperature coefficient is greater than the effect that would have been anticipated from the reduction in shim boron alone. The reduction in moderator coefficient from shim boron reduction alone is shown in Figure 3-4.

With the borosilicate glass (Pyrex) as burnable poison, a boron loading [redacted] length is feasible since Pyrex [redacted]. Since the B_2O_3 is in soolution in the glass, it is homogeneous and particle self-shielding is not a factor.

Power Distribution Studies

From the results of the temperature coefficient studies, a burnable poison loading of approximately 12 rods in every other fuel assembly was chosen. A series of two dimensional (PDQ) calculations of the power distribution was made to find an arrangement that resulted in a satisfactory radial hot channel factor. The final arrangement is shown in Figure 3-5. In this figure, the numbers represent the number of burnable poison rods in the assembly. The location of these rods in the water holes of the assemblies are shown in Figure 3-6. In 24 fuel assemblies, 16 burnable poison rods were used to depress local peaking. In the fuel assemblies at the edges of the core only 6 burnable poison rods were used. The initial assembly-wise power distribution in the core is shown in Figure 3-7. The calculated radial peaking factor ($F_{\Delta H}^{N}$) is 1.314 compared to the design value of 1.58. The reactivity held down by the burnable poison is 7.2% $\Delta k/k$.

Moderator Temperature Coefficient

The moderator temperature coefficient at 572.9°F was calculated using a two dimensional diffusion code (PDQ), for the arrangement shown in Figure 3-5. The hot, operating coolant boron concentration was 1300 ppm. The calculated value of the coefficient was -0.62×10^{-4}/°F. This value is slightly more negative than the uniform array results presented in Figure 3-4, primarily because the assemblies that have 16 burnable poison rods are in a more important part of the core from a nuclear standpoint. The design value of the moderator temperature coefficient with the burnable poison rods is -0.5×10^{-4}/°F at full power.

Depletion Studies

The behavior of the core with burnable poison during the first cycle has been calculated using the two dimensional depletion code TURBO*. The core was described with a two dimensional array of approximately 7500 mesh points. The fuel isotopic composition and burnable poison concentration are calculated pointwise as a function of burnup. The power distribution in the core was recalculated at 1000 MWD/MT intervals during the first 5000 MWD/MT and then at 2000 MWD/MT intervals. The burnable poison self-shielding factor was changed as a function of burnup.

The coolant boron concentration is shown as a function of burnup in Figure 3-8. The boron concentration drops from an initial value of 1300 ppm to 960 ppm as Xenon-135 builds up. The coolant boron concentration stays relatively constant for 4000 MWD/MT and then decreases nearly linearly.

The concentration of boron in the burnable poison rods is shown in Figure 3-9 as a function of fuel burnup. The average B-10 concentration decreases by a factor of 10 in 10,000 MWD/MT and the residual B-10 at the end of the cycle is only 1/30 of the initial value.

Since the neutron flux at the center of the core is higher than in the outer region, the burnable poison is depleted more rapidly at the center. This causes some redistribution of power toward the center of the core during the early part of the first cycle. The calculated radial hot channel factor ($F_{\Delta H}^{N}$) increases from 1.32 to 1.48 during the first 1000 MWD/MT and then decreases gradually to 1.30 at 4000 MWD/MT. The effects of the fuel temperature coefficient on power distribution were neglected in this calculation and would tend to reduce the calculated radial hot channel factor to 1.42.

Effect of Burnable Poison Addition on Other Design Parameters

Because the coolant boron conccentration is decreased, the rod worth increases slightly. With burnable poison rods, the initial coolant boron requirement is 1300 ppm and the 53 control rods are worth 8.5% as compared to an initial boron requirement of 1960 ppm and 53 control rod worth of 8% without burnable poison rods. At the end of the cycle there is no difference and the control rods are worth 8%.

Since this study was performed the enrichments in the three regions have been changed to 2.2, 2.7, and 3.2 wt% U-235 and the initial boron concentration reduced to 1200 ppm. The corresponding multiplication factors with and without the burnable poison are tabulated in Table I.

3.2.2 Thermal and Hydraulic Design and Evaluation

The core hot spot initially occurs near the core center with the poison rod loading and shifts outward as the poison rods deplete. The hot channel factors and minimum DNB ratio remain within values given in the PSAR. The overall effect of the poison rod addition on coolant flow distribution and core pressure drop is not significant.

The gamma and (n,α) reaction in the poison rods will result in a peak heat generation rate of 1.32 kw/ft. in the poison rods. This heat generation rate will decrease as the poison rod B_{10} depletes. The coolant flow for cooling the poison rods is provided by the flow annulus between the rod and the guide thimble and the exit coolant temperature is maintained below system saturation temperature. The peak temperature in the glass occurs on initial rise to power. Figure 3-10 shows the initial peak axial temperature distribution in the peak poison rod. The Pyrex temperature will decrease rapidly for the following reasons: less power generation due to B_{10} depletion; better gap conductance as He produced diffuses to gas gap; and decreasing external gap due to creep of the Pyrex.

Test specimens of borosilicate glass irradiated at KAPL (Ref. 1) show evidence of high diffusivity of the He generated (greater than 80% He release). Sufficient void has been designed into the poison rod inner cylinder to maintain internal pressure less than external pressure. Assuming complete release of the He generation the calculated internal pressure at end of exposure is approximately 2000 psi.

3.2.3 Mechanical Design and Evaluation

In the reactor cores, the burnable poison rods would be statically suspended and positioned in vacant RCC thimble tubes within the fuel assemblies at nonrodded core locations. The poison rods in each fuel assembly would be grouped and attached together at the top end of the rods by a flat spider plate which fits with the fuel assembly top nozzle and rests on the top adaptor plate. The spider plate (and the poison rods) are held down and restrained against vertical motion through a spring pack which is attached to the plate and is compressed by the upper core plate when the reactor upper internals package is lowered into the reactor. This ensures that the poison rods cannot be lifted out of the core by flow forces.

In construction, the poison rods will consist of pyrex glass tubes contained within type 304 stainless steel tubular cladding which is plugged and seal welded at the ends to encapsulate the glass. The glass will also be supported along the length of its inside diameter by a thin wall type 304 stainless steel tubular inner liner. A typical burnable poison rod is shown in longitudinal and transverse cross-sections in Figure 3-11.

The rods have been designed in accordance with the standard fuel rod design criteria; i.e., the cladding will be free standing at reactor operating pressures and temperatures and sufficient cold void volume has been provided within the rods to limit internal pressures to less than the reactor operating pressure assuming total release of all helium generated in the glass as a result of the B_{10} (n,α) reaction. The large void volume required for the helium is obtained through the use of glass in tubular form which provides a central void along the length of the rods. The resulting clad stresses at temperature and pressure are given in Table I. With the selected clad diameter and wall thickness the maximum net external pressure that the cladding can withstand is limited by the elastic stability of the tubing.

The critical buckling pressure as established by the elastic stability and the corresponding factor of safety in the clad design based on the net external pressure imposed on the cladding at operating conditions is also listed in Table I.

Based on available data on properties of Pyrex glass and on nuclear and thermal calculations for the rods, gross swelling or cracking of the glass tubing is not expected during operation. Some minor creep of the glass at the hot spot on the inner surface of the tube is expected to occur but will continue only until the glass comes into contact with the inner liner. The inner liner is provided to maintain the central void along the length of the glass and to prevent the glass from slumping or creeping into the void as a result of softening at the hot spot. The wall thickness of the inner liner is sized to provide adequate support in the event of slumping but to collapse locally before rupture of the exterior cladding if large volume changes due to swelling or cracking should possibly occur. The top end of the inner liner is open to receive the helium which will diffuse out of the glass.

To ensure the integrity of the burnable poison rods, the tubular cladding and end plugs will be procurred to the same specifications and standard of quality as used for stainless steel fuel rod cladding and end plugs. In addition, the end plug seal welds will be checked for integrity by visual inspection and x-ray and the finished rods will be helium leak checked.

4. SAFETY ASPECTS

Analyses of the hypothetical double ended coolant loop rupture loss of coolant accident show that the safety injection system will meet its design criterion of no clad melting with a slightly positive moderator reactivity temperature coefficient. Hence the design coefficient of $-0.5 \times 10^{-4}/°F$ with the burnable poison rods assures margin in clad temperature in meeting this criteria. Similarly the design coefficient is sufficiently negative that any unexpected azimuthal or diametral xenon oscillation would be damped and the radial hot channel factor will remain within design values.

The burnable poison rods are positively positioned in the core inside RCC assembly guide thimbles and held down in place by attachment to a spider assembly compressed beneath the upper core plate and hence cannot be the source of any reactivity transient. Due to the low heat generation rate, and the conservative design of the poison rods there is no possibility for release of the poison as a result of helium pressure or clad heating during accident transients including loss of coolant.

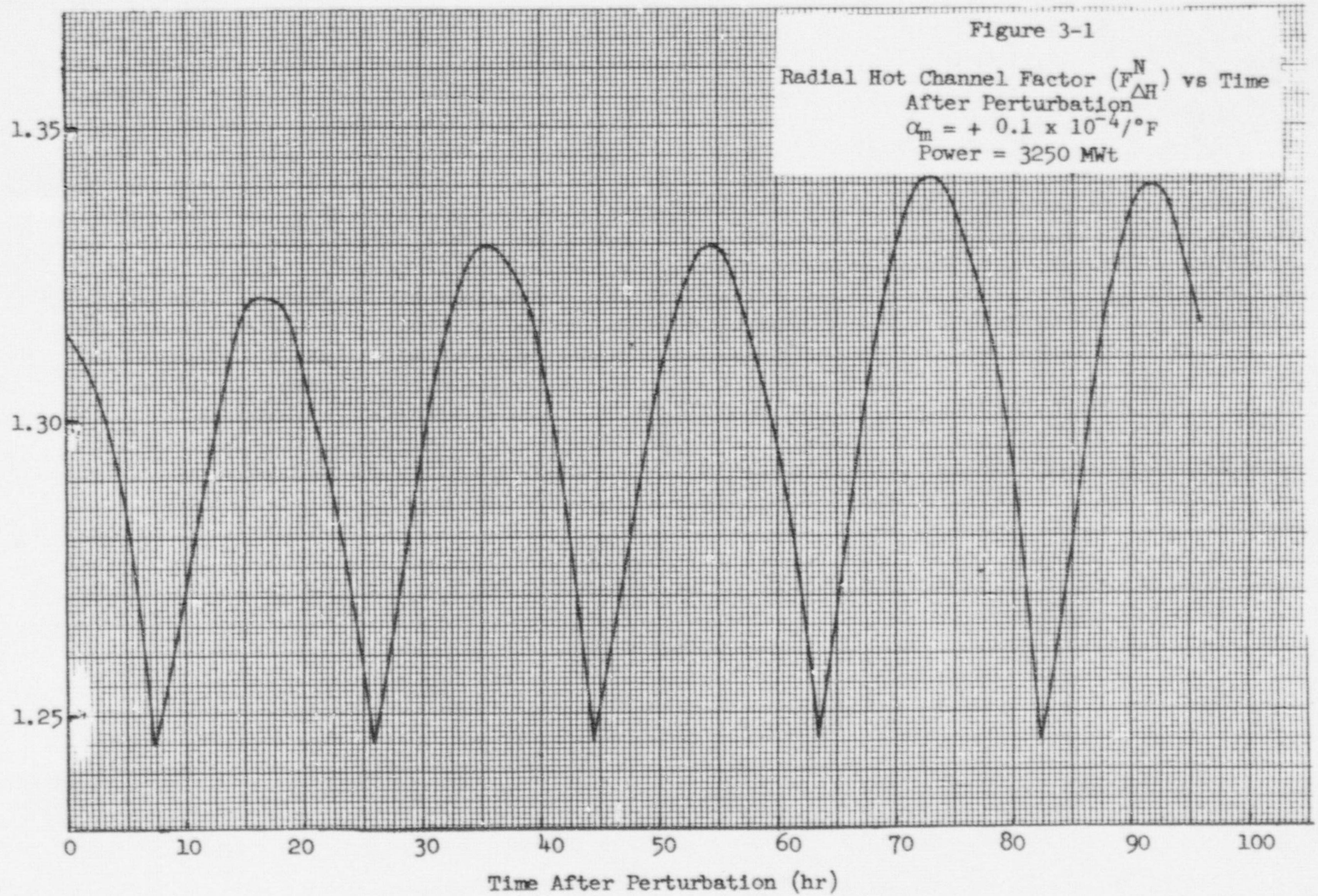


Figure 3-1

Radial Hot Channel Factor ($F^N_{\Delta H}$) vs Time After Perturbation

$\alpha_m = + 0.1 \times 10^{-4}/°F$

Power = 3250 MWt

FIGURE 3-1

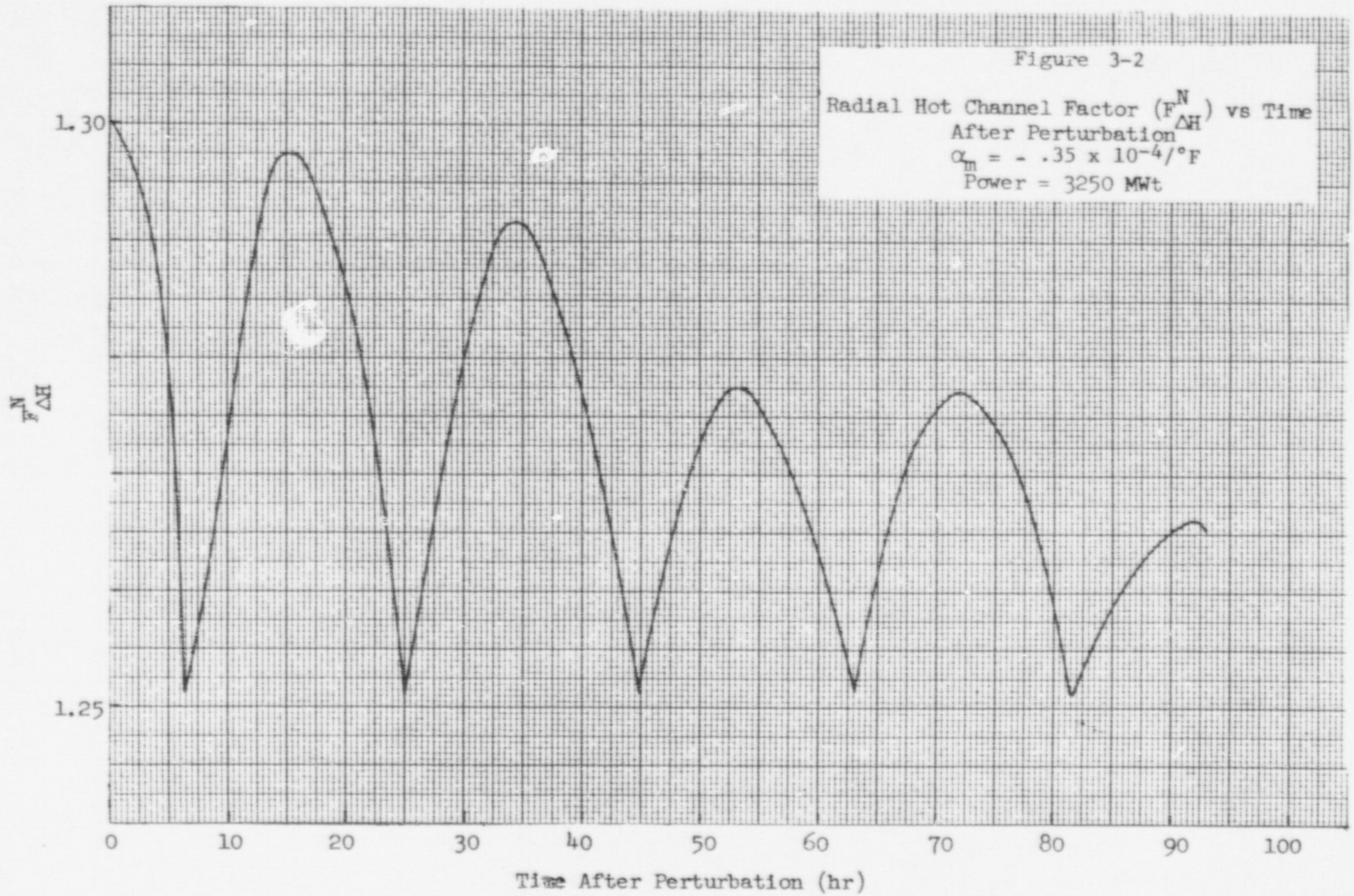
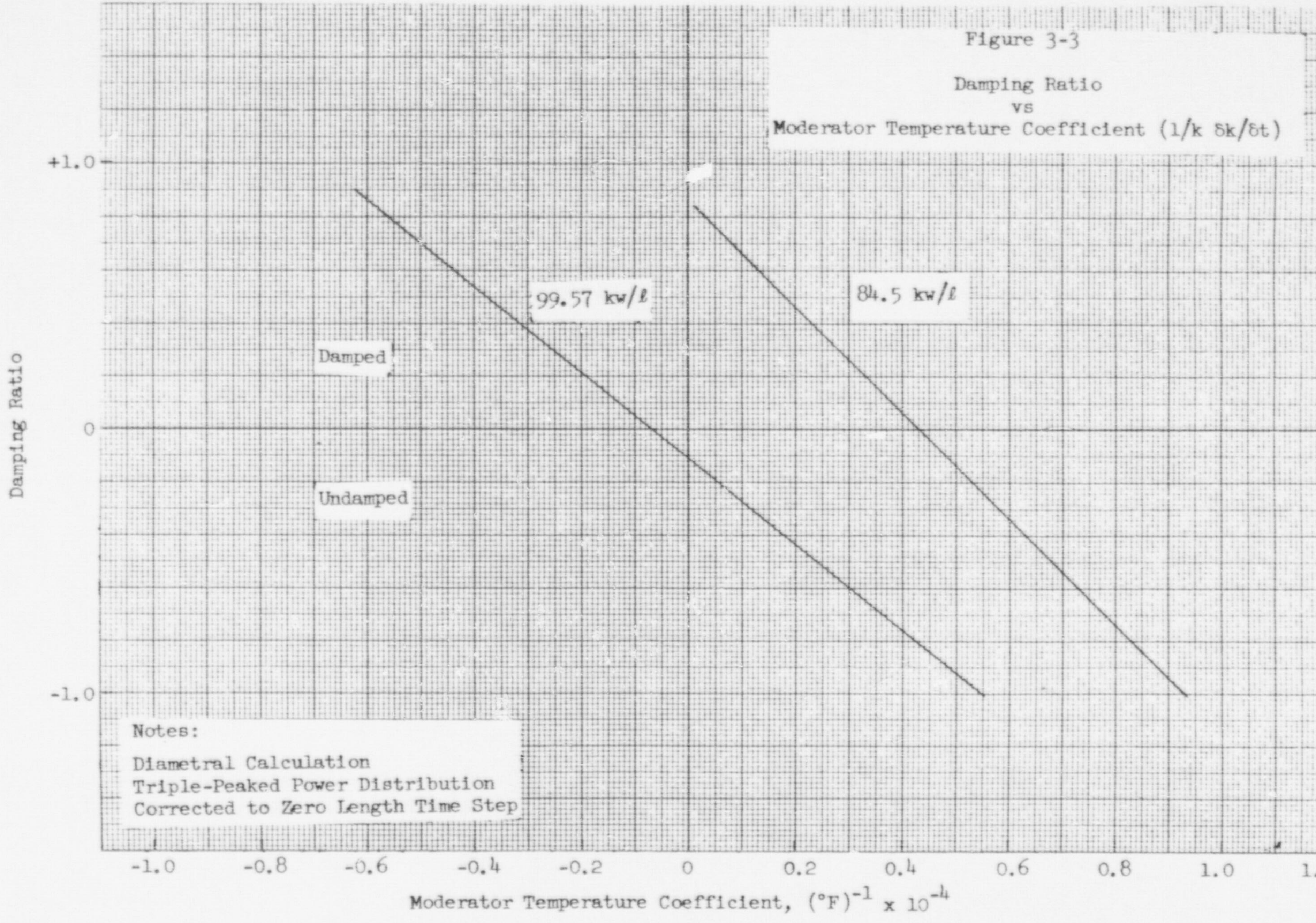


Figure 3-2
Radial Hot Channel Factor ($F^N_{\Delta H}$) vs Time After Perturbation
α_m = - .35 x 10^{-4}/°F
Power = 3250 MWt
1.30
1.25
$F^N_{\Delta H}$
0
10
20
30
40
50
60
70
80
90
100
Time After Perturbation (hr)

FIGURE 3-2

Figure 3-3

Damping Ratio
vs
Moderator Temperature Coefficient (1/k δk/δt)



Notes:

Diametral Calculation
Triple-Peaked Power Distribution
Corrected to Zero Length Time Step

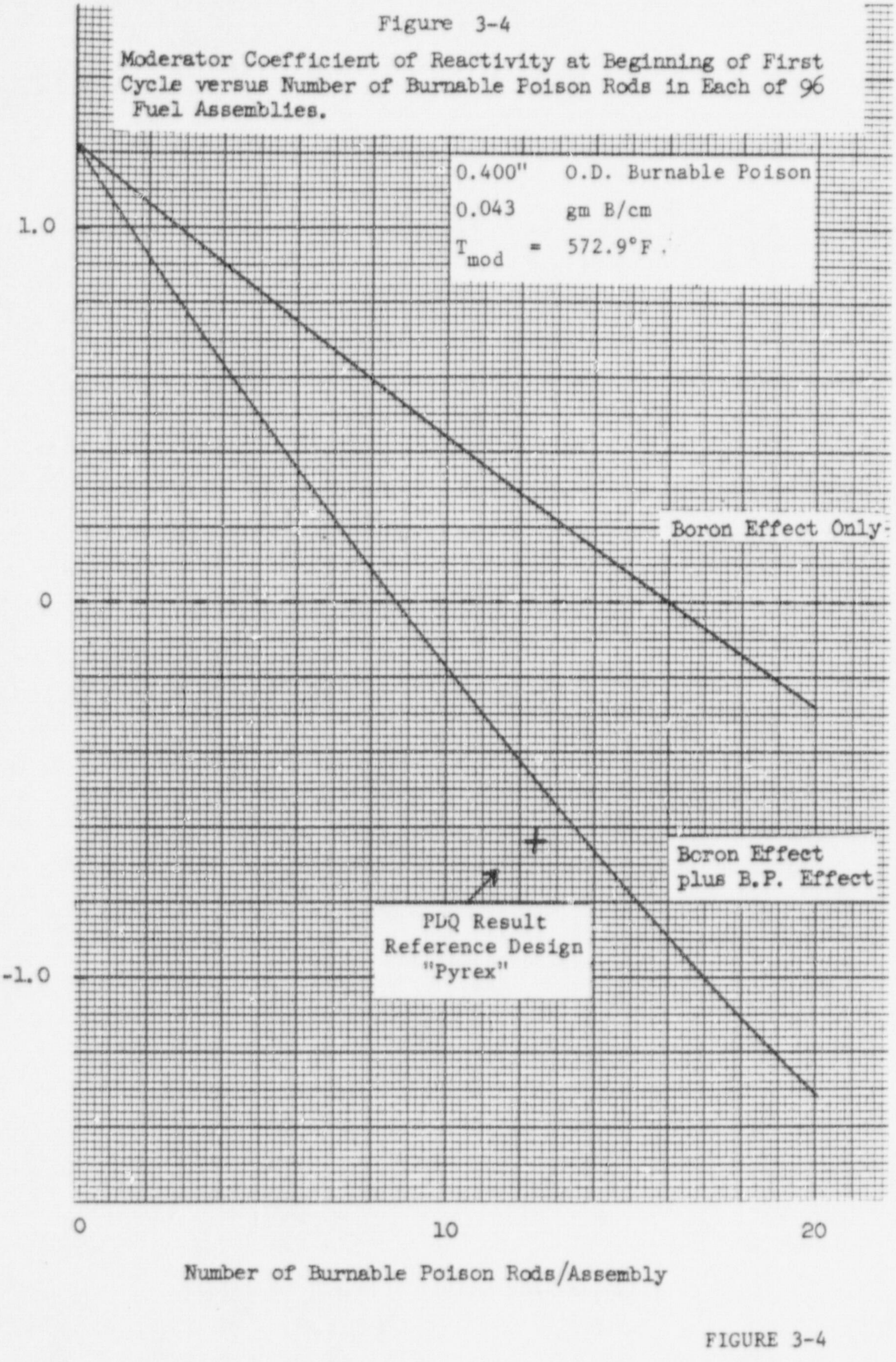


Figure 3-4
Moderator Coefficient of Reactivity at Beginning of First Cycle versus Number of Burnable Poison Rods in Each of 96 Fuel Assemblies.
0.400" O.D. Burnable Poison
0.043 gm B/cm
T mod = 572.9°F
1.0
0
-1.0
1/K dK/dT mod x 10^4 (/°F)
Boron Effect Only
Boron Effect plus B.P. Effect
PLQ Result Reference Design "Pyrex"
0
10
20
Number of Burnable Poison Rods/Assembly

FIGURE 3-4

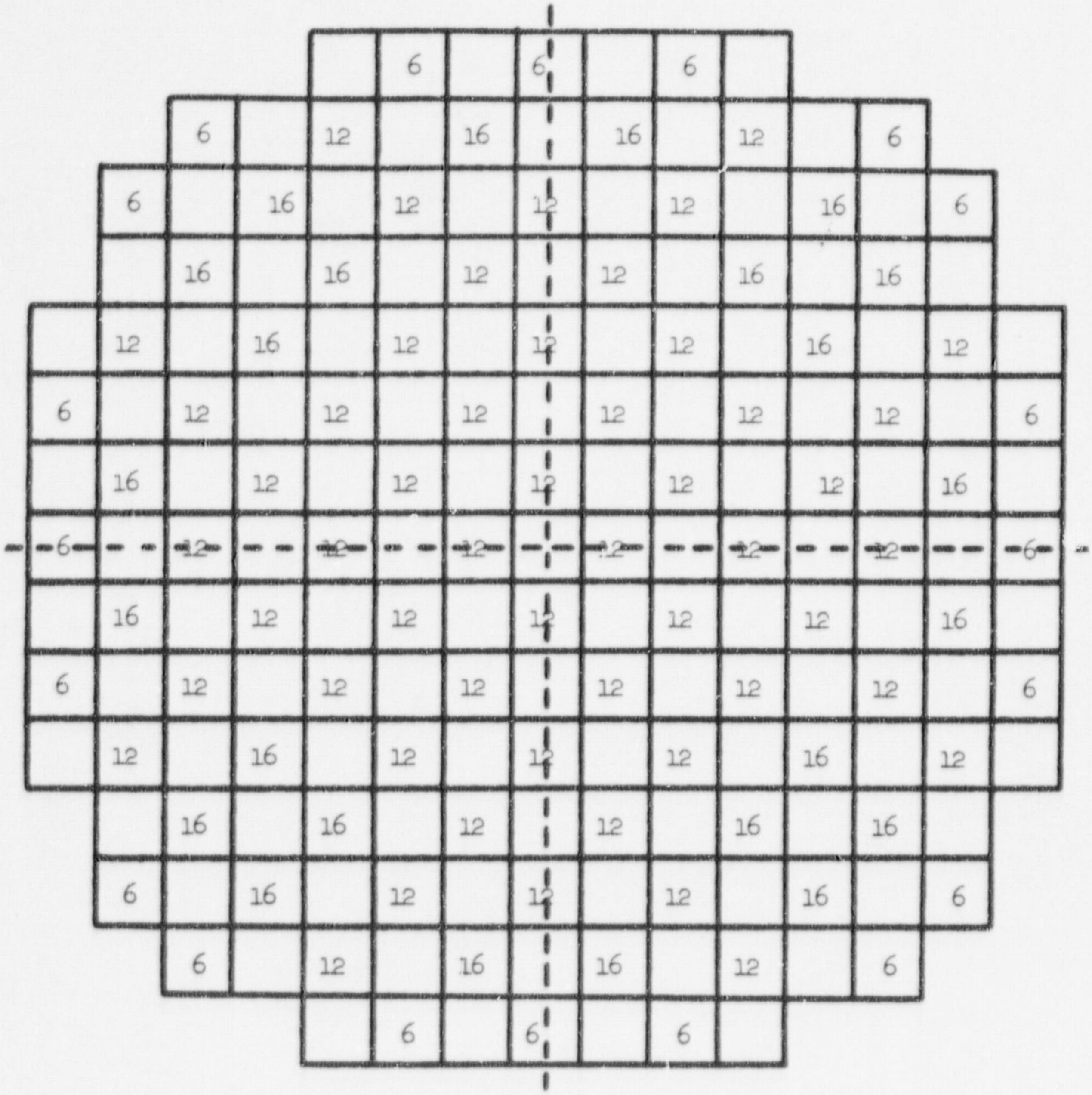
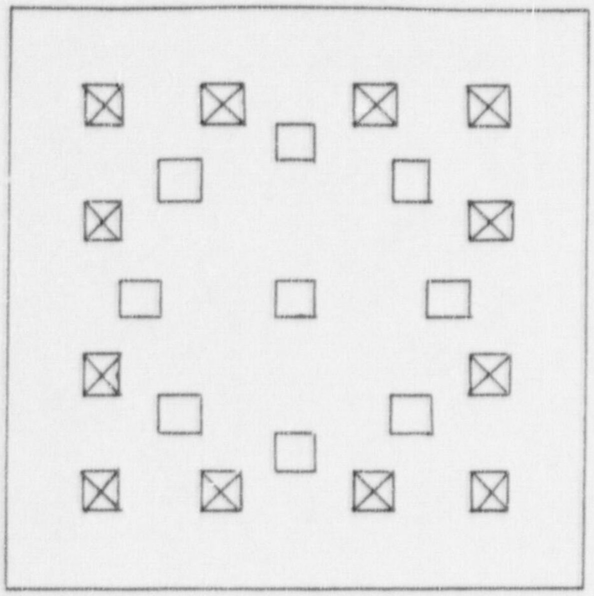


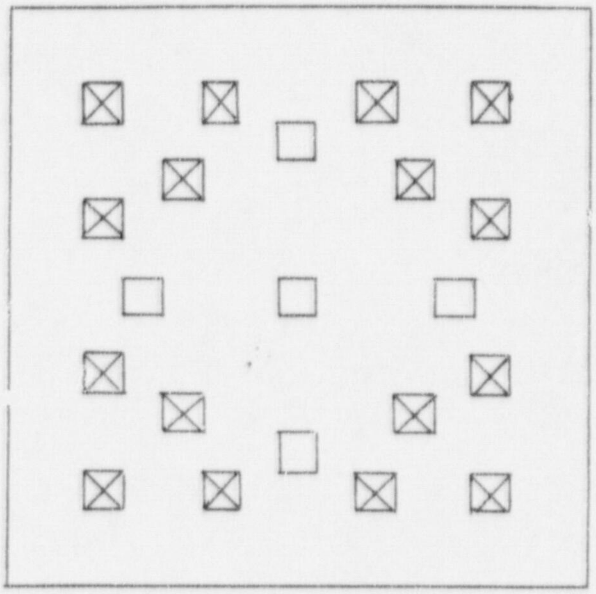
Figure 3-5

Distribution of Burnable Poison Rods - Number of B. P. Rods per Assembly

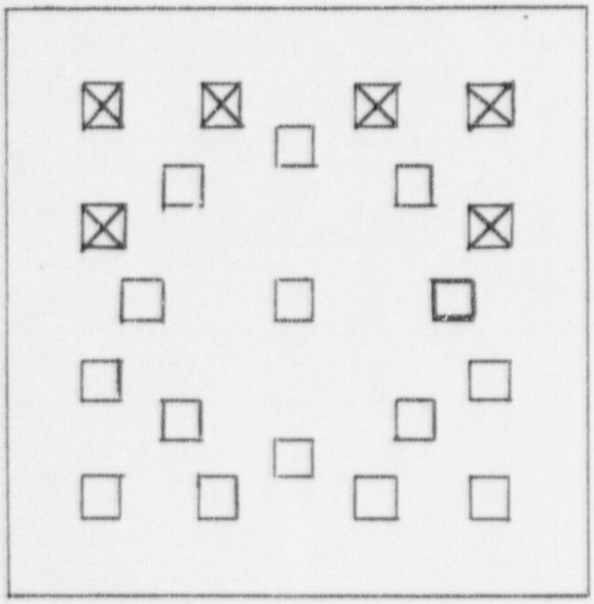
FIGURE 3-5



A. 12 Burnable Poison Rods



B. 16 Burnable Poison Rods



C. 6 Burnable Poison Rods

Note: x denotes burnable poison rods

Figure 3-6

Location of Burnable Poison Rods in Fuel Assemblies

1.244 x	F						
1.206	1.229						
1.216	1.176	1.177					
1.158	1.173	1.104	1.070				
1.155	1.111	1.084	0.962	1.150			
1.096	1.105	1.031	0.995	0.882	1.048		
1.046	1.100	0.968	0.949	0.867	0.548		
0.836	0.891	0.739	0.590				

Figure 3-7

Assemblywise Power Distribution
Burnup = 0 MWD/MT
Shim Boron = 1300 ppm
$F^{n}_{\Delta h}$ = 1.314

Figure 3-8

First Cycle Shim Boron versus Burnup with Burnable Poison

E = 2.25, 2.8, and 3.42%

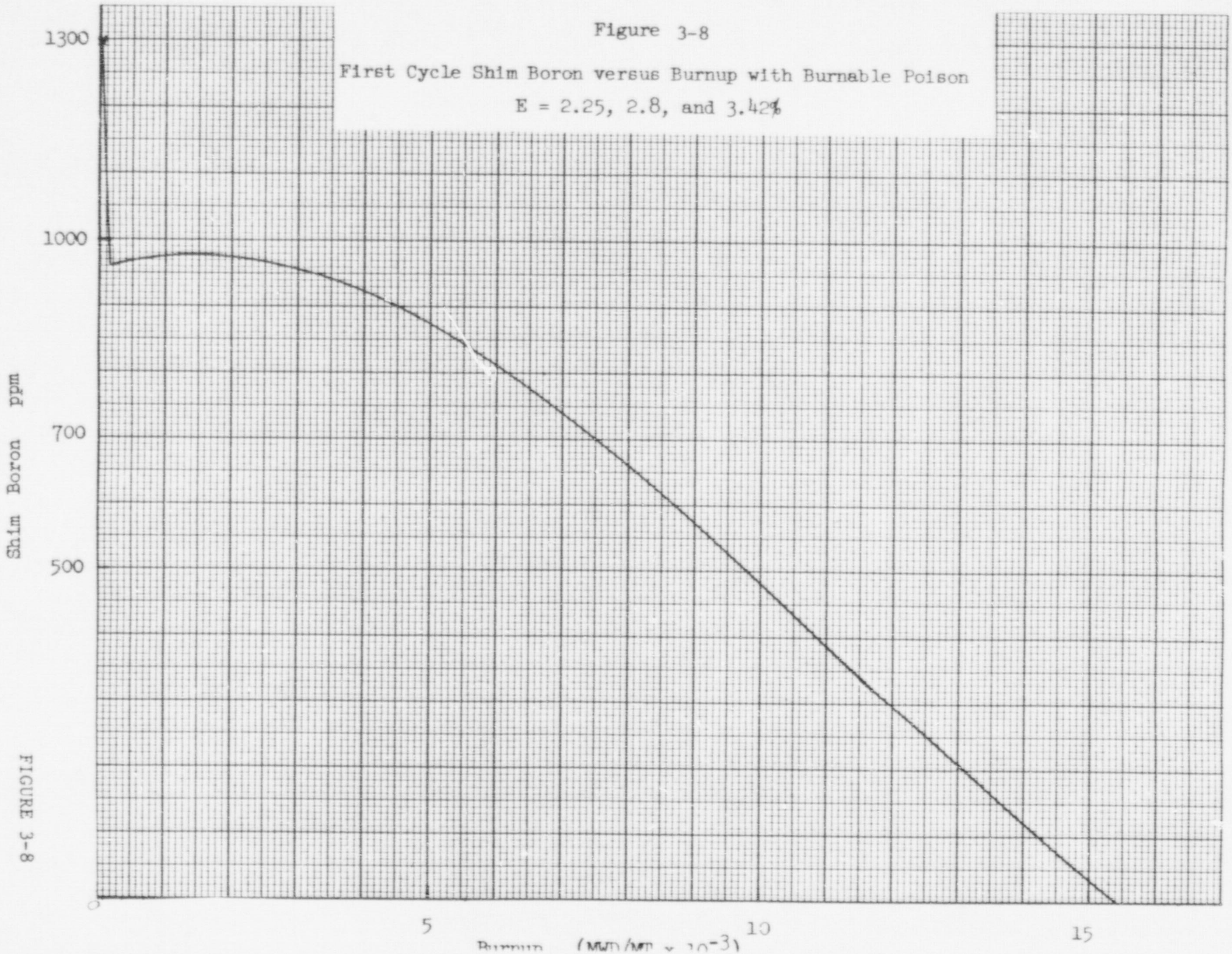


FIGURE 3-8

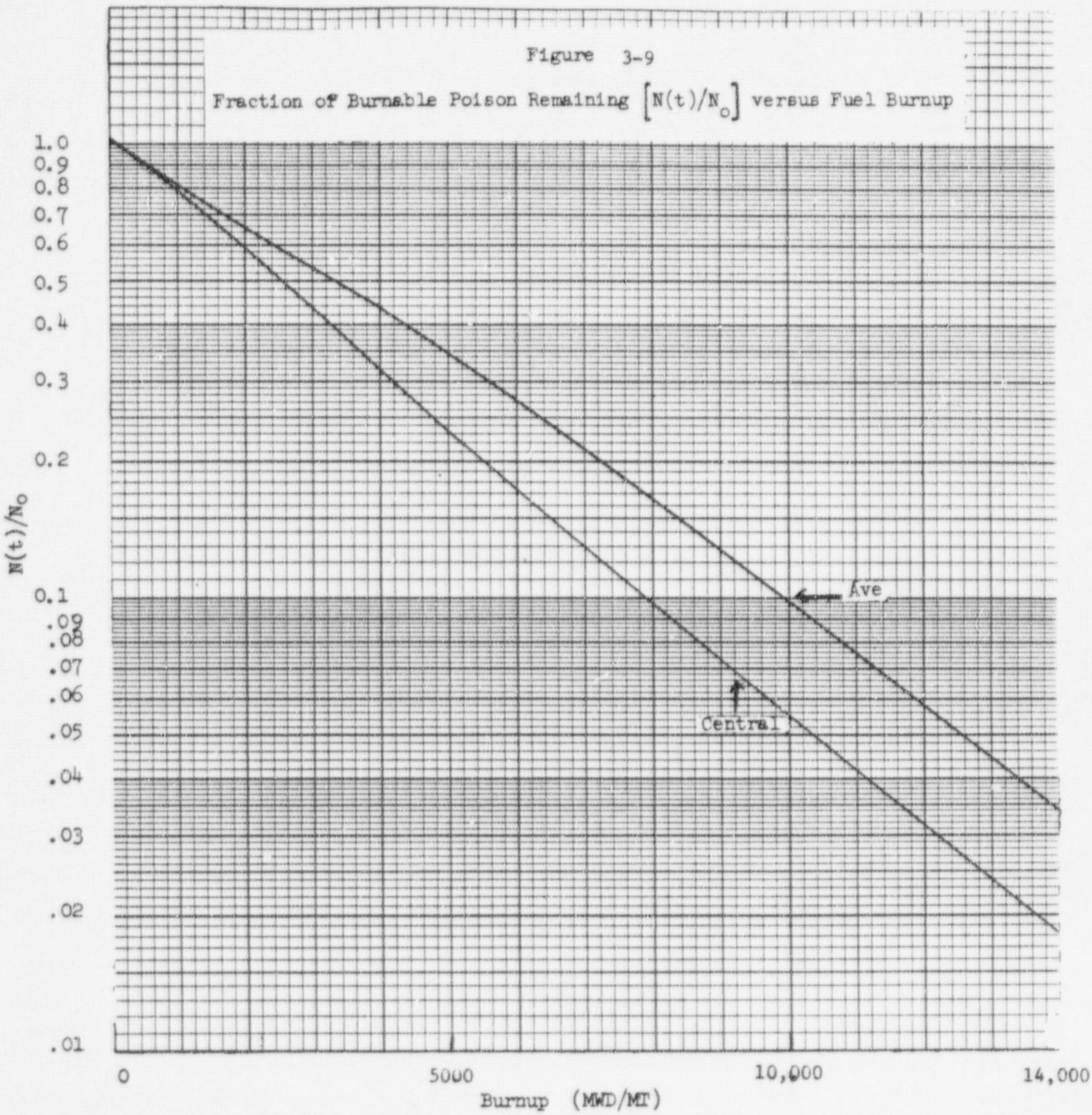


Figure 3-9

Fraction of Burnable Poison Remaining $[N(t)/N_o]$ versus Fuel Burnup

FIGURE 3-9

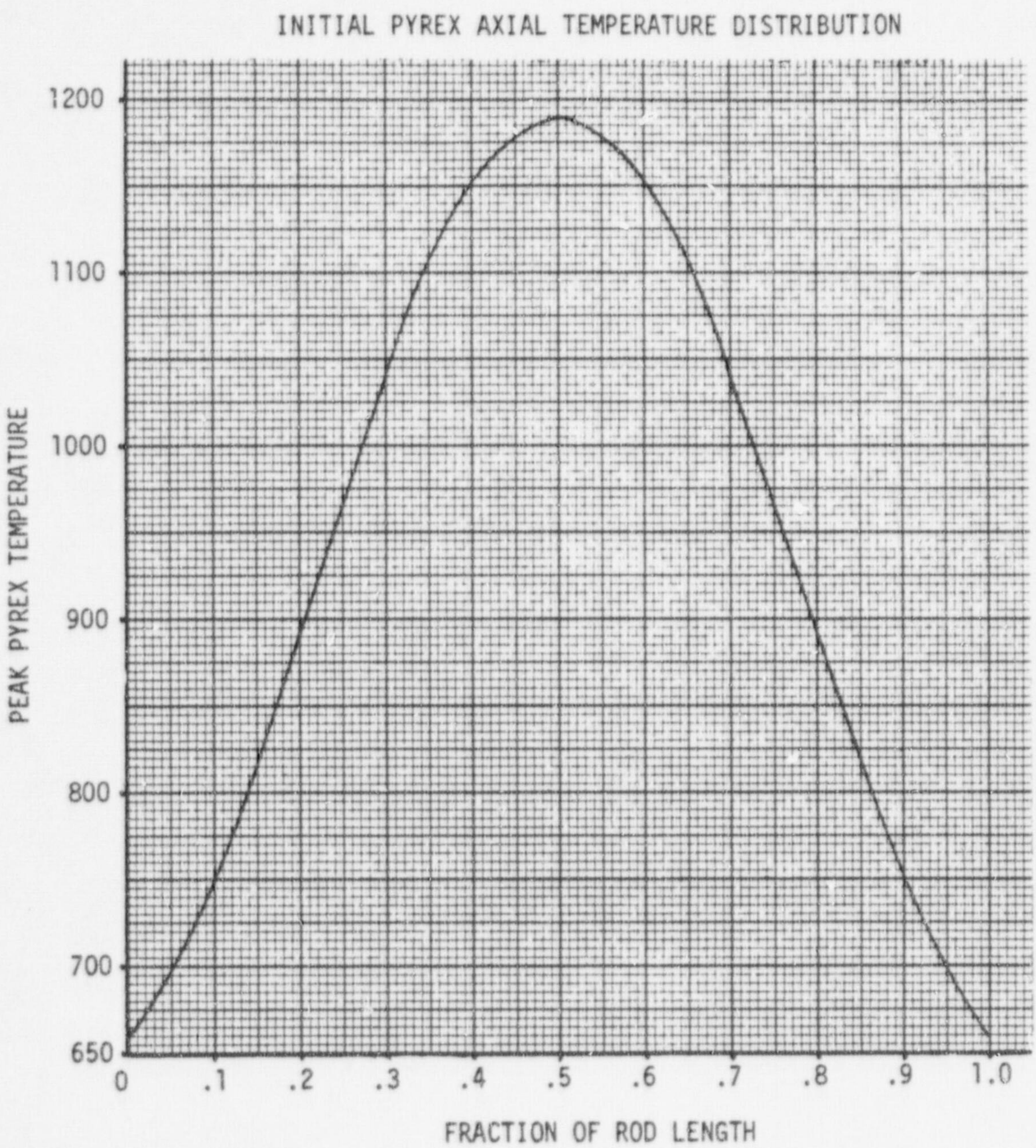

INITIAL PYREX AXIAL TEMPERATURE DISTRIBUTION
PEAK PYREX TEMPERATURE
1200
1100
1000
900
800
700
650
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
FRACTION OF ROD LENGTH

FIGURE 3-10

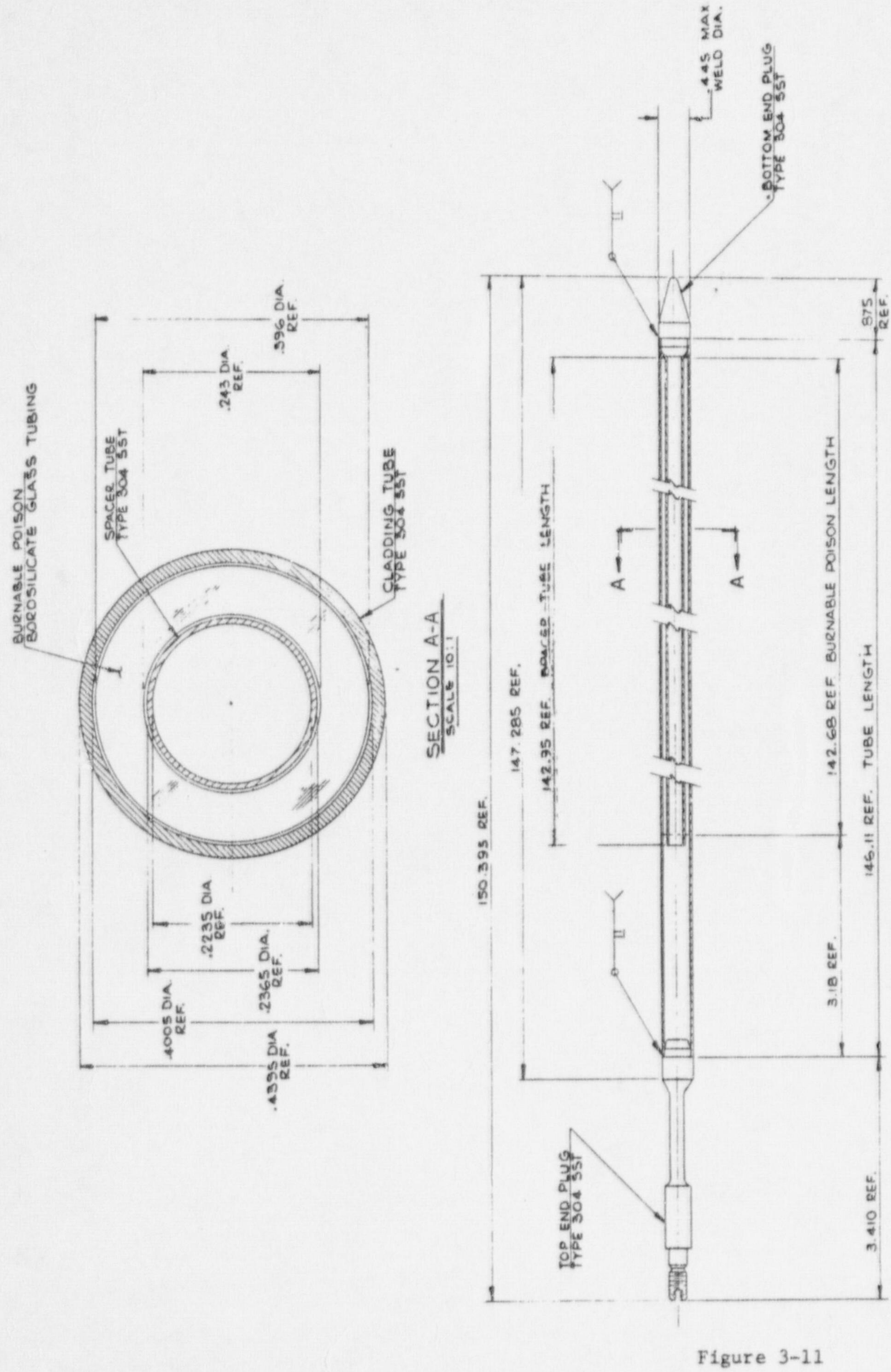

BURNABLE POISON BOROSILICATE GLASS TUBING
SPACER TUBE TYPE 304 SST
CLADDING TUBE TYPE 304 SST
SECTION A-A
SCALE 10:1
.396 DIA. REF.
.243 DIA. REF.
.2235 DIA. REF.
.2365 DIA. REF.
.4005 DIA. REF.
.4395 DIA. REF.
150.395 REF.
147.285 REF.
142.95 REF. SPACER TUBE LENGTH
142.68 REF. BURNABLE POISON LENGTH
146.11 REF. TUBE LENGTH
3.18 REF.
3.410 REF.
.875 REF.
.445 MAX WELD DIA.
BOTTOM END PLUG TYPE 304 SST
TOP END PLUG TYPE 304 SST
A
A

Figure 3-11