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Argonne National Laboratory

BORAX-V NEUTRONICS

by

J. I. Hagen and R. W. Goin

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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

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by

J. I. Hagen and R. W. Goin

Idaho Division

RELEASED FOR ANNOUNCEMENT
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December 1965

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I. INTRODUCTION

BORAX-V was designed and constructed as the result of a joint conception by personnel of the Idaho Division and the Reactor Engineering Division of Argonne National Laboratory. The primary objective of the program was to examine the feasibility and characteristics of a boiling-water reactor having an integral or coupled subcritical superheating section. The original plan called for a rather extensive program of study on the general aspects of boiling-water reactor stability involving such factors as variable metal-to-water ratios, forced and natural convection, etc.¹ Only part of this has been accomplished within the allotted time.

A minimum-sized critical assembly consisting of boiling fuel assemblies was achieved on February 9, 1962, and operation with varied core configurations was continued to August 1964. The BORAX-V plant is fully described in Ref. 2 and will not be repeated here.

While many of the general features of the system appear as the result of previous work in the BORAX series, several other considerations were recognized in arriving at the reference design and may be summarized as follows:

- a. The facility was to be low in cost, utilizing existing structures as far as possible.
- b. A maximum degree of flexibility was desired. This included provision for achieving a variable metal-to-water ratio, extensive use of in-core instrumentation, adaptability for differing superheater designs, provision for forced and natural convection, etc.
- c. A high-power density boiler was desired for examining instabilities in the higher power regions.

Four principal core configurations were contemplated: (1) an all-boiling core, (2) a boiling core with a superheating section in the center, (3) a boiling core with superheating elements along the perimeter, and (4) a core with an intermediate superheating zone, i.e., a square annulus with boiling regions inside and outside. An early decision was made to

eliminate the last core configuration because of the additional expense and mechanical complications. The entire core included a volume roughly 34 x 34 x 24 in. high. Figure 1 illustrates diagrammatically the superheater core geometries that were actually constructed. The core is further subdivided into 60 assemblies (4 x 4 in.) and nine control rods.

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Fig. 1. Superheating Cores.

An integral superheater, depending on thermal fissioning, is characterized by special problems of operation. From the reactivity standpoint, attention must be given to flooding the steam spaces, as necessitated in the BORAX design, for shutdown and decay heat removal. With the relatively small, leaky core of BORAX, this becomes an important point. This and other questions of reactivity effects entering into the design are treated in Section III. The results of more detailed calculations are also given in Section III, the experimental findings are surveyed in Section IV, and additional topics are covered in Section V.

Many details of the earlier work have been lost, partly as a result of changing personnel and partly due to normal attrition. It is felt, however, that as much of the record as can be assembled should be preserved in the form of this report; and while much of the original work and methods used are now obsolete, they are listed to make the record complete.

The characteristics sought in the design and other miscellaneous plant data influencing the neutronic calculations are listed in Table I.

Experimental operations were conducted on four distinct cores, classified as B-1, B-2, CSH-1, and PSH-1. The B-1 all-boiler core was assembled with four variants distinguished as B-1A to -1D, and was in all cases composed of 49-fuel-rod boiler assemblies. Because of a high-temperature reactivity defect, power operation was not conducted with the B-1 core. The B-2, also an all-boiler core, was operated at 22 MWt maximum power. In the B-2 core, four fuel rods were removed from the central region of each fuel assembly, and water-filled rods were installed in their places. The CSH-1 core contained the central superheater and

utilized eight water-filled rods with 41 fuel rods per boiler assembly. Because of welding failures in the superheater elements, operation was discontinued early in the experimental program, although sustained operation at 15 MWt had been achieved. The PSH-1, or peripheral superheating core, performed very well with a maximum power in excess of 20 MWt. This core used 12 water-filled rods with 37 fuel rods per boiling assembly. Reactivity was depressed in all cores, as needed, by the use of boron-stainless steel rods.

TABLE I. Summary of BORAX-V Design Characteristics

Reactor reference design power	20 MWt, nominal
Core with superheater	
Boiling region	16.6 MWt, nominal
Superheater	3.4 MWt, nominal
Steam pressure	600 psig
Saturated-steam temperature	489°F
Superheated-steam temperature (reactor exit)	850°F
Average power density	
Boiler	95 kW/liter
Superheater	80 kW/liter
Maximum fuel temperature	
Superheater, fuel-plate center	1125°F
Superheater, fuel-plate surface	1110°F
Boiler fuel, center of rod	3100°F
Boiler fuel, surface of rod	515°F
Control rods (driven from below)	
Absorber material	Boral, 50 w/o B ₄ C
Cladding	Type 304 stainless steel
Follower	X-8001 aluminum

II. DEVELOPMENT OF FUEL GEOMETRY

A. Boiling Core

Enriched UO_2 pellets in tubular metallic sheaths were selected for boiler fuel. These were designed to be supported in a twist-lock fashion for easy removal. The original design, with a goal of high power density, had envisaged a small fuel rod of 0.26-in. diam. Close packing on 3/8-in. centers would make an assembly of 100 rods. Aluminum cladding 0.015 in. thick was planned, and UO_2 pellet size was set at 0.230-in. diam. The UO_2 density was to be 0.91 of theoretical maximum.

Subsequent considerations led to a considerable increase in the burnout flux limit that can be ascribed to a larger rod. The ultimate choice thus became forty-nine 3/8-in.-diam rods per assembly (0.5-in. lattice spacing). This consideration is fully described in Ref. 3. The cladding was also changed from aluminum to Type 304 stainless steel. Other more or less obvious factors favored the larger rod: (1) simplified fuel handling, (2) simplified fabrication, and (3) reduced cladding material.

A summary comparison of neutronic calculations for the two cases is presented in Table II.

TABLE II. Comparison of Core Characteristics with
49 and 100 Fuel Rods per Assembly

	100-rod Assembly	49-rod Assembly
Cladding Material:	Aluminum	Stainless Steel
Calculated minimum critical loading at power		
U^{235} per rod, g	5.7	13.3
Total U^{235} , kg	34.2	38.2
Percent steam voids assumed	17.5	15.0
Water-to- UO_2 volume ratio, based on a rod cell	3.36	2.26

Disadvantage factors are compared in Fig. 2. These were calculated by the method described in Section III-B. The final fuel-rod design detail is shown in Fig. 3.

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Fig. 2. A Comparison of Disadvantage Factors

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Fig. 3. Boiling Fuel Rod

The use of 3/8-in.-diam stainless-steel rods containing 2 w/o natural boron was envisaged as a means of controlling overall and local reactivity effects as such need might arise when one boiler enrichment is used for all core configurations. The plan, as adopted, entailed the removal of fuel rods in selected positions and replacing them with poison rods. Rod worth in cases in which the withdrawal of a single rod could make the reactor critical was satisfactorily depressed by placing one or more such poison rods near the control rod.

B. Superheater

The superheater section was originally visualized as a tubular structure. Considerable effort was expended in assessing this and other variants. The use of a solid moderator such as zirconium hydride was also considered, but because of the lack of complete knowledge of moderating characteristics and/or structural stability at high temperatures, this was ruled out. A flat-plate cermet with a water moderator was finally chosen, the fuel therein being fully enriched.

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Fig. 4. Superheater Fuel Assembly

The first concept of a water-moderated design consisted of four elements per assembly, each element consisting of 16 plates (0.10-in. cermet thickness, 0.010-in. cladding thickness, with 0.047-in. steam gaps). Reference 3 describes this earlier design, together with the first version of the final design.

Power-distribution characteristics and considerations of cost of fabrication led to the final design, shown in Fig. 4. The use of less stainless steel in the final design results in better neutron economy. The same general pattern was used for both central and peripheral superheating assemblies, differing only in the U^{235} content.

The many special problems encountered and methods employed in the fabrication of the superheater fuel have been reported by Kramer and Bean,⁴ and work accomplished by others in this and related fields is summarized in Ref. 5.

III. NEUTRONIC CALCULATIONS

A. General

During the BORAX-V project, three sets of criticality calculations were preformed. In all cases, standard computer production codes were employed primarily, the principal difference being in the methods used for homogenization and in the cross-section codes used. Since this reactor was not intended for long-time operation, problems such as burnup received little attention. Of greater importance were the factors of safety, the prediction of operational characteristics, and, as is always the case, the effort to find what is necessary to obtain agreement with experiment. It is not possible in much of the experimental work, however, to find points at which experiment and theory can be compared satisfactorily. The reason for this is that frequent changes were necessitated, such as positioning boron poison rods in a particular pattern to prohibit criticality on the withdrawal of a single control rod or the placement of an oscillator unit within the core, etc. The design work was not guided by a separate critical facility, but certain index points were obtained from critical experiments^{6,7} made with BORAX-V fuel at the ZPR-7 facility at Argonne, Illinois, and an exponential experiment⁸ was performed with the aid of the TREAT facility.

In addition to static-reactivity calculations, other studies were made on control-rod effects, perturbations due to boron poison rods, flux-flattening methods, and several other items. These are outlined in the text.

To facilitate the discussion, the calculational procedures employed in obtaining constants can be designated as follows:

1. In the original design calculations, the UO_2 enrichment of the boiler was determined, as well as the required fuel distribution to achieve the desired power sharing between boiler and super-heater. MUFT⁹ and SOFOCATE¹⁰ constants were used.
2. The same computer codes were used, but emphasis was on optimization of flow-rod arrangements as a guide for operations.
3. Calculations were made with GAM¹¹ and TEMPEST¹² constants designed specifically to check experimental methods and results.

Table III compares the procedural differences employed in the three cases.

TABLE III. Comparison of Methods Used for Obtaining Homogenized Constants for Static Reactivity Calculations

METHOD I (Design Calculations)	METHOD II	METHOD III
Section III-B	Section III-C	Section III-D
Calculate overall homogenized atom densities, boiler and superheater separately.	Calculate number of densities of subregions of a control cell.	Calculate N_j for subregions and for homogenized regions.
Calculate thermal disadvantage factors.	Adjust N_j of fuel region with disadvantage factors obtained in Method I.	1. Thermal constants for various temperatures and boric acid concentrations. Obtain thermal spectrum for homogenized region--TEMPEST.
Adjust proportionate part of water and fuel-rod constituent N_j for SOFOCATE constants in accordance with fuel-rod disadvantage factors.	Calculate MUFT L-factors for fuel region.	Average cell-subregion constants over homogenized spectrum--TEMPEST.
Calculate L-factor for MUFT input.	Run MUFT and SOFOCATE problems for 2-4 group constants.	Obtain disadvantage factors from cell calculations (pin or plate)--S ₄ or DP-1.
	Run PDQ cell problems to obtain an "assembly disadvantage factor," d_a .	Obtain homogenized subregion constants by flux and volume weighting subregion constants.
	Adjust overall homogenized N_j with d_a .	2. Fast constants for various temperatures and boric acid concentrations. Calculate Dancoff-Ginsberg shadowing factor.
	Rerun MUFT and SOFOCATE with adjusted N_j to obtain new homogenized constants.	Obtain fast spectrum for homogenized region--GAM. Average subregion constants over homogenized spectrum--GAM.

B. Design Calculations

Figures 5 and 6 illustrate the configurations from which atom densities were calculated for the boiling and superheater section, respectively. Since the relative boiler-superheater loadings were unknown at this phase, it was decided that constants should be obtained for a range of enrichments and conditions. An arbitrary set of U^{235} contents per rod was assumed; disadvantage factors were calculated by using Maxwellian-averaged thermal constants; and a series of SOFOCATE problems was run for thermal constants for the boiler. "L," or self-shielding, factors were supplied for companion MUFT-IV problems. SNG slab problems gave an estimation of the superheater disadvantage factor, but the superheater fuel was to be fully enriched and the L-factor was taken as unity.

The atom densities (uncorrected) are represented by the following formulas:

Boiling Core (forty-nine 3/8-in.-diam fuel rods per assembly)

$$N_H = (0.28987)(\rho)(1 - Z) + (0.004949) \rho,$$

$$N_O = N_H/2 + 2(N_{U^{235}} + N_{U^{238}}),$$

$$N_{Fe} = 2.54121 \times 10^{-3},$$

$$N_{Ni} = 4.6949 \times 10^{-4},$$

$$N_{Al} = 1.32561 \times 10^{-2},$$

$$N_{Cr} = 6.5338 \times 10^{-4},$$

$$N_{U^{235}} = 1.59717 G_r \times 10^{-5},$$

$$N_{U^{238}} = (1.57932)(323.04 - G_r) 10^{-5};$$

Superheater

$$N_H = 0.027275 \rho + 0.015883 \rho^i, \text{ where } \rho^i \text{ is zero if not flooded,} \\ \text{or is equal to } \rho \text{ if flooded,}$$

$$N_O = N_H/2 + 2(N_{U^{235}} + N_{U^{238}}),$$

$$N_{Fe} = 0.0110146 - 0.86358 \times 10^{-6} L,$$

$$N_{Ni} = 0.0018189 - 0.13885 \times 10^{-6} L,$$

$$N_{Al} = 0.010433,$$

$$N_{Cr} = 0.0028320 - 0.22204 \times 10^{-6} L,$$

$$N_{U^{235}} = 0.32595 \times 10^{-6} L,$$

$$N_{U^{238}} = 0.23479 \times 10^{-7} L;$$

where

$$G_r = \text{g of } U^{235} \text{ per fuel rod,}$$

$$\rho = \text{density of water}$$

$$= 1.000 \text{ for cold or room temperature}$$

$$= 0.793 \text{ for hot or } 489^\circ\text{F water,}$$

$$Z = \text{void fraction due to boiling (applies only to fraction of water} \\ \text{adjacent to fuel rods),}$$

and

$$L = \text{g of } U^{235} \text{ per superheater assembly.}$$

Total Core Area = 7737.55 cm^2
 Unit Cell = $7737.55/60 = 128.959 \text{ cm}^2$
 Volume Fractions/Unit Cell
 Total Al, Including Structural -- 0.22215
 UO_2 ----- 0.2292
 SS ----- 0.04159
 H_2O (Boiling) ----- 0.43315
 (Non Boiling) ----- 0.07395

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Fig. 5. Diagram for Calculating Atom Densities,
Boiling Region

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Fig. 6. Atomic Density Calculation Diagram, Superheater Fuel Assembly

1. Disadvantage Factors and Thermal Constants

The disadvantage factors for the boiling rods were calculated by modification of a method suggested by Copic and Thie.¹³ The method used involves (1) calculation of diffusion-theory flux ratios for the cylinder, (2) transformation of the cylinder to an "equivalent" slab, (3) calculation of P_3 and diffusion-theory flux ratios for this slab, and (4) estimation of P_3 flux ratios for the original cylinder. This procedure was used because the P_3 and SNG codes for cylindrical geometry and Amouyal's method¹⁴ gave physically unreasonable results in this case. Since this time, however, the problem has been resolved by using an isotropic scattering boundary condition.¹⁵ The disadvantage factors (DF) calculated for the boiler fuel are displayed graphically in Figs. 7 and 8.

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Fig. 7. Calculated Disadvantage Factors

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Fig. 8. Variation of Boiler Fuel Disadvantage Factors with Temperature; Calculated Values

Atom densities were adjusted in accordance with the following rule:

$$DF = \frac{D_w}{D_f} > 1,$$

$$D_f = \frac{1}{V_f + (DF) V_w} < 1,$$

$$D_w V_w + D_f V_f = 1,$$

$$N_{\text{fuel}} \times D_f = N_{\text{fuel}} (\text{effective}),$$

$$N_{\text{mod}} \times D_w = N_{\text{mod}} (\text{effective}),$$

where V_f and V_w are volume fraction of the fuel and moderator, respectively, and D_f and D_w are proportional to the average flux in the fuel and moderator, respectively. The cladding material was considered as part of the fuel. This would introduce some error, since the reaction rate in stainless steel is underestimated. Also, in the assembly homogenization, the aluminum structure was included with the moderator.

Disadvantage factors for the superheater were obtained by running SNG slab-cell problems. The material within a four-fuel-plate superheater element, including the stainless-steel side plates, was homogenized on a first trial, but later problems considered each plate. The usual zero-current condition was assumed to exist midway in the water gaps between elements. The later problems helped to adjust the loading within the individual fuel plates to effect a slightly flatter power distribution. Figures 9 and 10 portray the final results. All N_i weighted as above were then entered as input for the SOFOCATE code, giving homogenized Wigner-Wilkins averaged cross sections.

2. Fast Cross Sections

Unaltered atom densities were supplied as input for MUFT-IV. The self-shielding or L-factor is given as $\sigma_a(\text{heterogeneous})/\sigma_a(\text{homogeneous})$, where σ_a is the effective resonance capture integral. The homogeneous value was obtained from published results for U^{238} metal (pp. 138-139 of Ref. 16a). The scattering cross section per absorber atom was taken as $(N_{\text{hydrogen}})(21 \text{ barns})/N_{U^{238}}$. The heterogeneous values were obtained from the Hellstrand formula^{17,18} with a Dancoff correction^{16a} and resulted in

$$\sigma_a^{\text{heter}} = 11 + 24.5(S/M)(1 - C),$$

where

$$\begin{aligned} S/M &= \text{surface area of rod/mass of absorber} \\ &= 0.4573, \end{aligned}$$

and

$$C = \text{Dancoff factor (approximated from p. 346 of Ref. 16a).}$$

In the hot boiler with dry central superheater, a variance of 10% in the L-factor indicated a difference of about 1% in k_{eff} and 1.7% in the superheater power fraction.

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Fig. 9. Fine Flux Structure in Superheater Fuel Element

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Fig. 10. Variation of Power Production in Superheater Fuel Plates as Related to U^{235} Content

A Doppler correction was attempted, although little information could be found on uranium oxide at that time. Knowledge of an effective fuel temperature as a function of power was also lacking. A linear approximation from data reported on U_3O_8 was finally used to make a slight adjustment in the heterogeneous value (p. 681 of Ref. 19). Values of the Doppler correction for U^{238} metal appear (p. 351 of Ref. 16a) in the form

$$1/A \cdot dA/dt = 1.425 \times 10^{-4}$$

(average of four values listed), where A is given by resonance integral_{eff} = $A(1 + \mu S/M)$ and t is in degrees Centigrade. How this could be applied to the present core with uranium oxide was not clear since the Hellstrand formula is of an empirical form and given to represent the oxide case.

3. Criticality Calculations

The first problem was to assign the proper loadings to achieve a critical configuration with an assumed total power and with a particular fraction of the total being developed in the superheater. An average value of 15% steam void was thus associated with a power of 20-30 MWt; to achieve an 850°F exit steam temperature, 19% of total power was calculated to be required in the superheater.

A graphical solution appeared to be most convenient. This was accomplished by obtaining k_{eff} (two-group, one-dimensional calculation) for a range of loadings with 6, 12, 18, and 24 g of U^{235} per fuel rod and 300, 400, 500, and 600 g of U^{235} per superheater assembly. The RE-122 code^{16b} (at this time known as RE-6, a Univac version) was used. Plots of k_{eff} vs g of U^{235} per fuel rod with superheater loading as a parameter yielded four critical points. A similar plot of the integral of the superheater source vs boiler fuel loading gave four points at which the superheater power fraction was 19% of the total. Finally, plotting these eight points on the superheater-loading vs boiler-fuel-loading coordinates resulted in two curves intersecting at the desired point. Plots and further details are given on pp. 60-61 of Ref. 2. Further four-group, one-dimensional problems and PDQ²⁰ (X-Y) problems established more accurately the values required. The cylindrical models used are shown in Fig. 11, and these computations are summarized in Table IV. The peripheral superheater was not well represented by a one-dimensional calculation (an annular region around a cylindrical boiler) insofar as giving a useful answer on power sharing, and the answer was derived from the two-dimensional X-Y PDQ problems. The calculational models used are shown on pp. 63-65 of Ref. 2.

Since the central superheating configuration designated the largest value of loading for the boiler, this was selected as the basis for the boiling-fuel enrichment. An approximate value of the reactivity required to override fission-product poisons and a small allowance for burnup set this loading finally at 16.2 g U^{235} per fuel rod. The central superheating assemblies and the peripheral superheating assemblies were similarly designated to contain 430 g of U^{235} and 680 g of U^{235} per assembly, respectively. One set of boiling fuel rods with a single enrichment served for all configurations. This value was thus set at 4.95 w/o U^{235} , and a few rods with twice this enrichment were obtained for experimental purposes.

To examine the possibility of achieving the desired power split at various power conditions and to study the reactivity effects of temperature, voiding, and superheater flooding, additional problems were run. The RE-122 code is designed to iterate on composition to give a critical configuration. In this instance, iteration was made on the three cores to give the volume fraction of a unit absorber in the thermal group to produce a k_{eff} of

savings was 0.00185 cm^{-2} . A value of $0.001889 \pm 0.0000026 \text{ cm}^{-2}$ was measured on the experiment. The axial reflector savings thus determined was $11.32 \pm 0.05 \text{ cm}$.

A minimum critical array was first achieved with 14 boiling fuel assemblies in a 4×4 array with opposite corner assemblies missing.²⁸ On the basis of RE-6, one-dimensional, cylindrical calculations, 11 assemblies had been predicted.

It is difficult to make many direct comparisons of calculation with experiment. It is desirable to obtain points at which criticality is well defined and the geometry is simple enough to be comparable with the calculation. A total available excess reactivity of 12% was obtained for the first B-1 core.²⁸ The method of finding this depended on integrating the differential rod worths vs rod height, the differential rod worths being obtained by the customary method of bumping control rods a small amount to put the reactor on a period. Successively higher rod positions were obtained by incremental additions of boric acid.

It may be suspected that the use of boric acid would underestimate the available excess reactivity. If all other factors such as the source effect on the asymptotic period and the available excess reactivity of 12% obtained for the full 49 rod/assembly core are assumed correct, the following comparison is typical of what is often done:

The RE-6 problem for the cold clean core gave a k_{eff} of 1.229. The core contained 36 boron-stainless steel poison rods. An approximation of the worth of these rods from Fig. 12 (36 poison rods are equivalent to 0.6 rod per assembly) gives about -5.5% ρ . A k_{eff} of 1.229 is equivalent to a ρ of 18.6%, or an available excess reactivity of ~12.1%.

A measurement of poison-rod worth in the B-1A core, in which the rod was located about 7.5 in. from the center of the core, gave a reactivity worth of -0.14%. From Fig. 12, the worth of one rod per assembly is -9.0%, or 1/60 of this (assuming linearity) is -0.15%.

Again, a rough comparison may be made with RE-6 problem 580013 (Table V) where an addition to the thermal Σ_a of an amount, 0.0355, resulted in a k_{eff} of unity. Approximately 20 g of boric acid per gallon of water would permit complete withdrawal of the control rods from core B-1A. Using the Maxwellian-averaged value from the SOFOCATE second deck,²⁵

a value of $\sigma_a = 3556$ barns is obtained for B^{10} . With a water fraction of 0.442, and allowing $3785.43 \text{ cm}^3/\text{gal}$, Σ_a for the boric acid is 0.0276. The difference in Σ_a above and Σ_a due to boric acid is 0.0079, which must then represent roughly the effective Σ_a of the poison rods. An error is present, of course, in ignoring the boric acid effect in the water reflector.

C. Metal-to-Water Optimization Studies

1. Purpose

At various times during the BORAX-V program, and as operational scheduling would permit, experiments were carried out in an attempt to optimize the metal-to-water ratios to obtain the maximum available excess reactivity. The metal-to-water ratio was variable because of the provision for replacing selected fuel rods with water-containing or "flow" rods. The term "flow rods" was derived from the consideration that their presence would maintain the same hydraulic conditions as the fuel rods. Of the same diameter as the fuel rods, the flow rods were made of X-8001 alloy aluminum tubing with a wall thickness of 0.020 in. Holes were drilled at each end to permit the rods to be filled with water.

The full 49-fuel-rod assembly proved to be somewhat under-moderated. Cadmium ratios obtained on the BORAX exponential experiment gave values ranging from 14 at the assembly edge to six near the center. Enriched uranium-zirconium wires, both bare and clad with 0.020-in.-thick cadmium, were used for this measurement. A comparison of various lattice spacings from the ZPR-7 results* indicated that a maximum reactivity would result when 12 of the 49 rods were flow rods. Actually, a gain in reactivity, at room temperature, may not in itself be the desired objective, for this would need suppression by extra poison rods to avoid the possibility of achieving criticality upon the withdrawal of a single control rod. The benefit would be expected from a reduced temperature and void coefficient.

2. Cell Problems

In an effort to guide the experimental work, a series of PDQ cell problems was run to observe the effect of flow-rod location on power distribution and to obtain a disadvantage factor for the assembly. The disadvantage factor was also used to adjust homogenized number densities for new reactor thermal constants.

Figure 17 illustrates the particular flow-rod geometries characterizing the several BORAX-V cores, and Fig. 18 depicts the cell model used for two-group PDQ problems. Cross sections for the several regions

*Made by D. H. Shaftman, Reactor Physics Division, ANL.

No Flow Rods,
Core B-1

$$\frac{\text{Vol H}_2\text{O}}{\text{Vol UO}_2} = 2.213$$

4 Flow Rods,
Core B-2

$$\frac{\text{Vol H}_2\text{O}}{\text{Vol UO}_2} = 2.561$$

8 Flow Rods,
Core CSH-1

$$\frac{\text{Vol H}_2\text{O}}{\text{Vol UO}_2} = 2.901$$

12 Flow Rods,
Core PSH-1

$$\frac{\text{Vol H}_2\text{O}}{\text{Vol UO}_2} = 3.319$$

● Fuel Rod

○ Flow Rod

Note:

Water-to-UO₂ ratios are given for
the cold reactor and include water
in the interassembly regions.

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Fig. 17. Flow-rod Patterns in Boiling Fuel Assembly

Region	Volume Fractions			
	Al	H ₂ O	SS	UO ₂
1	1.0	---	--	---
2	0.424	0.577	--	---
3	--	0.558	0.068	0.374
4	0.274	0.740	--	---
5	Variable			

ID-103-A3520

Fig. 18. Calculational Cell Model for a Single Boiling Fuel Assembly

were derived by methods previously described, with the exception of the resonance self-shielding factors wherein the Dancoff correction was evaluated by considering each fuel rod of a fuel region and including the contribution of every neighboring rod within two lattice distances (1 in.).

The thermal disadvantage factors to associate with fuel rods in the mixed fuel and flow region were not corrected. No simple expedient for this seemed to exist, although a later thought of finding an average "effective" lattice spacing to use in computing an adjusted disadvantage factor might afford some improvement (see Section III-D).

Figure 19 compares thermal fluxes plotted from the PDQ results for the representative BORAX-V cores. The plots are normalized on a point-to-average basis, where the average is the volume average of the fuel regions, rather than the profile average. Comparison with measured flux patterns obtained with enriched uranium-zirconium wires, if made on the basis of the ratio of maximum (on line of traverse and within fuel region) to minimum, gave values for the 49-fuel-rod assembly ranging from about 3.4 to 2.6, the larger value being near the core center. The equivalent cell problem gave a value of about 2.0, but some difference would be expected from the fact that the calculation is based on a thermal flux averaged to 0.625 eV, whereas the U^{235} activation was quite sensitive to variations in the detailed spectrum.

ID-103-A3507

Fig. 19. Thermal Flux Patterns from PDQ Cell Problems

The various combinations of flow and fuel rods considered are listed in Table VIII, together with the values of the ratio $\bar{\phi}_{\text{nonfuel}}/\bar{\phi}_{\text{fuel}}$ for the thermal group. Cold (room temperature), hot (489°F), and hot with 10% steam void (fuel-rod region only) cores are listed. The ratio is calculated as follows:

$$\frac{\bar{\phi}_{\text{nonfuel region}}}{\bar{\phi}_{\text{fuel region}}} = \frac{\frac{\int_{\text{Reg 1}} \phi dv + \int_{\text{Reg 2}} \phi dv + \int_{\text{Reg 4}} \phi dv}{\text{Volume of Regions 1, 2, and 4}}}{\frac{\int_{\text{Reg 3}} \phi dv + \int_{\text{Reg 5}} \phi dv}{\text{Volume of Regions 3 and 5}}}$$

TABLE VIII. Thermal Flux Ratios of Nonfuel-to-fuel Regions;
Two-group PDQ Cell Results

Fuel-region Geometry			Condition of Reactor*	$\frac{\bar{\phi}_{\text{nonfuel}}}{\bar{\phi}_{\text{fuel}}}$	PDQ Problem No.
Region 3, Fuel Rods	Region 5				
	Fuel Rods	Flow Rods			
49 (Core B-1)			Cold	1.77	22067
40 (Core B-2)	5	4	Cold	1.55	76
			Hot	1.38	77
			Hot, 10% void	1.40	92
40	4	5	Cold	1.52	78
			Hot	1.34	79
			Hot, 10% void	1.37	93
40	3	6	Cold	1.49	80
			Hot	1.31	81
			Hot, 10% void	1.33	94
40 (Core CSH)	1	8	Cold	1.41	82
			Hot	1.24	83
			Hot, 10% void	1.27	95
24	17	8	Cold	1.45	84
			Hot	1.33	85
			Hot, 10% void	1.34	96
24	16	9	Cold	1.42	86
			Hot	1.30	87
			Hot, 10% void	1.32	97
24 (Core PSH)	13	12	Cold	1.36	88
			Hot	1.21	89
			Hot, 10% void	1.23	98
0	33	16	Cold	1.43	90
			Hot	1.31	91
			Hot, 10% void		

*Cold: room temperature.

Hot: 489°F.

3. Reactor Problems

The above ratio was treated as an assembly disadvantage factor and applied to the fuel and nonfuel atom densities in accordance with the rule previously listed, and input for new homogenized SOFOCATE problems was obtained. Unaltered averaged atom densities were used in MUFT calculations for fast cross sections. A new resonance self-shielding factor was obtained wherein the Dancoff correction was made for an averaged fuel region. The cross sections thus obtained are given as Appendix B, and a condensed summary of reactor calculations (three-group, RE-122) as Table IX. The old superheater constants were used. Included in the table are values of k_{eff} for the case of peripheral superheater elements used in the central superheater configuration.

TABLE IX. Calculated k_{eff} for Representative Flow-rod Geometries and Comparative Reactivity Effects, Three-group RE-122 Radial (One-dimensional) Problems

	Room Temp	489°F	489°F 10% Voids	Reactivity Effects, % ρ		
				Temp	Voids	Flooding 70°F/489°F
All boiler, four flow rods	1.250	1.166		-6.0*		
All boiler, eight flow rods	1.254	1.176		-5.3**		
All boiler, 12 flow rods	1.261	1.189		-5.0		
<u>CSH (430 g of U^{235} per assy, 12 flow rods)</u>						
Superheater dry	1.178	1.108	1.082	-6.4	-2.1	
Superheater flooded	1.186	1.126		-4.5		+0.6/+1.5
<u>CSH (680 g of U^{235} per assy, 12 flow rods)</u>						
Superheater dry	1.217	1.144	1.121	-5.2	-1.8	
Superheater flooded	1.246	1.186		-4.0		+1.9/+3.1
<u>PSH (680 g of U^{235} per assy, 12 flow rods)</u>						
Superheater dry	1.250	1.178	1.147	-5.0	-2.3	
Superheater flooded	1.260	1.188		-4.7		+0.5/+0.8

Superheater power fraction, 489°F, 10% average steam void:

680 g of U^{235} per assy, central superheater: 0.22

680 g of U^{235} per assy, peripheral superheater: 0.14.

*Comparative experimental value for B-2: -4.6.

**Comparative experimental value for CSH-1: -3.9.

The effect of spiking the outer three corner elements of each quadrant with fuel rods of double enrichment, to an equivalent of 7.5 w/o enriched within the assembly, gave a reactivity gain (PDQ calculation) of 0.4%. If the spiking were to be done in the outer row of boiler fuel assemblies as well, the calculation indicates that 2.4% ρ would then be gained, but that the superheater power fraction would lose 4% of its original value. The superheater was considered to be flooded and the reactor at room temperature in these computations.

D. Detailed Calculations

1. Introduction

Because of the extreme heterogeneity of the BORAX-V cores, especially core PSH-1, much consideration has been given to the question of how best to develop a calculational model. Many of the methods used in previous work have been discussed earlier in this report.

Later developments in calculational technique indicated that it would be possible to significantly improve calculated predictions of reactor behavior, and this has proved to be true. For example, to homogenize the boiler fuel rod and water over a specified region, what is the best way to obtain disadvantage factors, especially when the fuel-rod lattice spacing is irregular? For cylindrical fuel-rod cells, it has been shown¹⁵ that flux distribution in good agreement with experiment can be obtained by applying an isotropic-scattering outer-boundary condition (rather than the mirror reflection, or zero-derivative outer-boundary condition) in a transport-theory approximation. An S_n code, TOPIC,²⁹ which contains the isotropic-scattering outer-boundary condition as an option, was used to obtain thermal disadvantage factors in these calculations. To account for the irregular fuel-rod spacing in the 12-flow-rod boiler assembly, each rod was designated as one of four different cell types, with various amounts of water associated with each cell type. The cell problems were run with the various water annulus thicknesses corresponding to the different cell types, the thermal constants were flux- and volume-weighted over each fuel rod cell, and the homogenized fuel-rod cell constants were then volume-weighted to give homogenized boiler fuel zone constants.

Another consideration was the use of MUFT constants for stainless steel. Table X compares stainless-steel constants from MUFT with those obtained from GAM-I.¹¹ Since GAM stainless-steel constants were considered to be much better than those from MUFT, GAM was used to obtain three fast-group constants.

TABLE X. Comparison of MUFT Constants for Type 304
Stainless Steel with GAM-I Constants

Group	D	Σ_a	Σ_r	Constant Set
1	1.03242	0.00005	0.040339	MUFT
1	1.65398	0.000235	0.029859	GAM-I
2	0.35002	0.0	0.003815	MUFT
2	0.80840	0.001380	0.003502	GAM-I
3	0.38939	0.04996	0.000269	MUFT
3	0.35042	0.014021	0.002642	GAM-I

A new U^{238} cross-section set from Hanford's RBU library³⁰ has been added to the ANL GAM-I library. Comparison of this cross-section set with BNL-325 indicates much better agreement than the original GAM-I U^{238} cross sections. Use of this new set, called element No. 139, has been shown³¹ to predict k_{eff} for low-enriched water-moderated systems much more accurately than has been possible by using the old element No. 12 in GAM.

Although these calculations incorporated such considerations, they could be improved in several ways. For example, a double P-1 approximation in slab geometry was used to flux-weight the constants in the superheater fuel region. A better approximation could be used. More important, and because of a time limitation, the boron-stainless steel poison-rod constants were hand-generated by using tabulated values for flux depression rather than actually running poison-rod cell problems. Also, the description of the reactor could be further improved by using more mesh points than the 7500 allowed in PDQ-3.³²

In spite of these "flaws," the calculations gave remarkably good agreement with experiment, resulting in calculated k_{eff} values less than 1.5% high, and in some cases less than 0.2% high (see Table XI).

2. Constants

Thermal constants for the final BORAX computations were obtained by using TEMPEST¹² to average constants for rod-cell or plate-cell regions over a homogenized fuel-assembly (including box, shroud, and control-rod follower) spectrum. These cell constants were used to obtain the thermal flux distribution over fuel cells, and were then flux- and volume-weighted to produce homogenized PDQ fuel-zone constants. Thermal constants for homogenized material zones outside a fuel region were obtained by averaging the volume-weighted constants over the appropriate homogenized assembly spectrum. The atomic densities for the various materials are listed in Appendix C.

The boiler fuel-rod cell calculations used TOPIC,²⁹ a cylindrical S_4 code that has an isotropic-scattering outer-boundary condition. A comparison of the ratio of average-to-edge flux in the fuel rod and the disadvantage factor (defined as the ratio of the average flux in the moderator to the average flux in the nonmoderator) obtained from TOPIC with measured values⁸ for 4.95 w/o-enriched fuel rods in a 0.5-in. center-to-center lattice indicates good agreement. The experimentally measured ratio of average-to-edge flux in the fuel rod was 0.91 (no experimental error given); the value calculated in the present work is 0.90. The experimentally measured disadvantage factor was 1.18 (not corrected for flux perturbation in water channel due to flux wires). If the experimentally measured value of $\bar{\phi}(H_2O)/\bar{\phi}$ (fuel rod) were corrected for the wire perturbation, it would agree well with the calculated value of 1.25.

TABLE XI. Comparison of Calculation and Experiment, Minimum Critical Assemblies

Configuration	Experimental k_{eff}	Calculated k_{eff}	PDQ Problem Number and Description
Sixteen 680-g superheater assemblies, flooded	<1.000	1.0195 ± 0.0025	1001 Fine mesh SS spacers omitted
		1.0201 ± 0.0025	1002 Coarse mesh SS spacers omitted
		1.0100 ± 0.0025	1003 Fine mesh SS spacers included
		1.0109 ± 0.0025	1004 Coarse mesh SS spacers included
		0.9896 ± 0.0009	1005 Coarse mesh corresponding to PSH-1 quarter-core PDQ, SS spacers included
12-flow-rod-boiler minimum critical slab, no poison rods	1.0043	1.0308 ± 0.0025	2001 Fine mesh, using GAM No. 12 for U^{238}
		1.0292 ± 0.0025	2002 Coarse mesh, using GAM No. 12 for U^{238}
		1.0060 ± 0.0025	2003 Fine mesh, using GAM No. 139 for U^{238}
		1.0044 ± 0.0025	2004 Coarse mesh, using GAM No. 139 for U^{238}
12-flow-rod-boiler minimum critical slab, two poison rods	1.0023	1.0032 ± 0.0004	2005 Fine mesh, using GAM No. 139 for U^{238}

The 12-flow-rod boiler assembly was broken down into four different cell types, depending on flow- and fuel-rod arrangements, as shown in Fig. 20. Each fuel rod was associated with a certain volume of water surrounding it and was designated as one of the four types. The model used for the cell calculations is shown in Fig. 21, and the thermal cross sections for each cell type are given in Appendix D. To obtain PDQ homogenized fuel-zone constants, the flux- and volume-weighted constants from each cell type were volume-weighted by the fraction of total fuel-zone volume occupied by the particular cell type. The dashed line shown in Fig. 20 indicates the boundary of the PDQ boiler fuel zone. Use of this boundary required the subtraction of water from the affected Type 1 cells. This was accomplished by flux-weighting the Type 1 cell-region constants

as though they actually covered the entire 0.5-in. square, but volume-weighting with the actual water volume as indicated by the dashed line in Fig. 20.

Note:

Numbers Refer to Cell Type

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Fig. 20. Cell Types in 12-flow-rod Boiler Assembly

ID-103-A3536

Fig. 21. Calculational Model for Boiler Fuel-rod Cell Calculation

Two possible improvements can be indicated here. The homogenized cell constants should be both flux- and volume-weighted over the entire fuel zone to obtain homogenized fuel-zone constants. In the case of the 12-flow-rod boiler assembly, however, the thermal flux across the fuel zone is quite flat, as shown in Fig. 19. Hence, the error involved here is small. Also, it would probably be better to use a two-dimensional assembly cell calculation for flux-weighting the outer rows of fuel rods, but for the present case it is doubtful that much improvement could be gained.

FLIP-1³³ (with a double P-1 approximation) was employed similarly on the 680-g superheater element cell. The model for these calculations, shown in Fig. 22, omits the stainless-steel spacers between fuel plates; therefore, the water (or steam) constants were adjusted by volume-weighting stainless steel and water (or steam) constants before flux- and volume-weighting to obtain PDQ homogenized fuel-zone constants. Since the PDQ model explicitly described the water between elements and the combined stainless-steel box and insulator-void region, the fuel-region homogenization involved only those regions up to and including the outer fuel-plate cladding in Fig. 22.

Fig. 22. Calculational Model for Superheater Fuel-element Cell Calculation

The three fast group constants were obtained from GAM-I¹¹ by first obtaining the fast spectrum for the homogenized fuel assembly and then averaging the constants for individual PDQ material zones over that spectrum. The boiler fuel-zone constants, however, were averaged over the spectrum for boiler fuel-zone material only. Constants for control-rod poison material (boral) were obtained by using the "blackness theory"^{34,35,36} option* in GAM-I and TEMPEST and the appropriate homogenized boiler-assembly spectrum. The four-group constants for the PDQ material zones are tabulated in Appendix E.

*This option was added to the Phillips Petroleum Company versions of GAM-I and TEMPEST by L. A. Schmittroth and R. L. Curtis.

A significant improvement in the superheater fuel-zone constants would be obtained by doing four-group element cell calculations and flux- and volume-weighting the cell-region constants for all four groups rather than for only the thermal group.

3. PDQ Problems and Results

Minimum critical experiments were done with both 680-g superheater assemblies and 12-flow-rod boiler assemblies, and the results of these experiments were used as a basis for judging the validity of the four-group constants in Appendix E. Unfortunately, criticality was not achieved with sixteen 680-g superheater assemblies, and only 16 were available. However, it was estimated from inverse count-rate curves that 18 assemblies would be supercritical and 17 would be nearly critical. The arrangement of the subcritical 16-assembly array is shown in Fig. 23.

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Fig. 23. Sixteen-680-g-superheater-fuel-assembly Array,
Minimum Critical Mass Experiment

With 12-flow-rod boiler assemblies, criticality was achieved with 14 assemblies. Fuel rods and flow rods were rearranged to give the rectangular array shown in Fig. 24. Two boron-stainless steel poison rods were present in the first arrangement, as indicated in Fig. 24, and the measured k_{eff} for this array with control rods removed was 1.0023. When the two poison rods were replaced with fuel rods, k_{eff} was estimated to be 1.0043.

each of these experiments, a fairly fine mesh and a coarser mesh corresponding to that used in the quarter-core PDQ description of core PSH-1. The first superheater problems omitted the 0.062 x 0.062-in. stainless-steel spacers between fuel plates, but in later problems they were included. Because of mesh-line limitations, the superheater fuel zone was shortened by ~0.3 cm on each end to correspond with the line describing the boundaries of the boiler fuel zones, and a problem (No. 1005) was run to determine the effect. The results of these calculations are compared with experiment in Table XI. The agreement between calculation and experiment is quite good, ~1% high for the 680-g superheater assemblies (Problem 1003) and ~0.2% high for the 12-flow-rod boiler assemblies.

The effect of decreasing the superheater fuel zones by 0.6 cm decreased k_{eff} by ~2%. Because of mesh-line limitations in PDQ-3, a choice was involved in PDQ mesh descriptions (of the PSH-1 quarter core) between having adjacent mesh intervals almost a factor of 10 different in width, or using the mesh line that described the boundary of boiler fuel to describe the end of the superheater fuel and shortening the superheater fuel zone by

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Fig. 25. PDQ-3 Calculational Model for 16-680-g-superheater-assembly Array

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Fig. 26. PDQ-3 Calculational Model for 12-flow-rod-boiler Minimum Critical Slab

0.6 cm. This and other considerations pertaining to accurate calculation of control-rod worth led to the decision to shorten the superheater fuel zone. The effect of this on the calculated k_{eff} for the full PSH-1 core should be much less than 2%, but this does affect the calculated flooding worth somewhat. Figure 27 shows the PDQ model of a quadrant of the PSH-1 core.

The results of the problems describing the PSH-1 core are given in Table XII. These results are discussed and compared with experimental measurements in Section IV.

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Fig. 27. PDQ Model for Core PSH-1

An anomaly was evidenced in core B-1D control-rod calibration. Experimentally, the calibrations performed during the hot criticals indicated a lesser rod worth than when cold. To examine this paradox, PDQ problems were run. Only a slight modification in the mesh description of the quarter-core PSH-1 problem was necessary. The constants for the fuel zone were obtained in the same manner as for the 12-flow-rod boiler assembly, using GAM-I element number 139 for U^{238} . Four problems were run with the core B-1D description, and the results are tabulated in Table XIII.

TABLE XII. Results of PDQ Problems on Core PSH-1

PDQ Problem No.	Temp, °F	Boric Acid Concentration	Superheater Condition	Control-rod Condition	Calculated $k_{eff} \pm 0.0009$
11001	68	0	Flooded	Out	1.1125
11002	68	0	Drained	Out	1.1005
11003	68	5	Drained	Out	1.0575
11004	68	10	Drained	Out	1.0188
11005	68	15	Drained	Out	0.9845
11006	300	0	Flooded	Out	1.0957
11007	489	0	Flooded	Out	1.0683
11008	489	0	Drained	Out	1.0555
11009*	489, 10% voids	0	Drained	Out	1.0268
11010	68	0	Flooded	In	0.8911
11011	68	0	Drained	In	0.8725
11012	68	5	Drained	In	0.8450
11013	68	10	Drained	In	0.8198
11014	68	15	Drained	In	0.7974
11015	300	0	Flooded	In	0.8517
11016	489	0	Flooded	In	0.7956
11017	489	0	Drained	In	0.7768
11018*	489, 10% voids	0	Drained	In	0.7469

*To simulate operation at power, the moderator in the fuel zone only was considered to be 10% voided, and the boiler fuel was assumed to be 900°F for the resonance self-shielding calculation in GAM.

TABLE XIII. Results of PDQ Problems on Core B-1D

PDQ Problem No.	Temp, °F	Control-rod Condition	Calculated $k_{eff} \pm 0.0009$
11019	68	Out	1.1292
11020	489	Out	1.0805
11021	68	In	0.8941
11022	489	In	0.8018

IV. COMPARISON WITH EXPERIMENTS

A. Core B-1D

One puzzling result of the core B-1D experiments, as mentioned in the preceding section, was the apparent decrease of control-rod worth with increasing temperature.²⁸ To determine if such was actually the case, PDQ problems were run with all rods in and all rods out, at 68 and 489°F. The results of these problems are given in Table XIII. These results indicate that the total rod worth should increase significantly with temperature, contrary to the experimental findings. Table XIV gives the calculated total control-rod worth for both temperatures.

TABLE XIV. Calculated Control-rod Worth,
Core B-1D

Temperature, °F	Nine-control-rod-bank Total Worth, $K_{(\text{rods out})} - K_{(\text{rods in})}$
68	0.2352
489	0.2787

It must be concluded that some experimental error was made in the hot-rod calibrations. One possible source of error was a fission chamber that had been saturating during the B-1 experiments, which might explain the apparent decrease in control-rod worth with temperature. As a result of this error, the measured overall excess reactivity would have been less than the true value, especially at 489°F.

B. Core PSH-1

1. Control-rod Calibration and Available Excess Reactivity; Boric Acid Effect

The procedure that has been used to calibrate control rods in BORAX cores, as well as in other reactors such as YANKEE, EBWR, and ALPR, involves incremental additions of boric acid to the coolant to allow the control rods to be withdrawn from the just-critical position with no boric acid. The control rods are calibrated at various positions from just critical, no boric acid, to fully withdrawn by withdrawing them slightly from the just-critical position and observing the resulting asymptotic positive period. This period is related to reactivity ($\Delta k/k$) by the standard kinetics equation, and at $h + \Delta h/2$ the control-rod worth is determined as $\Delta k/k$ per unit height.

This method of control-rod calibration introduces an error due to boric acid perturbing the system. However, it has been the consensus that this error is much smaller in magnitude than that introduced by other practicable methods of control-rod calibration. It has also been the consensus that, in systems such as BORAX-V and YANKEE, the effect of boric acid is to decrease control-rod worth. Thus, the available excess reactivity obtained by integrating the control-rod calibration curve (obtained by this method) is an underestimate.

To estimate the effect of boric acid on control-rod worth from the calculated results given in Table XII, the results of experimental measurements must be discussed first. The usual procedure for determining total available excess reactivity has been to plot measured $\% \Delta k/k$ in. as a function of position, and then to integrate over position from just critical, no boric acid, to fully withdrawn. This supposedly results in total available excess reactivity, or integrated $\% \Delta k/k$. But what is the value of k in the denominator? The measured values of reactivity for a change in control-rod position, at least in BORAX-V, are typically in the range of 0.001 to 0.002. Or, the measured change in k is in the range of 0.001001 to 0.002004. The result, then, is that the denominator of the integrated $\% \Delta k/k$ should be ~ 1.001 to 1.002 .

On the other hand, as was pointed out by D. Shaftman,* one can argue from one-group theory that the sum of incremental reactivities over the range of control-rod travel is equal to the reactivity that would be observed if the control rods could be withdrawn completely in one step. With the system just critical, $k_0 = C/\Sigma_a = 1$. When the control rods are withdrawn slightly to obtain a small reactivity, $k_1 = C/(\Sigma_a - \Delta\Sigma'_a)$, and the reactivity observed is $\rho_1 = (k_1 - k_0)/k_1 k_0 = \Delta\Sigma'_a/C$. Then, enough homogeneous poison is added to add $\Delta\Sigma'_a$ back to the absorption cross section, and the system is now critical at the position of the preceding period. The control rods are withdrawn slightly again, and a second reactivity ρ_2 is measured where $\rho_2 = \Delta\Sigma''_a/C$. These steps are repeated until the control rods have been completely withdrawn.

If the control rods could be withdrawn in one step, the observed total reactivity would be

$$\rho = \sum_i \frac{\Delta\Sigma_a^i}{C} = \sum_i \rho_i.$$

This says that the sum of the incremental changes in reactivity is equal to the total available reactivity of the system.

Certain approximations are implied in the above hypothetical experiment, among which are the fact that no change is allowed in flux shape

*Private communication.

(or importance) along the axis of control-rod travel; and the homogeneous poison added to compensate for control-rod withdrawal is assumed to have no effect on diffusion length or other system characteristics.

It would seem that a less confusing procedure would be to determine $\Delta k/\Delta h$ at each measured point and then to integrate the resulting curve to obtain $k_{\text{eff}} - 1$. Then, if it is desired to talk about reactivity, ρ , instead of the multiplication factor, k , ρ would result from $(k_{\text{eff}} - 1)/k_{\text{eff}}$. This procedure yields a considerably different result than that obtained by simply integrating $(\Delta k/k)/\Delta h$ and calling the result "total available excess reactivity." To make comparisons with calculations, it is more convenient to discuss things in terms of the multiplication factor, k , rather than reactivity, ρ .

If control-rod worth at any position is defined as $\Delta k/\Delta h$ and total control-rod worth as $(k_{\text{out}} - k_{\text{in}})$, and reference is made to Table XII, the total calculated worth for core PSH-1, with superheater drained and no boric acid, is 0.2280. With 5 g of H_3BO_3 per gallon of H_2O , the worth is 0.2125; with 10 g/gal, the worth is 0.1990; and with 15 g/gal, it is 0.1871.

The fractional decrease in total control-rod worth as a function of boric acid concentration is shown in Fig. 28. A first thought was that this

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Fig. 28. Calculated Fractional Decrease in Control-rod Worth as a Function of Boric Acid Concentration, Core PSH-1

curve could be used as a basis for correcting the measured control-rod worths for the boric acid defect in the following manner:

Assume that the point-to-average rod worth is not changed by boric acid, and that the calculated values of total control-rod worth are correct. The point-to-average rod worth can be obtained by dividing the measured worth at any point by the average worth corresponding to the boric acid concentration at that measured point. The true rod worth is obtained by multiplying the point-to-average value by the average rod worth with no boric acid.

Subsequent calculations indicated that while the total control-rod worth (full in to full out) decreases appreciably with increasing boric acid concentration, the effect is not uniform over the range of control-rod travel. In fact, calculations indicated that over the range of the measurements there is no appreciable effect. These calculations were one-dimensional, slab-geometry, diffusion-theory, flux-synthesis type, using the homogenized, four-group, fuel-region constants and group-dependent radial bucklings from the appropriate PDQ problem output for the rodged and unrodged portions of the core, and with a water reflector at each end. Values of k_{eff} were computed for various control-rod positions from full in to full out by increasing the thickness of the unrodged region and decreasing the thickness of the rodged region while maintaining a total core height of 24 in. The bucklings of the adjacent core region were used in each of the two reflector regions. The resulting values of k_{eff} are listed in Table XV. The homogenized constants and bucklings are given in Appendix F.

TABLE XV. Calculated k_{eff} as a Function of Control-rod Position for Various Boric Acid Concentrations, Core PSH-1

Control-rod Position, from Bottom of Core, in.	Boric Acid Concentration, g(H ₃ BO ₃)/gal(H ₂ O)			
	0	5	10	15
0	0.8841	0.8527	0.8253	0.8018
1	0.8902	-	0.8283	0.8042
2	0.9004	0.8634	0.8337	0.8086
3	0.9168	0.8751	0.8433	0.8167
4	0.9374	0.8914	0.8577	0.8292
5	0.9587	0.9100	0.8750	0.8448
5.5	0.9688	0.9194	0.8840	0.8531
6	0.9786	0.9285	0.8929	0.8615
6.5	0.9877	0.9372	0.9015	0.8696
7	0.9964	0.9455	0.9098	0.8775
7.5	1.0045	0.9534	0.9176	0.8851
8	1.0120	0.9609	0.9251	0.8922
9	1.0257	0.9744	0.9386	0.9054
10	1.0375	0.9862	0.9506	0.9171
12	1.0569	1.0057	0.9704	0.9364
14	1.0719	1.0208	0.9856	0.9513
16	1.0836	1.0327	0.9976	0.9630
18	1.0929	1.0420	1.0069	0.9722
20	1.1004	1.0494	1.0143	0.9793
24	1.1129	1.0493	1.0243	0.9885

Derivatives of k_{eff} with respect to height were obtained from these values, and the results are shown in Fig. 29. The resulting curves thus indicate that the total control-rod worth is decreased by increasing boric acid concentration, and that the position of the peak worth is shifted slightly toward the core center line, which was, of course, expected. The curves also indicate that there is no appreciable change in the control-rod worth above ~9 in.

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Fig. 29. Nine-control-rod Bank, Calculated Differential Worth, Core PSH-1

The measured values of control-rod worth are also shown in Fig. 29 for comparison, and they indicate that the calculated values are far from absolute agreement. It is expected that if an iterative process

were employed (as in the flux-synthesis technique) to converge on group- and region-dependent radial bucklings, and if the axial reflector regions were treated as accurately as possible, much better agreement would be obtained. It might be implied that since the calculated control-rod worths are considerably less than the measurements, the overall control-rod worth has been grossly underestimated in the calculations, and thus the reactor was considerably more subcritical with the control rods fully inserted than had been previously estimated.

2. Flooding Worth

The flooding worth, i.e., the reactivity effect of flooding the superheaters, was calculated to be 1.20% Δk at room temperature and 1.28% Δk at 489°F. These can be compared to the "safety coefficient of flooding" as determined from experiment by multiplying the change in control-rod critical position by the average of the rod worth at two positions. This "safety coefficient" was determined to be 1.66% Δk at room temperature and 1.30% Δk at 489°F. Thus, while the actual reactivity effect of flooding the superheaters increases slightly with temperature, the "safety coefficient" decreases with temperature. Examination shows that the "safety coefficient" is greater than the change in k (in the case of core PSH-1, at least) by the area between the two curves of control-rod worth. This is illustrated in Fig. 30, where curve A represents the flooded-superheater case and B represents the curve of control-rod worth with

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Fig. 30. Comparison of Experimental and Calculated Changes in Reactivity

superheaters drained. The reactivity effect of flooding would be the area under curve B subtracted from the area under curve A, or

$$\text{Flooding worth} = (b+d) - (c+d) = b - c.$$

The "safety coefficient of flooding" is simply $a + b$. The difference between the "safety coefficient" and the reactivity flooding worth is

$$(a+b) - (b-c) = a + c.$$

3. Temperature Coefficient

The temperature coefficient as a function of temperature was determined in core PSH-1, with the superheaters flooded, by observing the critical control-rod position as a function of temperature and assuming that the control-rod calibration curve at room temperature held for all temperatures. Referring to Table XII, one sees that the calculated k_{eff} is decreased by 0.0450 in going from 68 to 489°F with superheaters drained. This gives an average temperature coefficient of $-1.07 \times 10^{-4} \Delta k/^{\circ}\text{F}$.

With the superheaters flooded, k_{eff} is decreased by 0.0168 in going from 68 to 300°F, and by 0.0274 from 300 to 489°F. Thus, the average temperature coefficient from 68 to 300°F is $-0.72 \times 10^{-4} \Delta k/^{\circ}\text{F}$; and from 300 to 489°F, the average temperature coefficient is $-1.45 \times 10^{-4} \Delta k/^{\circ}\text{F}$. The average from 68 to 489°F is $-1.05 \times 10^{-4} \Delta k/^{\circ}\text{F}$ with superheaters flooded. These values are plotted in Fig. 31 as a function of temperature, along with some experimentally determined values. The agreement is good, especially since the room-temperature rod-worth curve as a function of position was used for all temperatures, and it is known that the control-rod worth increases with temperature. As a result, the experimentally determined values are too large in magnitude, the error becoming larger with increasing temperature.

4. Power Coefficient

If the assumption is made that the normalization on calculated k_{eff} for 68°F, drained, holds for the 489°F case (that is, adding 0.0145 to calculated k) then k_{eff} at 489°F with superheaters drained is 1.0700. The maximum power obtained in core PSH-1, before fission-product poisons built in and without cooling the inlet water, was about 20 MWt. Thus, the average power coefficient of reactivity was about $-0.0035 \Delta k/\text{MWt}$ from 0 to 20 MWt.

Again assuming that adding 0.0145 to the calculated k_{eff} holds for the PDQ problem representing power operation with 10% voids in the boiler fuel-region coolant, and boiler fuel temperature at 900°F, k_{eff} for this situation would be 1.0413. If it is assumed that the power coefficient

is a linear function of void fraction in the boiler fuel-region coolant, this implies that at full power of 20 MW the average void fraction in the 3.375-in.-sq boiler fuel region is about 25%.

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Fig. 31. Temperature Coefficient, Core PSH-1

C. Neutron-flux Measurements*

A rather extensive program of experimental flux mapping was carried out on the various cores of BORAX-V. The measurements included coarse flux distributions, fine power distributions, and cadmium ratio measurements. Some of the results are presented here; additional results as well as methods and procedures are presented in Refs. 28, 37, 38, and 39.

1. Fine-power Distribution

Normalized fine-power distributions for the various cores are shown in Figs. 32, 33, 34, and 35. These data were obtained at zero power and room temperature by irradiating flux wires of uranium (235)-aluminum and uranium (235)-zirconium.

*This section written by D. C. Cutforth, Idaho Division.

CORE CENTER

Code:

- (No.) Power in fuel rod/Power in average fuel rod in core.
 ● Brron-stainless steel rod. All others 4.95% enriched fuel rods.
 * Power produced in that fuel assembly/Power produced in "average" fuel assembly.
 (No.) Power produced in "average" fuel rod in that assembly/Power of average fuel rod in the core.

ID-103-A3270 Fig. 33. Final Normalized Fine-power Map, Core CSH-1

ID-103-A3527

Fig. 34. Normalized Boiler-region Fine-flux Map, Core PSH-1

NOTES: ROOM TEMPERATURE
 SUPERHEATER DRAINED
 NO BORIC ACID
 ZERO POWER
 NUMBERS ARE RELATIVE POWER

NOTES: ROOM TEMPERATURE
 SUPERHEATER DRAINED
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Fig. 35. Normalized Superheater-region Fine-flux Map

Similar measurements could not be made at operating conditions because of the blockage of coolant channels during the irradiation. Measurements were made in one octant of the core on the assumption that symmetry existed. The existence of symmetry was verified in core B-1 by special traverse measurements.²⁸

Figure 36 shows the experimental results of the effect of various flow-rod configurations on the power distribution within a boiling fuel assembly. These results compare favorably with calculations (see Fig. 19). Proper replacement of the fuel rods with flow rods reduced the peak-to-average power production within a fuel assembly, as shown in Table XVI.

TABLE XVI. Effect of Flow Rods on Power Distribution within Boiling Fuel Assemblies

No. of Flow Rods	Individual Fuel-rod Peak-to-average Power Production
0	1.47
4	1.27
8	1.51
12	1.20

2. Axial Flux Distributions

Axial neutron-flux distribution measurements were made in each core at various power levels. From these measurements, axial flux shapes, axial peak-to-average ratios, and axial bucklings were obtained. The measurements were obtained from gold-wire irradiations in the earlier cores, and from Al-1% Cu wire and miniature fission ion chambers in the peripheral superheater core.

Figure 37 shows axial neutron-flux distributions for power levels of 0.5, 5, 10, 15, and 20 MWt. Note that the axial position of the peak activation shifts downward with increasing power level. A comparison of these data with those obtained from the U²³⁵-loaded ion chambers showed excellent agreement.

Experimental axial bucklings were obtained from a least-squares cosine-curve fit. In this fit, only those data that had the appearance of not being influenced by either the control rods or the reflector were used. Several axial bucklings are presented in Table XVII.

A maximum fission-causing flux of $2 \pm 0.2 \times 10^{13}$ at 18.4 MWt was obtained by using the chamber sensitivity from the manufacturer. This value was not corrected for the flux depression caused by the thimble or the local depression caused by the absorption of the miniature ion chamber. However, it compares favorably with the value of 2.97×10^{13} obtained from PDQ calculations.

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Fig. 36. Fine-flux Traverse through a Boiling Assembly with Various Metal-to-Water Ratios

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Fig. 37. Axial Neutron-flux Distributions at Power, Core Position 43, Core PSH-1A

TABLE XVII. Experimental Axial Bucklings

Core Position	Control-rod Position, in.	Boric Acid Concentration, g(H ₃ BO ₃)/gal(H ₂ O)	Power Level, MWt	B ² , cm ⁻²
55 PSH	9.6	0	0.5	0.00362
66 PSH	9.6	0	0.5	0.00343
77 PSH	9.6	0	0.5	0.00422
44 PSH	14.1	0	0.5	0.00318
43 PSH	14.1	0	0.5	0.00263
42 PSH	14.1	0	0.5	0.00236
22 PSH	14.1	0	0.5	0.00268
41 PSH	14.1	0	0.5	0.00289
41 PSH	25.0	0	15	0.00209
42 PSH	25.0	0	15	0.00186
43 PSH	25.0	0	15	0.00130
44 PSH	25.0	0	15	0.00099
36 PSH	25.0	0	22.4	0.00135
36 PSH	25.0	0	18.4	0.00145
36 PSH	25.0	0	15.4	0.00148
36 PSH	25.0	0	12.4	0.00138
36 PSH	25.0	0	10	0.00117
36 PSH	19.5	0	4.5	0.00165
36 PSH	20.5	0	4	0.00170
22 PSH	20.6	11.96	0.5	0.00184
41 PSH	20.6	11.96	0.5	0.00203
42 PSH	20.6	11.96	0.5	0.00189
43 PSH	20.6	11.96	0.5	0.00195
44 PSH	20.6	11.96	0.5	0.00184

3. Cadmium Ratios

Figures 38 and 39 show the axial cadmium-ratio variation in the pressure thimbles for power levels of 5 and 15 MWt in PSH-1. In these figures, cadmium ratios from miniature ion chambers can be compared with cadmium ratios from flux wires. Both sets of data show similar trends, with a much smaller axial variation than was anticipated. The data indicate that approximately the same degree of thermalization occurs throughout the axial traverse of the core. The value of the cadmium ratio decreased with increasing power.

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Fig. 38. Cadmium-ratio Distributions at 5 MWt, Cores PSH-1A and C

ID-103-A3453

Fig. 39. Cadmium-ratio Distributions at 15 MWt, Cores PSH-1A and C

V. MISCELLANEOUS TOPICS

A. Approximations in Few-group Reactor-physics Calculations*

Methods of reactor-physics analysis used in the design calculations of BORAX-V reactors have been previously outlined in Sections III-B and III-D. Specifically, the MUFT program with its associated library of cross sections was used to compute diffusion-theory parameters for one, two, or three collapsed-energy groups of above-thermal neutrons. The SOFOCATE program was applied to the computation of diffusion-theory parameters for a single group of thermal neutrons.

In MUFT computations for BORAX-V analysis, the option of the so-called "conventional Selengut-Goertzel (S-G)" model of neutron slowing down had been selected. For small bucklings, $B^2 \approx 0$, the computed value of $k_{\text{eff}}(B^2)$ decreases more rapidly than it would if the few-group parameters were obtained from the alternative model option, "consistent P_1 ; no S-G." In the case of the 60-fuel-assembly reference boiler core, the difference in reactivity is approximately 1% at room temperature.

Strictly, the few-group parameters obtained from MUFT and SOFOCATE computations are associated with a single value of the buckling, namely, the value of the buckling (B_{input}^2) assigned as input. However, often it is desirable to compute the effective multiplication factor, $k_{\text{eff}}(B^2)$, for other values of the buckling, without recomputing the few-group parameters in each case. Wick⁴⁰ has reported on numerical studies of the sign and the magnitude of the errors in $k_{\text{eff}}(B^2)$ resulting from the use of a buckling-independent, fixed set of few-group parameters. These computations were made for some special cases of thermal reactors. Similar computations have been performed for several BORAX-V lattices. For $B_{\text{input}_1}^2 = 0.0035 \text{ cm}^{-2}$, and $B_{\text{input}_2}^2 \approx 0.015 \text{ cm}^{-2}$, four-group fundamental-mode computations yielded the inequality

$$k_{\text{eff}}(B^2; B_{\text{input}_1}^2) \geq k_{\text{eff}}(B^2; B_{\text{input}_2}^2)$$

between 0 and 0.02 cm^{-2} . Using the properties of the continuity and monotonicity of $k_{\text{eff}}(B^2)$ as a function of B^2 , we conjecture that $k_{\text{eff}}(B^2; B_{\text{input}}^2)$ is bounded by these two functions within that same buckling interval.

The above-mentioned inequality appears to be due largely to a decrease in $\Sigma_a/\Sigma_{\text{rem}}$ in the collapsed group covering the range of resonance energies in U^{238} , group 3, at the lower value of B_{input}^2 . In the vicinity of $B^2 = 0.0035 \text{ cm}^{-2}$, the difference in k_{eff} is $\approx 0.9\%$, where the "difference" is defined to be

$$k_{\text{eff}}(B^2; B_{\text{input}_1}^2) - k_{\text{eff}}(B^2; B_{\text{input}_2}^2).$$

* Memorandum from D. H. Shaftmān, RE Division, to R. E. Rice, October 29, 1962.

The procedures used in the MUFT program to collapse the 54 neutron-energy groups to three groups, two groups, or one group are consistent in the sense that the computed absorption rate, fission rate, probability of slowing down to thermal energies, etc., per source neutron are the same in all three few-group calculations, provided $B^2 = B_{\text{MUFT}}^2$ input. In computations of BORAX-V lattices, the two-group and four-group values of $k_{\text{eff}}(B^2)$ obtained on the basis of $B_{\text{input}}^2 \approx 0$ were greatly different (of the order of 4%) for $B^2 \approx 0.015 \text{ cm}^{-2}$, and as would be expected, were quite close for bucklings near zero. Indeed, as $B^2 \rightarrow 0$, the values of $k_{\text{eff}}(B^2)$ tended to the same number regardless of the choice of B_{input}^2 or whether the computations were by two-group or four-group diffusion theory. The reason for this is that, at least in the few-group structure selected for these analyses, the probability that a given neutron capture would be parasitic was not much affected by the details of the neutron-flux spectrum. It was for bucklings in the middle of the range between 0 and $B_{\text{input}}^2 = 0.015 \text{ cm}^{-2}$ that the corresponding four-group and two-group computations showed the greatest differences in $k_{\text{eff}}(B^2)$. These computations clearly indicated that if k_{eff} computations are to be performed with a single set of diffusion-theory parameters, it would be less inconsistent to do the four-group analysis than the two-group analysis for B^2 much different from the input buckling.

B. Superheater-Boiler Coupling*

1. Effective Buckling Calculation

The provocation to examine coupling theory in connection with the BORAX-V reactor originated as a result of questions concerning the proper buckling to give as MUFT input for the regionwise fast cross sections. Since the total buckling for a multiregion system (bare reactor) can be represented as the sum of the bucklings of the separate regions multiplied by the respective region importance functions, application of coupling theory would seem to provide a convenient method of obtaining such functions. Avery's approach⁴¹ to coupling has been usefully applied to fast-thermal systems and is applicable to the BORAX-V superheating reactor.

In the design calculations, a full-core geometrical buckling of 0.0035 was used for all reactor cross-section problems. Possibly, if the calculational procedure were iterated, i.e., material bucklings were calculated from a first run on constants and weighting functions from the first reactor problems, a better estimation of bucklings appropriate for the two fuel-region compositions could be stated. Because of the uncertainties of homogenization validity, accuracy of the MUFT and SOFOCATE cross-section libraries, and a time limitation, the possibilities here indicated were not exhaustively explored.

*Study made in 1960-1961.

2. Prediction of Operational Characteristics

Treating the superheater-boiler combination as a coupled system provides results that are at least comprehensionally useful. An interesting approach to the subject is given by Radkowsky and Bayard⁴² wherein the ratio of power produced between the two regions of the Pressurized Water Reactor (PWR) is calculated. The Laplacians of the diffusion equations are integrated and converted to surface integrals, thus obtaining leakages between regions.

The approach taken by Avery defines a term, k_{ij} , as the expectation value of a fission neutron in reactor j creating a next-generation fission neutron in reactor i . Similarly, S_{ij} is the fission-neutron source in reactor i resulting from fissions caused by neutrons originating in reactor j . Total fission source in reactor i is then

$$S_i = \sum_{j=1}^N S_{ij},$$

where N is the number of reactors in the system. For the present consideration, the following stable ratios result (B: boiling reactor; S: superheating reactor):

$$\frac{S_{BB}}{S_B} = k_{BB}, \quad \frac{S_{BS}}{S_S} = k_{BS};$$

$$\frac{S_{SB}}{S_B} = k_{SB}, \quad \frac{S_{SS}}{S_S} = k_{SS}.$$

Following Avery, other relations are obtained. If $\Delta_i \equiv 1 - k_{ii}$, criticality is given by

$$k_{BS}k_{SB} = \Delta_B\Delta_S;$$

and if ρ is small compared to the Δ_i , and $k_{eff} = 1 + k_{ex}$,

$$k_{ex} \approx \rho \approx \frac{k_{BS}k_{SB} - \Delta_B\Delta_S}{\Delta_B + \Delta_S},$$

or, in terms of deviations from the critical values,

$$\rho \approx \frac{\Delta_B\Delta_S}{\Delta_B + \Delta_S} \left(-\frac{\delta\Delta_B}{\Delta_B} - \frac{\delta\Delta_S}{\Delta_S} + \frac{\delta k_{BS}}{k_{BS}} + \frac{\delta k_{SB}}{k_{SB}} \right),$$

and

$$\rho \approx \sum_{i=1}^N \alpha_i \frac{\delta \nu_i}{\nu_i},$$

where ν_i is the number of neutrons born per fission in reactor i , and $\delta \nu_i$ is a change in this quantity.

The fraction of reactivity in reactor i is

$$\alpha_i = \frac{\frac{1}{\Delta_i}}{\sum_{j=1}^N \frac{1}{\Delta_j}},$$

or α_i is the ratio of overall reactivity to $\delta \nu_i / \nu_i$.

Avery's original paper discusses the kinetic equation and gives a complete formulation in terms of the adjoint and real functions.

A method* of approximating the k_{ij} and the S_{ij} is that of using the output sources from a typical three-region problem (superheater, boiler, and reflector) and running a second single-iteration problem where only the input source for a single fueled region is given. When this is done for each of the two regions in turn (using RE-122), values of the S_{ij} are obtained and the various other expressions may be calculated. An example of what this means for BORAX-V is given by the abbreviated display of k_{ij} in Table XVIII.

TABLE XVIII. Coupling Coefficients

Reactor Temp, °F	% Voids, Boiler	Superheater	Configuration	k_{eff}	k_{SS}	k_{SB}	k_{BS}	k_{BB}	M^2	
									Boiler	SH
489	15	Dry	CSH	1.010	0.598	0.094	0.476	0.901	76.9	113.5
489	0	Dry	CSH	1.048	0.596	0.089	0.074	0.951	64.8	113.5
489	0	Flooded	CSH	1.068	0.734	0.106	0.393	0.943	64.8	60.0
70	0	Dry	CSH	1.130	0.668	0.087	0.474	1.041	47.2	81.7
70	0	Flooded	CSH	1.137	0.791	0.099	0.363	1.032	47.2	41.6
489	15	Dry	PSH	1.017	0.523	0.096	0.559	0.909	76.7	111.1
489	0	Dry	PSH	1.057	0.442	0.100	0.327	1.004	64.6	111.1
489	0	Flooded	PSH	1.067	0.524	0.122	0.312	0.998	64.6	58.8
70	0	Dry	PSH	1.142	0.468	0.086	0.345	1.098	47.0	80.6
70	0	Flooded	PSH	1.150	0.580	0.111	0.321	1.088	47.0	41.1

*Suggested by Dr. R. Avery.

The value of the coupling approach was not fully established. A wider range of calculations would need to be performed. Consideration of what practical value may be seen here leads to such thoughts as:

a. If it was desirable, say, to increase the power fraction handled by the superheater, k_{SB} might be expeditiously increased. An empirical dependence of this factor on the integral neutronic properties of the boiler region adjacent to the superheater could conceivably be established, and the maximizing factors determined. Comparison of the first and second examples of Table XVIII shows a slight increase in k_{SB} as the CSH boiler is voided, whereas the effect is in the reverse direction (if any) for the PSH boiler voiding (sixth and seventh examples). An almost linear trend appears to exist between k_{SB} and $M_{Boiler}^2/M_{Superheater}^2$ for the three hot cases of the CSH core. A more realistic void distribution or the insertion of a zone adjacent to the superheater consisting of a different $H_2O:U^{235}$ ratio could lead to information of practical value.

b. The construction of a model to describe the kinetic behavior of the system for the assumption of a rapid perturbation in a single region would be facilitated by thinking in terms of coupling theory.

C. A TDC⁴³ Calculation of the BORAX-V Exponential Experiment⁸

The exponential assembly was originally conceived as a convenient way of obtaining certain lattice measurements on BORAX-V boiler fuel. Time available for the actual experimental work was restricted because of the need to use the fuel in loading the BORAX-V reactor.

Three hundred forty-nine fuel rods were arranged in a cylinder supported so as to maintain the reference 0.5-in. spacing. Constructed in the form of three trays, the cylinder was crisscrossed with aluminum sheets to approximate the actual condition of the interassembly regions within the core. For safety reasons, the entire assembly was surrounded by cadmium sheets to cancel the effect of a radial reflector. Figure 40 reproduces a cross-sectional drawing of the assembly. Enriched 3.38 w/o U^{235} -zirconium alloy wires, 3/8 in. long, were used for flux measurements.

Cadmium ratios were measured along axial and radial traverses for a variety of moderator voids, which were simulated by using a number of small-diameter pieces of polyethylene tubing closed at the ends. These were placed within the central "assembly" square only. The fact that the negative buckling had the same value, regardless of the amount of simulated void, was something of a surprise. This fact is perhaps explained by the insulating effect of the surrounding unvoided medium.

ID-103-A3523

Fig. 40. Cross Section of Exponential Assembly

TDC is a two-dimensional, cylindrical-geometry, transport-theory counterpart of DSN. TDC allows the specification of a source in the first axial region, which, in the representation of the BORAX-V exponential, was done by giving a source of unity in each of four groups in that region. In effect, this unit source was put into a 26-cm-thick region of water. MUFT and SOFOCATE cross sections were used in all regions, except that the radial reflector was given a cadmium thermal-absorption cross section.

Figure 41 gives the calculated thermal flux plotted from the TDC output. The $1/e$ -folding length for the experiment was 17.9 cm, and this value was retained, with or without voids. The experimental plot is superimposed on the figure, normalized at the boundary between the nonvoided and 40% void regions. The calculated $1/e$ -folding length appears to be somewhat shorter; a value of 12.3 to 12.5 is approximated, being also about the same in both regions. In both experiment and calculation, the epithermal flux falls off at the same rate as the corresponding thermal flux.

Actually, it would have been better to have designated the inter-assembly region of increased water with aluminum separately. The calculation seems to imply a somewhat less reactive situation than what was actually present. If the calculated thermal flux were spectrally corrected to correspond with the U^{235} activation cross section, magnitude shifts from voids to no voids would be expected to be in better agreement.

The radial thermal-flux dip across an assembly was not shown by the problem. The experiment gave a value of 2.8 for the ratio of the flux at the assembly corner to that at the center, the measurement being along a diagonal.

ID-103-A3521

Fig. 41. Exponential Experiment, Center-line Flux Plot

APPENDIX A A Summary of MUFT/SOFOCATE Cross Sections for Uniformly Homogenized Cores

Group 1: 10-0.821 MeV
 2: 0.821 MeV-5.53 keV
 3: 5.53 keV-0.625 eV

Fission in U^{238} occurs
 primarily in Group 1 and
 resonance capture in Group 3

"Interpolated" constants were
 obtained by plotting the values
 from the first series in which
 U^{235} content was varied.

					Cross Sections				
Composition	Condition	Source of Cross Sections		Type	Three Fast Groups			One Fast Group	Thermal
					1 of 3	2 of 3	3 of 3	1 of 1	
Homogenized boiler with 16.2 g of U^{235} per rod	489°F 0% voids	Interpolated	60.67	D				1.4998	0.4337
				Σ_a				0.008143	0.1012
				Σ_r				0.01657	-
				$\nu\Sigma_f$				0.00642	0.1716
Homogenized boiler with 16.2 g of U^{235} per rod	489°F 7½% voids	Interpolated		D				1.5420	0.4589
				Σ_a				0.01691	0.1003
				Σ_r				0.01522	-
				$\nu\Sigma_f$				0.00644	0.1708
Homogenized boiler with 16.2 g of U^{235} per rod	489°F 15% voids	M/S 11615056	70.46	D	2.7284	1.2708	0.9698	1.5870	0.4848
				Σ_a	0.0035	0.0021	0.0198	0.0081	0.0992
				Σ_r	0.0603	0.0530	0.0439	0.0139	-
				$\nu\Sigma_f$	0.0062	0.0011	0.0135	0.1694	0.1694
Homogenized boiler with 16.2 g of U^{235} per rod	70°F 0% voids	M/S 21600062	44.25	D	2.3835	1.0557	0.7681	1.3517	0.3224
				Σ_a	0.0037	0.0021	0.0193	0.0082	0.1259
				Σ_r	0.0776	0.0765	0.0681	0.0221	-
				$\nu\Sigma_f$	0.0063	0.0011	0.0127	0.0064	0.2115
Homogenized boiler with 16.2 g of U^{235} per rod	70°F Contains B^{10} ($N_{B^{10}} = 0.42 \times 10^{-5}$)	M/S 21600061	44.21	D	2.3834	1.0556	0.7670	1.3518	0.3245
				Σ_a	0.0037	0.0021	0.0199	0.0084	0.1338
				Σ_r	0.0776	0.0765	0.0676	0.0219	-
				$\nu\Sigma_f$	0.0063	0.0011	0.0127	0.0064	0.2081
Homogenized boiler with 32.4 g of U^{235} per rod	70°F 0% voids	M/S 23200104	44.08	D	2.3828	1.0541	0.7613	1.3578	0.3328
				Σ_a	0.0039	0.0026	0.0255	0.0102	0.1869
				Σ_r	0.0774	0.0763	0.0653	0.0205	-
				$\nu\Sigma_f$	0.0068	0.0021	0.0241	0.0104	0.3492
Homogenized boiler	336°F 0% voids	M/S 31600084	51.58	D	2.4872	1.1181	0.8248	1.4205	0.3779
				Σ_a	0.0036	0.0021	0.0194	0.0081	0.1086
				Σ_r	0.0719	0.0687	0.0601	0.0194	-
				$\nu\Sigma_f$	0.0063	0.0011	0.0129	0.0064	0.1832
Water reflector	489°F	M/S 59000129 $B^2 = 0.001$	53.89	D	4.2792	1.2308	0.7182	2.1268	0.2592
				Σ_a	0.001089	0.00001	0.00076	0.00063	0.0115
				Σ_r	0.08440	0.1196	0.1202	0.03883	-
				$\nu\Sigma_f$	0.0	0.0	0.0	0.0	0.0
Water reflector	336°F	M/S 30000090	38.27	D	3.3279	1.0980	0.6427	1.7153	0.2119
				Σ_a	0.0013	0.00001	0.0009	0.0007	0.0142
				Σ_r	0.0974	0.1339	0.1361	0.0441	-
				$\nu\Sigma_f$	0.0	0.0	0.0	0.0	0.0
Water reflector	70°F	M/S 59000131 $B^2 = 0.001$	34.05	D	3.4082	-0.9759	0.5695	1.6947	0.1594
				Σ_a	0.001393	0.000013	0.000952	0.000798	0.0193
				Σ_r	0.1059	0.1509	0.1517	0.04897	-
				$\nu\Sigma_f$	0.0	0.0	0.0	0.0	0.0
Al-H ₂ O Volume fraction of Al = 0.35		22680133	48.96	D	2.8991	1.1300	0.8506	1.6003	-
				Σ_a	0.0010	0.00007	0.0010	0.0007	-
				Σ_r	0.0761	0.0943	0.0948	0.0320	-
				$\nu\Sigma_f$	0.0	0.0	0.0	0.0	0.0

Composition	Condition	Source of Cross Sections		Type	Cross Sections				
					Three Fast Groups			One Fast Group	Thermal
					1 of 3	2 of 3	3 of 3	1 of 1	
Superheater with 680 g of U ²³⁵ per assembly	489°F Dry	M/S 11680073	105.94	D	3.4113	1.5552	0.9128	1.8992	0.4778
				Σ_a	0.0007	0.0005	0.0104	0.0038	0.0899
				Σ_r	0.0495	0.0487	0.0439	0.0142	-
				$\nu\Sigma_f$	0.0007	0.0009	0.0129	0.0047	0.1345
Superheater with 680 g of U ²³⁵ per assembly	489°F Flooded	Interpolated	55.36	D				1.5305	0.3549
				Σ_a				0.0041	0.1006
				Σ_r				0.0236	-
				$\nu\Sigma_f$				0.0049	0.1484
Superheater with 680 g of U ²³⁵ per assembly	336°F Dry	M/S 31680088	89.90	D	3.2572	1.4616	0.8582	1.8032	0.3214
				Σ_a	0.0008	0.0005	0.0106	0.0039	0.1202
				Σ_r	0.0540	0.0548	0.0499	0.0162	-
				$\nu\Sigma_f$	0.0007	0.0009	0.0130	0.0048	0.1303
Superheater with 680 g of U ²³⁵ per assembly	336°F Flooded	M/S 32680089	45.93	D	2.6343	1.2600	0.6795	1.4308	0.3077
				Σ_a	0.0011	0.0004	0.0086	0.0042	0.1054
				Σ_r	0.0776	0.1248	0.0616	0.0270	-
				$\nu\Sigma_f$	0.0007	0.0007	0.0104	0.0049	0.1540
Superheater with 680 g of U ²³⁵ per assembly	70°F Dry	Interpolated		D				1.7162	0.3441
				Σ_a				0.0039	0.1042
				Σ_r				0.0183	-
				$\nu\Sigma_f$				0.0048	0.1522
Superheater with 680 g of U ²³⁵ per assembly	70°F Flooded	M/S 22680076	38.97	D	2.4882	1.0323	0.6068	1.3462	0.2585
				Σ_a	0.0012	0.0005	0.0112	0.0042	0.1210
				Σ_r	0.0848	0.0965	0.0921	0.0303	-
				$\nu\Sigma_f$	0.0007	0.0009	0.0135	0.0050	0.1755
Superheater with 430 g of U ²³⁵ per assembly	489°F Dry	M/S 11430067	106.93	D	3.4127	1.5569	0.9108	1.18904	0.4791
				Σ_a	0.0006	0.0003	0.0076	0.0028	0.0715
				Σ_r	0.0495	0.0488	0.0452	0.0149	-
				$\nu\Sigma_f$	0.0004	0.0006	0.0084	0.0032	0.0922
Superheater with 430 g of U ²³⁵ per assembly	489°F Flooded	Interpolated	56.67	D				1.5253	0.3501
				Σ_a				0.0030	0.0792
				Σ_r				0.0243	-
				$\nu\Sigma_f$				0.0031	0.1002
Superheater with 430 g of U ²³⁵ per assembly	336°F Dry	M/S 31430086	90.63	D	3.2584	1.4631	0.8565	1.7956	0.4137
				Σ_a	0.0007	0.0003	0.0077	0.0029	0.0751
				Σ_r	0.0540	0.0548	0.0513	0.0169	-
				$\nu\Sigma_f$	0.0004	0.0006	0.0085	0.0031	0.0958
Superheater with 430 g of U ²³⁵ per assembly	336°F Flooded	M/S 32430087	46.14	D	2.6348	1.1101	0.6510	1.4264	0.3020
				Σ_a	0.0010	0.0003	0.0081	0.0031	0.0847
				Σ_r	0.0776	0.0867	0.0836	0.0278	-
				$\nu\Sigma_f$	0.0004	0.0006	0.0086	0.0032	0.1055
Superheater with 430 g of U ²³⁵ per assembly	70°F Dry	Interpolated	77.839	D	3.1160	1.3789	0.8077	1.7094	0.3440
				Σ_a	0.0007	0.0003	0.0078	0.0029	0.0864
				Σ_r	0.0586	0.0610	0.0575	0.0190	-
				$\nu\Sigma_f$	0.0004	0.0006	0.0085	0.0032	0.1093
Superheater with 430 g of U ²³⁵ per assembly	70°F Flooded	M/S 22430070	39.132 39.132	D	2.4885	1.0330	0.6060	1.3424	0.2513
				Σ_a	0.0011	0.0003	0.0082	0.0032	0.0990
				Σ_r	0.0848	0.0966	0.0937	0.0311	-
				$\nu\Sigma_f$	0.0004	0.0006	0.0087	0.0032	0.1228

APPENDIX B

Three-group Cross-section Set Used in Flow-rod Studies

Composition	Condition	Type	Cross Sections		
			Group 1	Group 2	Thermal
Boiler	Cold	D	1.7322	0.7291	0.3029
Four flow rods	68°F	Σ_a	0.0027	0.0160	0.1098
45 fuel rods		Σ_r	0.0464	0.0768	-
		$\nu\Sigma_f$	0.0032	0.0108	0.1804
Boiler	489°F	D	2.0441	0.8967	0.3731
Four flow rods	No steam voids	Σ_a	0.0026	0.0158	0.0916
45 fuel rods		Σ_r	0.0373	0.0595	-
		$\nu\Sigma_f$	0.0032	0.0110	0.1523
Boiler	Cold	D	1.7603	0.7282	0.3023
Eight flow rods	68°F	Σ_a	0.0027	0.0149	0.1067
41 fuel rods		Σ_r	0.0474	0.0800	-
		$\nu\Sigma_f$	0.0030	0.0098	0.1741
Boiler	489°F	D	2.1978	0.9332	0.3723
Eight flow rods	No steam voids	Σ_a	0.0023	0.0147	0.0887
41 fuel rods		Σ_r	0.0378	0.0619	-
		$\nu\Sigma_f$	0.0029	0.0100	0.1467
Boiler	Cold	D	1.7889	0.7214	0.2851
12 flow rods	68°F	Σ_a	0.0023	0.0138	0.1002
37 fuel rods		Σ_r	0.0485	0.0832	-
		$\nu\Sigma_f$	0.0027	0.0089	0.1631
Boiler	489°F	D	1.9805	0.8568	0.3671
12 flow rods	No steam voids	Σ_a	0.0022	0.0131	0.0828
37 fuel rods		Σ_r	0.0395	0.0654	-
		$\nu\Sigma_f$	0.0026	0.0089	0.1354
Boiler	489°F	D	2.0404	0.9007	0.4213
12 flow rods	10% steam voids	Σ_a	0.0022	0.0144	0.0802
37 fuel rods		Σ_r	0.0370	0.0597	-
		$\nu\Sigma_f$	0.0026	0.0095	0.1327
Superheater	Cold	D	1.7088	0.6060	0.2513
430 g of U ²³⁵	Flooded	Σ_a	0.0006	0.0082	0.0990
per assembly		Σ_r	0.0518	0.0937	-
		$\nu\Sigma_f$	0.0005	0.0087	0.1228
Superheater	Cold	D	2.1556	0.8077	0.3440
430 g of U ²³⁵	Dry	Σ_a	0.0005	0.0077	0.0864
per assembly		Σ_r	0.0337	0.0575	-
		$\nu\Sigma_f$	0.0005	0.0084	0.1093

Cross Sections					
Composition	Condition	Type	Group 1	Group 2	Thermal
Superheater 430 g of U^{235} per assembly	489°F Flooded	D	1.9331	0.7050	0.3501
		Σ_a	0.0005	0.0080	0.0792
		Σ_r	0.0417	0.0733	-
		$\nu\Sigma_f$	0.0005	0.0086	0.1002
Superheater 430 g of U^{235} per assembly	489°F Dry	D	2.3702	0.9108	0.4791
		Σ_a	0.0005	0.0077	0.0715
		Σ_r	0.0274	0.0452	-
		$\nu\Sigma_f$	0.0005	0.0084	0.0922
Reflector	Cold 68°F	D	2.2311	0.5695	0.1594
		Σ_a	0.0735	0.1527	0.0193
		Σ_r	0.0730	0.1517	-
		$\nu\Sigma_f$	0.0	0.0	0.0
Reflector	489°F	D	2.8011	0.7182	0.2592
		Σ_a	0.0586	0.1210	0.0115
		Σ_r	0.0581	0.1202	-
		$\nu\Sigma_f$	0.0	0.0	0.0
Superheater 680 g of U^{235} per assembly	Cold Flooded	D	1.7085	0.6068	0.2585
		Σ_a	0.0008	0.0113	0.1210
		Σ_r	0.0517	0.0921	-
		$\nu\Sigma_f$	0.0008	0.0135	0.1755
Superheater 680 g of U^{235} per assembly	Cold Dry	D	2.1552	0.8091	0.3441
		Σ_a	0.0007	0.0106	0.1042
		Σ_r	0.0366	0.0565	-
		$\nu\Sigma_f$	0.0008	0.0133	0.1522
Superheater 680 g of U^{235} per assembly	489°F Flooded	D	1.9331	0.7061	0.4314
		Σ_a	0.0007	0.0109	0.1006
		Σ_r	0.0416	0.0719	-
		$\nu\Sigma_f$	0.0008	0.0133	0.1484
Superheater 680 g of U^{235} per assembly	489°F Dry	D	2.3691	0.9128	0.4778
		Σ_a	0.0006	0.0104	0.0899
		Σ_r	0.0274	0.0439	-
		$\nu\Sigma_f$	0.0008	0.0129	0.1345

APPENDIX C

Atomic Densities Used in BORAX-V Core PSH-1

Composition	Element	68°F	300°F	489°F	489°F 10% Void
Water	Hydrogen	0.06672	0.06138	0.05267	
	Oxygen	0.03336	0.03069	0.026337	
	Natural boron				
	5 g(H ₃ BO ₃)/gal(H ₂ O)	0.0000129	-	-	
	Nat boron 10 g/gal	0.0000257	-	-	
	Nat boron 15 g/gal	0.0000386	-	-	
Saturated steam	Hydrogen		0.000168	0.001424	
	Oxygen		0.000084	0.000712	
<u>68-489°F</u>					
6001 aluminum	Aluminum	0.06009	-	-	
	Nickel	0.00028	-	-	
304 stainless steel	Iron	0.06114	-	-	
	Nickel	0.00774	-	-	
	Chromium	0.01747	-	-	
	Manganese	0.00178	-	-	
4.95 w/o-enriched UO ₂	Oxygen	0.04589			
	Uranium-235	0.00115			
	Uranium-238	0.02179			
680 g superheater inner plate meat	Oxygen	0.01249			
	Uranium-235	0.00582			
	Uranium-238	0.00042			
	Iron	0.04560			
	Nickel	0.00577			
	Chromium	0.01303			
	Manganese	0.00133			
680-g superheater outer plate meat	Oxygen	0.00687			
	Uranium-235	0.003204			
	Uranium-238	0.000231			
	Iron	0.05259			
	Nickel	0.00666			
	Chromium	0.01503			
	Manganese	0.00153			
12-flow-rod boiler assembly homogenized over 4.406 in. sq. including aluminum follower, box, and shroud	Hydrogen	0.03915	0.03602	0.03091	0.02910
	Oxygen	0.02766	0.02609	0.02354	0.02263
	Uranium-235	0.00020			
	Uranium-238	0.00384			
	Iron	0.00194			
	Nickel	0.00032			
	Chromium	0.00057			
	Manganese	0.00003			
	Aluminum	0.01221			
	Nat boron 5 g/gal	0.0000076			
	Nat boron 10 g/gal	0.0000151			
	Nat boron 15 g/gal	0.0000227			

Composition	Element	68°F	300°F	489°F	489°F 10% Void
12-flow-rod boiler fuel homogenized over 3.375 in. sq.	Hydrogen	0.04157	0.03824	0.03282	0.02954
	Oxygen	0.03456	0.03289	0.03018	0.02854
	Uranium-235	0.00035			
	Uranium-238	0.00654			
	Iron	0.00326			
	Nickel	0.00042			
	Chromium	0.00093			
	Manganese	0.00010			
	Aluminum	0.00141			
	Nat boron 5 g/gal	0.0000080			
49-fuel-rod boiler assembly homogenized over 4.406 in. sq. including aluminum follower, box, and shroud	Nat boron 10 g/gal	0.0000160			
	Nat boron 15 g/gal	0.0000240			
	Hydrogen	0.03580	0.03293	0.08282	
	Oxygen	0.02860	0.02717	0.02483	
	Uranium-235	0.00027			
	Uranium-238	0.00508			
	Iron	0.00253			
	Nickel	0.00037			
	Chromium	0.00072			
49-fuel-rod boiler fuel region homogenized over 3.375 in. sq.	Manganese	0.00007			
	Aluminum	0.01134			
	Hydrogen	0.03549	0.03264	0.02802	
	Oxygen	0.03598	0.03456	0.03225	
	Uranium-235	0.00046			
	Uranium-238	0.00866			
	Iron	0.00432			
	Nickel	0.00055			
Boiler assembly box and wafer between boxes, homogenized	Chromium	0.00123			
	Manganese	0.00013			
	Hydrogen	0.03336	0.03069	0.02634	
	Oxygen	0.01668	0.01534	0.01317	
	Aluminum	0.03004			
	Nickel	0.00014			
	Nat boron 5 g/gal	0.0000064			
Boiler assembly box, shroud, water between box and shroud, and water between shroud and follower, homogenized	Nat boron 10 g/gal	0.0000129			
	Nat boron 15 g/gal	0.0000193			
	Hydrogen	0.02783	0.02557	0.02407	
	Oxygen	0.01391	0.01279	0.01203	
	Aluminum	0.03505			
	Nickel	0.000163			
	Nat boron 5 g/gal	0.0000054			
Superheater assembly box and insulator gap homogenized	Nat boron 10 g/gal	0.0000107			
	Nat boron 15 g/gal	0.0000161			
	Iron	0.03057			
	Nickel	0.00387			
	Chromium	0.00874			
	Manganese	0.00089			

Composition	Element	68°F	300°F	489°F	489°F 10% Void
680-g superheater homogenized over 4.406 in. sq. including aluminum follower and shroud	Hydrogen } Drained	0.02879	0.02652	0.02306	
	Oxygen } Drained	0.01488	0.01375	0.01202	
	Hydrogen } Flooded	0.04011	0.03689	0.03166	
	Oxygen } Flooded	0.02054	0.01894	0.01632	
	Uranium-235	0.000228			
	Uranium-238	0.000016			
	Iron	0.01059			
	Nickel	0.00148			
	Chromium	0.00309			
	Manganese	0.00015			
	Aluminum	0.00842			
	Nat boron 5 g/gal	0.0000055			
	Nat boron 10 g/gal	0.0000111			
	Nat boron 15 g/gal	0.0000166			
680-g superheater fuel region, bounded by end of fuel meat and outer plate cladding, including spacers	Hydrogen } Drained	0.0	0.00010	0.00084	
	Oxygen } Drained	0.00177	0.00182	0.00219	
	Hydrogen } Flooded	0.03911	0.03598	0.03087	
	Oxygen } Flooded	0.02133	0.01976	0.01721	
	Uranium-235	0.000826			
	Uranium-238	0.000059			
	Iron	0.02414			
	Nickel	0.00306			
	Chromium	0.00690			
	Manganese	0.00070			
Superheater element box, end, water between box ends, homogenized	Hydrogen } Drained	0.01678	0.01544	0.01345	
	Oxygen } Drained	0.00839	0.00772	0.00673	
	Hydrogen } Flooded	0.02650	0.02437	0.02091	
	Oxygen } Flooded	0.01325	0.01218	0.01045	
	Iron	0.03399			
	Nickel	0.00430			
	Chromium	0.00971			
Superheater element box, end, water between box ends, homogenized	Manganese	0.00099			
	Nat boron 5 g/gal	0.0000032			
	Nat boron 10 g/gal	0.0000065			
	Nat boron 15 g/gal	0.0000097			
Control-rod cladding material, homogenized	Iron	0.04541			
	Nickel	0.00617			
	Chromium	0.01324			
	Manganese	0.00066			
	Aluminum	0.01461			
Control-rod poison boral	Aluminum	0.02898			
	Carbon	0.01544			
	Nat boron	0.06176			
Poison rod poison, B ₄ C, stainless steel	Iron	0.05734			
	Nickel	0.00726			
	Chromium	0.01639			
	Manganese	0.00167			
	Carbon	0.002024			
	Nat boron	0.008095			

APPENDIX D

Thermal Constants for Fuel-assembly Cell Calculations1. Thermal Constants for 4.95 w/o-enriched UO₂ Boiler Pin Cell Calculations

Temp, °F	Boric Acid Concentration, g(H ₃ BO ₃)/ gal(H ₂ O)	Material	Σ_a	Σ_{s0}	Σ_{s1}
68	0	UO ₂	0.6026	0.3805	0.0085
	0	304 stainless steel	0.1919	0.8562	0.0101
	0	H ₂ O	0.0164	2.705	0.613
68	5	UO ₂	0.3996	0.3805	0.0085
	5	304 stainless steel	0.1910	0.8562	0.0101
	5	H ₂ O plus H ₃ BO ₃	0.0235	2.697	0.614
68	10	UO ₂	0.5966	0.3805	0.0085
	10	304 stainless steel	0.1901	0.8562	0.0101
	10	H ₂ O + H ₃ BO ₃	0.0306	2.690	0.616
68	15	UO ₂	0.5937	0.3805	0.0085
	15	304 stainless steel	0.1892	0.8562	0.0101
	15	H ₂ O + H ₃ BO ₃	0.0376	2.683	0.618
300	0	UO ₂	0.5190	0.3805	0.0085
	0	304 stainless steel	0.1683	0.8562	0.0101
	0	H ₂ O	0.0132	2.311	0.608
489	0	UO ₂	0.4690	0.3805	0.0085
	0	304 stainless steel	0.1536	0.8562	0.0101
	0	H ₂ O	0.0103	1.887	0.546
489 10% void	0	UO ₂	0.4665	0.3805	0.0085
	0	304 stainless steel	0.1528	0.8562	0.0101
	0	H ₂ O, 10% voids	0.0093	1.6938	0.492

2. Thermal Constants for 680-g Superheater Plate Cell Calculations

Superheater Condition	Temp. °F	C _B	Material	Σ_a	Σ_{s0}	Σ_{s1}
Flooded	68	0	H ₂ O	0.01585	2.657	0.625
		0	304 SS	0.1861	0.8562	0.0101
		0	Outer-plate meat	1.666	0.7993	0.0100
		0	Inner-plate meat	2.878	0.7528	0.0100
Drained	68	0	H ₂ O	0.01504	2.577	0.644
		0	304 SS	0.1765	0.8562	0.0101
		0	Outer-plate meat	1.575	0.7993	0.0100
		0	Inner-plate meat	2.719	0.7528	0.0100
Drained	68	2	H ₂ O + H ₃ BO ₃	0.01767	2.575	0.645
		2	304 SS	0.1762	0.8562	0.0101
		2	Outer-plate meat	1.572	0.7993	0.0100
		2	Inner-plate meat	2.714	0.7528	0.0100
Drained	68	5	H ₂ O + H ₃ BO ₃	0.02162	2.572	0.646
		5	304 SS	0.1758	0.8562	0.0101
		5	Outer-plate meat	1.569	0.7993	0.0100
		5	Inner-plate meat	2.708	0.7528	0.0100
Drained	68	10	H ₂ O + H ₃ BO ₃	0.02815	2.567	0.647
		10	304 SS	0.1752	0.8562	0.0101
		10	Outer-plate meat	1.563	0.7993	0.0100
		10	Inner-plate meat	2.703	0.7528	0.0100
Drained	68	15	H ₂ O + H ₃ BO ₃	0.03465	2.562	0.649
		15	304 SS	0.1746	0.8562	0.0101
		15	Outer-plate meat	1.557	0.7993	0.0100
		15	Inner-plate meat	2.693	0.7528	0.0100
Flooded	300	0	H ₂ O	0.01289	2.281	0.615
		0	304 SS	0.1644	0.8562	0.0101
		0	Outer-plate meat	1.448	0.7993	0.0100
		0	Inner-plate meat	2.498	0.7528	0.0100
Drained	300	Saturated Steam:		3.075×10^{-5}	5.546×10^{-3}	1.561×10^{-3}
		0	H ₂ O	0.01237	2.231	0.628
		0	304 SS	0.1579	0.8562	0.0101
		0	Outer-plate meat	1.388	0.7993	0.0100
		0	Inner-plate meat	2.394	0.7528	0.0100

Superheater Condition	Temp, °F	C _B	Material	Σ _a	Σ _{s0}	Σ _{s1}
Flooded	489	0	H ₂ O	0.01012	1.867	0.552
		0	304 SS	0.1579	0.8562	0.0101
		0	Outer-plate meat	1.388	0.7993	0.0100
		0	Inner-plate meat	2.265	0.7528	0.0100
		Saturated Steam:		1.955 × 10 ⁻⁴	3.664 × 10 ⁻²	1.119 × 10 ⁻²
Drained	489	0	H ₂ O	0.009787	1.834	0.560
		0	Saturated steam	0.0002646	0.04958	0.01514
		0	304 SS	0.1455	0.8562	0.0101
		0	Outer-plate meat	1.269	0.7993	0.0100
		0	Inner-plate meat	2.188	0.7528	0.0100

APPENDIX E
Four-group Constants for PDQ Calculations

12-FLOW-ROD BOILER 680-g SUPERHEATER PSH CORE						
1. 68°F, No Boric Acid						
PDQ Comp. No.	Material	Group	D	Σ_a	Σ_r	$\nu\Sigma_f$
1	Reflector water	1	1.9916	0.00058	0.10645	
		2	1.0582	0.0	0.14654	
		3	0.6053	0.00100	0.14196	
		4	0.1577	0.01931	-	
2	Water around boiler	1	1.7168	0.00047	0.11434	
		2	0.8457	0.0	0.14702	
		3	0.6162	0.00090	0.12682	
		4	0.1581	0.01635	-	
3	Water around superheater a. Superheater drained	1	1.6734	0.00043	0.11843	
		2	0.8518	0.0	0.14366	
		3	0.6231	0.00089	0.12458	
		4	0.1711	0.01504	-	
	b. Superheater flooded	1	1.6991	0.00046	0.11573	
		2	0.8540	0.0	0.14485	
		3	0.6171	0.00092	0.12963	
		4	0.1627	0.01585	-	
4	Aluminum	1	2.5497	0.00025	0.01470	
		2	1.5453	0.00048	0.00084	
		3	3.3812	0.00077	0.00054	
		4	3.376	0.01166	-	
5	Blackness theory Poison section	1	1.9562*	0.00310	-	
		2	1.0557*	0.03864		
		3	0.3526**	0.77844		
		4	0.0094**	6.902		
6	Al-SS control-rod cladding	1	1.9069	0.00024	0.02615	
		2	0.9288	0.00116	0.00286	
		3	0.4545	0.01052	0.00208	
		4	0.4157	0.14657	-	
7	Aluminum-water Box, water, shroud, water	1	2.1224	0.00035	0.05627	
		2	1.1519	0.00028	0.06181	
		3	1.1955	0.00083	0.05321	
		4	0.3911	0.01342	-	
8	Aluminum-water Box, water ($\frac{1}{2}$ H ₂ O)	1	2.0530	0.00036	0.06458	
		2	1.0952	0.00024	0.07400	
		3	1.0540	0.00084	0.06375	
		4	0.3021	0.01401		
9	a. Stainless steel, void Superheater box, insulator void ($\frac{1}{2}$ SS) Superheater drained	1	3.2987	0.00012	0.01504	
		2	1.6218	0.00069	0.00242	
		3	0.7003	0.00685	0.00810	
		4	0.6385	0.09010	-	

1. 68°F, No Boric Acid (Contd.)

PDQ Comp. No.	Material	Group	D	Σ_a	Σ_r	$\nu\Sigma_f$
9	b. Stainless steel, void	1	3.3080	0.00012	0.01493	
	Superheater box,	2	1.6168	0.00069	0.00175	
	insulator void	3	0.7008	0.00701	0.00132	
	Superheater flooded	4	0.6384	0.09414	-	
10	Stainless steel, water	1	2.1034	0.00024	0.04637	
	a. Superheater box end, water	2	1.0277	0.00076	0.03806	
	Superheater drained	3	0.5032	0.00783	0.03273	
		4	0.3140	0.10246	-	
	b. Superheater box end,	1	1.8038	0.00031	0.06255	
	water	2	0.8755	0.00077	0.05947	
	Superheater flooded	3	0.4495	0.00816	0.05294	
		4	0.2403	0.10975	-	
	Boiler fuel	1	1.8338	0.00394	0.08830	0.00815
	Homogenized over 3.375 in. sq.	2	0.9745	0.00291	0.09184	0.00162
	a. GAM No. 139 for U ²³⁸	3	0.5643	0.03079	0.07511	0.02454
		4	0.1895	0.17249	-	0.28999
11	b. GAM No. 12 for U ²³⁸	1	1.6822	0.00386	0.08847	0.00840
		2	0.8632	0.00178	0.09257	0.00161
		3	0.5276	0.03097	0.07971	0.02511
		4	0.1895	0.17249	-	0.28999
12	a. Superheater fuel	1	1.7040	0.00147	0.08069	0.00305
	Superheater flooded	2	0.8388	0.00231	0.08633	0.00385
		3	0.4556	0.04560	0.77057	0.06079
		4	0.1678	0.45566	-	0.77635
	b. Superheater fuel	1	3.8008	0.00120	0.01287	0.00304
	Superheater drained	2	1.9301	0.00231	0.00140	0.00384
		3	0.7999	0.04443	0.00102	0.05993
		4	0.4302	0.43407	-	0.75449

*From homogenized boiler.

**From blackness calculation.

13 Boron -SS poison rod--method of obtaining constants

$$\left. \begin{array}{l} 1.83 \text{ w/o B}^{\text{nat}} \\ \text{in 304 SS} \end{array} \right\} \text{radius} = 0.32893 \text{ cm}$$

$$\text{SS clad, outer radius} = 0.47625 \text{ cm}$$

Pin-cell area in 12-flow-rod boiler homogenized over 3.375 in. sq. =
1.9861555 cm².

Poison-section area = 0.33990 cm ² ,	Volume fraction = 0.171137;
Stainless-steel-clad	
section = 0.37265 cm ² ,	Volume fraction = 0.187625;
Water area = 1.273598 cm ² ,	Volume fraction = 0.641238.

The poison section has

$$\begin{aligned} \text{SS volume fraction} &= 0.937905; \\ \text{B}^{\text{nat}} \text{ volume fraction} &= 0.062095; & N(\text{B}^{\text{nat}}) &= 0.008095 \times 10^{24}; \\ & & N(\text{B}^{\text{nat}}) &= 0.001524 \times 10^{24}. \end{aligned}$$

Self-shielding Factor

From TEMPEST, $\sigma_a(\text{B}^{10})$ at 68°F is 2950 barns; applying a $\sqrt{T_0/T}$ temperature correction, we get 2457 barns at 300°F and 2201 barns at 489°F.

From Ref. 44, we obtain $f = 0.310$ at 68°F; 0.355 at 300°F;
 0.385 at 489°F.

Doing some manipulating, assume that $\bar{\phi}_{\text{pois}} = f \bar{\phi}_{\text{H}_2\text{O}}$; $\bar{\phi}_{\text{clad}} = \bar{\phi}_{\text{cell}}$. Then,

$$\bar{\phi}_{\text{cell}} = \frac{\bar{\phi}_{\text{pois}} V_{\text{pois}} + \bar{\phi}_{\text{clad}} V_{\text{clad}} + \bar{\phi}_{\text{H}_2\text{O}} V_{\text{H}_2\text{O}}}{V_{\text{cell}}} = \frac{\bar{\phi}_{\text{H}_2\text{O}} (f V_{\text{pois}} + V_{\text{H}_2\text{O}})}{V_{\text{cell}}}$$

$$\bar{\phi}_{\text{cell}} = \frac{V_{\text{cell}}}{V_{\text{cell}} - V_{\text{clad}}}$$

The result is

68°F	300°F	489°F
$\bar{\phi}_{\text{H}_2\text{O}} = 1.170 \bar{\phi}_{\text{cell}}$	$\bar{\phi}_{\text{H}_2\text{O}} = 1.157 \bar{\phi}_{\text{cell}}$	$\bar{\phi}_{\text{H}_2\text{O}} = 1.149 \bar{\phi}_{\text{cell}}$
$\bar{\phi}_{\text{pois}} = 0.363 \bar{\phi}_{\text{cell}}$	$\bar{\phi}_{\text{pois}} = 0.411 \bar{\phi}_{\text{cell}}$	$\bar{\phi}_{\text{pois}} = 0.442 \bar{\phi}_{\text{cell}}$

These factors were used to weight the volume fractions (for thermal group) and thus the cross sections.

The cross sections were obtained from the GAM and TEMPEST problems used as the source of all the preceding constants.

1. 68°F, No Boric Acid (Contd.)

PDQ Comp. No.	Material	Group	D	Σ_a	Σ_r	$\nu \Sigma_f$
13	Boron-SS poison rod	1	1.4873	0.00051	0.08789	
		2	0.7286	0.00948	0.09587	
		3	0.4121	0.05067	0.08248	
		4	0.1573	0.33864	-	

2. 68°F, 5 g(H₃BO₃)/gal(H₂O)

PDQ Comp. No.	Material	Group	D	Σ_a	Σ_r	$\nu\Sigma_f$
1	Reflector water	1	1.9914	0.00058	0.10646	
		2	1.0580	0.00001	0.14653	
		3	0.6051	0.00145	0.14164	
		4	0.1590	0.02766	-	
2	Water around boilers	1	1.7166	0.00047	0.11435	
		2	0.8456	0.00001	0.14702	
		3	0.6157	0.00131	0.12682	
		4	0.1582	0.02348	-	
3	Water around superheater Superheater drained	1	1.6732	0.00043	0.11843	
		2	0.8517	0.00001	0.14366	
		3	0.6225	0.00130	0.12458	
		4	0.1711	0.02162	-	
4	Aluminum	1	2.5497	0.00025	0.01470	
		2	1.5453	0.00048	0.00084	
		3	3.3812	0.00077	0.00054	
		4	3.378	0.01160	-	
5	Poison section of control rod	1	1.9562*	0.00310	-	
		2	1.0557*	0.03864		
		3	0.3526**	0.77844		
		4	0.0095**	6.89300		
6	Aluminum-stainless steel control-rod poison clad	1	0.9069	0.00024	0.02615	
		2	0.9288	0.00116	0.00286	
		3	0.4545	0.01052	0.00208	
		4	0.4161	0.14590		
7	Aluminum-water Box, water, shroud, water	1	2.1223	0.00035	0.05627	
		2	1.1518	0.00028	0.16181	
		3	1.1946	0.00100	0.05321	
		4	0.3914	0.01606	-	
8	Aluminum-water Box, water ($\frac{1}{2}$ H ₂ O)	1	2.0529	0.00036	0.06458	
		2	1.0951	0.00024	0.07401	
		3	1.0532	0.00104	0.06375	
		4	0.3023	0.01754	-	
9	Stainless steel, void Superheater box, insulator void ($\frac{1}{2}$ SS) Superheater drained	1	3.2987	0.00012	0.01504	
		2	1.6218	0.00069	0.00242	
		3	0.7003	0.00685	0.00810	
		4	0.6390	0.08974	-	
10	Stainless steel, water Superheater box end, water Superheater drained	1	2.1033	0.00024	0.04637	
		2	1.0277	0.00077	0.03806	
		3	0.5031	0.00794	0.03273	
		4	0.3151	0.10317	-	
11	Boiler fuel a. GAM No. 139 for U ²³⁸	1	1.8337	0.00394	0.08830	0.00815
		2	0.9744	0.00292	0.09184	0.00162
		3	0.5640	0.03104	0.07511	0.02454
		4	0.1898	0.17677	-	0.28874

2. 68°F , 5 g(H_3BO_3)/gal(H_2O) (Contd.)

PDQ Comp. No.	Material	Group	D	Σ_a	Σ_r	$\nu\Sigma_f$
11	b. GAM No. 12 for U^{238}	1	1.6821	0.00386	0.08847	0.00840
		2	0.8632	0.00178	0.09257	0.00161
		3	0.5273	0.03122	0.07971	0.02511
		4	0.1898	0.17677	-	0.28874
12	Superheater fuel Superheater drained	1	3.8008	0.00120	0.01287	0.00304
		2	1.9301	0.00231	0.00140	0.00384
		3	0.7999	0.04443	0.00102	0.05993
		4	0.4312	0.43235	-	0.7516
13	Boron-SS poison rod	1	1.4873	0.00051	0.08789	
		2	0.7286	0.00949	0.09587	
		3	0.4121	0.05092	0.09248	
		4	0.1573	0.34376	-	

*From homogenized boiler.

**From blackness.

3. 68°F , 10 g(H_3BO_3)/gal(H_2O)

1	Reflector water	1	1.9911	0.00058	0.10646	
		2	1.0579	0.00002	0.14653	
		3	0.6049	0.00189	0.14133	
		4	0.1602	0.03588	-	
2	Water around boiler	1	1.7164	0.00047	0.11435	
		2	0.8455	0.00002	0.14702	
		3	0.6152	0.00172	0.12682	
		4	0.1584	0.03055	-	
3	Water around superheater Superheater drained	1	1.6730	0.00043	0.11844	
		2	0.8516	0.00002	0.14366	
		3	0.6220	0.00171	0.12458	
		4	0.1711	0.02815	-	
4	Aluminum	1	2.5497	0.00025	0.01470	
		2	1.5453	0.00048	0.00084	
		3	3.3812	0.00077	0.00054	
		4	3.3790	0.01155	-	
5	Poison section of control rod	1	1.9562*	0.00310		
		2	1.0557*	0.03864		
		3	0.3526**	0.77844		
		4	0.0096**	6.88400		
6	Al-SS control-rod cladding	1	1.9069	0.00024	0.02615	
		2	0.9288	0.00116	0.00286	
		3	0.4545	0.01052	0.00208	
		4	0.4165	0.14520	-	
7	Aluminum-water Box, water, shroud, water	1	2.1222	0.00035	0.05627	
		2	1.1517	0.00029	0.06181	
		3	1.1938	0.00117	0.05321	
		4	0.3918	0.01868	-	

3. 68°F, 10 g(H₃BO₃)/gal(H₂O) (Contd.)

PDQ Comp. No.	Material	Group	D	Σ_a	Σ_r	$\nu\Sigma_f$
8	Aluminum-water Box, water ($\frac{1}{2}$ Al)	1	2.5028	0.00036	0.06458	
		2	1.0951	0.00025	0.07401	
		3	1.0525	0.00125	0.06375	
		4	0.3026	0.02105	-	
9	Stainless steel, void Superheater box, insulator void ($\frac{1}{2}$ SS) Superheater drained	1	3.2987	0.00012	0.01504	
		2	1.6218	0.00069	0.00242	
		3	0.7003	0.00685	0.00810	
		4	0.6394	0.08943	-	
10	Stainless steel-water Superheater box end, water Superheater drained	1	2.1032	0.00024	0.04637	
		2	1.0276	0.00077	0.03806	
		3	0.5030	0.00804	0.03273	
		4	0.3151	0.10447	-	
11	Boiler fuel a. GAM No. 139 for U ²³⁸	1	1.8335	0.00394	0.08830	0.00815
		2	0.9743	0.00292	0.09184	0.00162
		3	0.5637	0.03130	0.07511	0.02454
		4	0.1900	0.18102	-	0.28749
	b. GAM No. 12 for U ²³⁸	1	1.6820	0.00387	0.08847	0.00840
		2	0.8631	0.00179	0.09257	0.00161
		3	0.5271	0.03148	0.07971	0.02511
		4	0.1900	0.18102	-	0.28749
12	Superheater fuel Superheater drained	1	3.8008	0.00120	0.01287	0.00304
		2	1.9301	0.00231	0.00140	0.00384
		3	0.7999	0.04443	0.00102	0.05993
		4	0.4318	0.43118	-	0.74866
13	Boron-SS poison rod	1	1.4873	0.00051	0.08789	
		2	0.7286	0.00949	0.09587	
		3	0.4121	0.05118	0.08248	
		4	0.1573	0.34885	-	

*From homogenized boiler.

**From blackness.

4. 68°F, 15 g(H₃BO₃)/gal(H₂O)

1	Reflector water	1	1.9908	0.00058	0.10646	
		2	1.0578	0.00002	0.14653	
		3	0.6047	0.00234	0.14101	
		4	0.1614	0.04399	-	
2	Water around boilers	1	1.7162	0.00048	0.11482	
		2	0.8453	0.00002	0.14705	
		3	0.6147	0.00213	0.12896	
		4	0.1585	0.03755	-	
3	Water around superheater Superheater drained	1	1.6728	0.00043	0.11844	
		2	0.8515	0.00002	0.14366	
		3	0.6215	0.00211	0.12458	
		4	0.1711	0.03465	-	

4. 68°F, 15 g(H₃BO₃)/gal(H₂O) (Contd.)

PDQ Comp. No.	Material	Group	D	Σ_a	Σ_r	$\nu\Sigma_f$
4	Aluminum	1	2.5497	0.00025	0.01470	
		2	1.5453	0.00048	0.00084	
		3	3.3812	0.00077	0.00054	
		4	3.3810	0.01149	-	
5	Poison section of control rods	1	1.9562*	0.00310	-	
		2	1.0557*	0.03864		
		3	0.3526**	0.77844		
		4	0.0097**	6.87500		
6	Al-SS control-rod cladding	1	1.9069	0.00024	0.02615	
		2	0.9288	0.00116	0.00286	
		3	0.4545	0.01052	0.00208	
		4	0.4168	0.14450	-	
7	Aluminum-water Box, water, shroud, water	1	2.1220	0.00035	0.05627	
		2	1.1516	0.00029	0.06181	
		3	1.1930	0.00134	0.05321	
		4	0.3921	0.02126	-	
8	Aluminum-water Box, water ($\frac{1}{2}$ H ₂ O)	1	2.0526	0.00036	0.06458	
		2	1.0950	0.00025	0.07401	
		3	1.0517	0.00145	0.06375	
		4	0.3029	0.02452	-	
9	Stainless steel, void Superheater box, insulator void Superheater drained	1	3.2987	0.00012	0.01504	
		2	1.6218	0.00069	0.00242	
		3	0.7003	0.00685	0.00810	
		4	0.6398	0.08912	-	
10	Stainless steel, water SS box end, water Superheater drained	1	2.1032	0.00024	0.04637	
		2	1.0276	0.00077	0.03806	
		3	0.3772	0.00814	0.03272	
		4	0.3153	0.10580	-	
11	Boiler fuel a. GAM No. 139 for U ²³⁸	1	1.8334	0.00394	0.08830	0.00815
		2	0.9742	0.00293	0.01984	0.00162
		3	0.5634	0.03155	0.07511	0.02454
		4	0.1903	0.18522	-	0.28648
	b. GAM No. 12 for U ²³⁸	1	1.6739	0.00387	0.08859	0.00840
		2	0.8592	0.00179	0.09260	0.00161
		3	0.1903	0.18522	-	0.28648
12	Superheater fuel Superheater drained	1	3.8008	0.00120	0.01287	0.00304
		2	1.9301	0.00231	0.00140	0.00384
		3	0.7999	0.04443	0.00102	0.05993
		4	0.4328	0.42958	-	0.74583
13	Boron-SS poison rod	1	1.4873	0.00051	0.08789	
		2	0.7286	0.00950	0.09587	
		3	0.4121	0.05144	0.08248	
		4	0.1573	0.35388	-	

*From homogenized boiler.

**From blackness.

5. 300°F, No Boric Acid

PDQ Comp. No.	Material	Group	D	Σ_a	Σ_r	$\nu\Sigma_f$
1	Reflector water	1	2.1537	0.00053	0.09794	
		2	1.1500	0.0	0.13452	
		3	0.6588	0.00092	0.13031	
		4	0.2013	0.01490	-	
2	Water around boilers	1	1.8551	0.00043	0.10570	
		2	0.9174	0.0	0.13517	
		3	0.6715	0.00082	0.11535	
		4	0.1942	0.01319	-	
3	Water around superheater a. Superheater drained	1	1.8068	0.00039	0.10959	
		2	0.9252	0.0	0.13179	
		3	0.6792	0.00081	0.11320	
		4	0.2064	0.01237	-	
	b. Superheater flooded	1	1.8349	0.00042	0.10705	
		2	0.9272	0.0	0.13301	
		3	0.6721	0.00084	0.11818	
		4	0.1986	0.01289	-	
4	Aluminum	1	2.5466	0.00025	0.01478	
		2	1.5466	0.00048	0.00084	
		3	3.3810	0.00076	0.00053	
		4	3.4250	0.01022	-	
5	Blackness theory Poison section of control rod	1	2.0451*	0.00310		
		2	1.1080*	0.03866		
		3	0.3558**	0.77193		
		4	0.0094**	6.9010		
6	Al-SS control-rod cladding	1	1.9025	0.00024	0.02616	
		2	0.9286	0.00116	0.00286	
		3	0.4543	0.01045	0.00205	
		4	0.4253	0.12850	-	
7	Aluminum, water Box, water, shroud, water	1	2.2065	0.00032	0.05264	
		2	1.2060	0.00028	0.05680	
		3	1.2813	0.00079	0.04837	
		4	0.4732	0.01133	-	
8	Aluminum-water Box, water ($\frac{1}{2}$ H ₂ O)	1	2.1487	0.00034	0.06022	
		2	1.1545	0.00024	0.06800	
		3	1.1346	0.00079	0.05794	
		4	0.3676	0.01171	-	
9	Stainless steel, void Superheater box, insulator void	1	3.2964	0.00012	0.01492	
		2	1.6233	0.00069	0.00173	
		3	0.7002	0.00680	0.00123	
		4	0.6515	0.08047	-	
	a. Superheater drained	1	3.3057	0.00012	0.01493	
		2	1.6179	0.00069	0.00175	
		3	0.7007	0.00698	0.00131	
		4	0.6528	0.08307	-	

5. 300°F, No Boric Acid (Contd.)

PDQ Comp. No.	Material	Group	D	Σ_a	Σ_r	$\nu\Sigma_f$
10	Stainless steel, water	1	2.1526	0.00023	0.04414	
	Superheater box end, water	2	1.0538	0.00076	0.03507	
	a. Superheater drained	3	0.5117	0.00776	0.02984	
		4	0.3456	0.09089	-	
	b. Superheater flooded	1	1.8611	0.00030	0.05911	
		2	0.9049	0.00077	0.05477	
		3	0.4603	0.00809	0.04838	
		4	0.2714	0.09651	-	
11	Boiler fuel	1	1.9167	0.00390	0.08296	0.00813
	a. GAM No. 139 for U ²³⁸	2	1.0217	0.00291	0.08447	0.00162
		3	0.5932	0.03083	0.06804	0.02438
		4	0.2285	0.15176	-	0.25594
	b. GAM No. 12 for U ²³⁸	1	1.7616	0.00383	0.08312	0.00836
		2	0.9084	0.00177	0.08519	0.00161
		3	0.5518	0.03112	0.07256	0.02500
		4	0.2285	0.15176	-	0.25594
12	Superheater fuel	1	1.7810	0.00145	0.07561	0.00305
	a. Superheater flooded	2	0.8790	0.00231	0.07938	0.00384
		3	0.4724	0.04546	0.07034	0.06059
		4	0.1947	0.39825	-	0.67662
	b. Superheater drained	1	3.7860	0.00120	0.01305	0.00303
		2	1.9255	0.00230	0.00162	0.00383
		3	0.7985	0.04429	0.00119	0.05967
		4	0.4611	0.38284	-	0.66269
13	Boron-SS poison rod	1	1.5516	0.00048	0.08234	
		2	0.7615	0.00948	0.08827	
		3	0.4273	0.05062	0.07513	
		4	0.1850	0.31634	-	

*From homogenized boiler.

**From blackness.

6. 489°F, No Boric Acid, Zero Power

1	Reflector water	1	2.4748	0.00045	0.08428	
		2	1.3359	0.0	0.11518	
		3	0.7678	0.00079	0.11157	
		4	0.2587	0.01148	-	
2	Water around boilers	1	2.1345	0.00036	0.09156	
		2	1.0646	0.0	0.11588	
		3	0.7859	0.00069	0.09688	
		4	0.2466	0.01033	-	
3	Water around superheater a. Superheater drained	1	2.0773	0.00032	0.09502	
		2	1.0762	0.0	0.11253	
		3	0.7956	0.00068	0.09493	
		4	0.2596	0.00979	-	

6. 489°F, No Boric Acid, Zero Power (Contd.)

PDQ						
Comp.						
No.	Material	Group	D	Σ_a	Σ_r	$\nu\Sigma_f$
3	b. Superheater flooded	1	2.1090	0.00035	0.09286	
		2	1.0779	0.0	0.11372	
		3	0.7863	0.00071	0.09960	
		4	0.2515	0.01012	-	
4	Aluminum	1	2.5443	0.00024	0.01485	
		2	1.5478	0.00048	0.00083	
		3	3.3808	0.00076	0.00052	
		4	3.4570	0.00933	-	
5	Blackness theory Control-rod poison section	1	2.2081*	0.00310		
		2	1.2055*	0.03865		
		3	0.3618**	0.76000		
		4	0.0099**	6.84700	-	
6	Al-SS control-rod cladding	1	1.8938	0.00024	0.02619	
		2	0.9281	0.00116	0.00285	
		3	0.4539	0.01031	0.00200	
		4	0.4315	0.11730	-	
7	Aluminum, water Box, water, shroud, water	1	2.2617	0.00031	0.05050	
		2	1.2444	0.00028	0.05344	
		3	1.3487	0.00076	0.04458	
		4	0.5879	0.00971	-	
8	Aluminum, water Box, water ($\frac{1}{2}$ H ₂ O)	1	2.3223	0.00030	0.05321	
		2	1.2644	0.00024	0.05836	
		3	1.2929	0.00072	0.04870	
		4	0.4605	0.00983	-	
9	Stainless steel, void Superheater box, insulator void	1	3.2925	0.00012	0.01491	
		2	1.6263	0.00068	0.00172	
		3	0.7000	0.00671	0.00120	
		4	0.6602	0.07408	-	
	a. Superheater drained	1	3.3014	0.00012	0.01492	
		2	1.6201	0.00069	0.00174	
		3	0.7005	0.00690	0.00127	
		4	0.6504	0.07602	-	
10	Stainless steel, water Superheater box end, water	1	2.2292	0.00022	0.04085	
		2	1.0952	0.00076	0.03065	
		3	0.5247	0.00763	0.02558	
		4	0.3813	0.08334	-	
	a. Superheater drained	1	1.9625	0.00027	0.05345	
		2	0.9575	0.00076	0.04708	
		3	0.4791	0.00795	0.04096	
		4	0.3086	0.08768	-	

6. 489°F, No Boric Acid, Zero Power (Contd.)

PDQ Comp. No.	Material	Group	D	Σ_a	Σ_r	$\nu\Sigma_f$
11	Boiler fuel a. GAM No. 139 for U ²³⁸	1	2.0686	0.00384	0.07424	0.00808
		2	1.1094	0.00291	0.07247	0.00162
		3	0.6476	0.03033	0.05673	0.02409
		4	0.2796	0.13819	-	0.23451
	b. GAM No. 12 for U ²³⁸	1	1.9078	0.00376	0.07438	0.00830
		2	0.9929	0.00177	0.07317	0.00161
		3	0.5967	0.03074	0.06103	0.02479
		4	0.2796	0.13819	-	0.23451
12	Superheater fuel a. Superheater flooded	1	1.9221	0.00140	0.06729	0.00304
		2	0.9535	0.00231	0.06806	0.00384
		3	0.5025	0.04512	0.05942	0.06020
		4	0.2262	0.36216	-	0.61486
	b. Superheater drained	1	3.6984	0.00121	0.01438	0.00303
		2	1.8849	0.00230	0.00317	0.00383
		3	0.7880	0.04396	0.00248	0.05918
		4	0.4695	0.35035	-	0.60385
13	Boron-SS poison rod	1	1.6687	0.00043	0.07328	
		2	0.8220	0.00948	0.07590	
		3	0.4542	0.05053	0.06329	
		4	0.2198	0.30183	-	

*From homogenized boiler.

**From blackness.

7. 489°F, No Boric Acid, 10% Void in Boiler Fuel Region, Boiler Fuel Temp: 900°F

1	Reflector water	1	2.4748	0.00045	0.08428	
		2	1.3359	0.0	0.11518	
		3	0.7678	0.00079	0.11157	
		4	0.2587	0.01148	-	
2	Water around boilers	1	2.1295	0.00035	0.09191	
		2	1.0634	0.0	0.11583	
		3	0.7879	0.00068	0.09587	
		4	0.2479	0.01028	-	
3	Water around superheater	1	2.0773	0.00032	0.09502	
		2	1.0762	0.0	0.11253	
		3	0.7956	0.00068	0.09493	
		4	0.2596	0.00979	-	
4	Aluminum	1	2.5429	0.00024	0.01490	
		2	1.5485	0.00048	0.00083	
		3	3.3807	0.00075	0.00051	
		4	3.4590	0.00928	-	

7. 489°F, No Boric Acid, 10% Void in Boiler Fuel Region, Boiler Fuel Temp: 900°F
(Contd.)

PDQ Comp. No.	Material	Group	D	Σ_a	Σ_r	$\nu\Sigma_f$
5	Blackness theory Control-rod poison section	1	2.2718*	0.00310		
		2	1.2441*	0.03865		
		3	0.3649**	0.75406		
		4	0.0099**	6.84700		
6	Al-SS control-rod cladding	1	1.8902	0.00024	0.02620	
		2	0.9278	0.00116	0.00285	
		3	0.4537	0.01025	0.00198	
		4	0.4296	0.12070	-	
7	Aluminum, water Box, water, shroud, water	1	2.2586	0.00030	0.05069	
		2	1.2438	0.00028	0.05342	
		3	1.3514	0.00075	0.04411	
		4	0.5903	0.00966	-	
8	Aluminum, water Box, water ($\frac{1}{2}$ H ₂ O)	1	2.3187	0.00030	0.05340	
		2	1.2638	0.00024	0.05833	
		3	1.2956	0.00072	0.04819	
		4	0.4624	0.00978	-	
9	Stainless steel, void Superheater box, insulator void	1	3.2925	0.00012	0.01491	
		2	1.6263	0.00068	0.00172	
		3	0.7000	0.00671	0.00120	
		4	0.6602	0.07408	-	
10	Stainless steel, water Superheater box end, water	1	2.2292	0.00022	0.04085	
		2	1.0952	0.00076	0.03065	
		3	0.5247	0.00763	0.02558	
		4	0.3813	0.08334	-	
11	Boiler fuel a. GAM No. 139 for U ²³⁸	1	2.1725	0.00380	0.06894	0.00804
		2	1.1704	0.00290	0.06520	0.00162
		3	0.6859	0.03029	0.04983	0.02385
		4	0.3042	0.13699	-	0.23358
	b. GAM No. 12 for U ²³⁸	1	2.0111	0.00373	0.06890	0.00828
		2	1.0528	0.00176	0.06592	0.00161
		3	0.6269	0.03090	0.05442	0.02469
		4	0.3042	0.13699	-	0.23358
12	Superheater fuel Superheater drained	1	3.6984	0.00121	0.01438	0.00303
		2	1.8849	0.00230	0.00317	0.00383
		3	0.7880	0.04396	0.00248	0.05918
		4	0.4695	0.35035	-	0.60385
13	Boron-SS poison rod	1	1.7568	0.00041	0.06741	
		2	0.8648	0.00948	0.06847	
		3	0.4717	0.05049	0.05707	
		4	0.2360	0.30083	-	

*From homogenized boiler.

**From blackness.

8. a. 49-fuel-rod Boiler, 68°F, No Boric Acid, Homogenized over 3.375 in. sq.

PDQ						
Comp.						
No.	Material	Group	D	Σ_a	Σ_r	$\nu\Sigma_f$
		1	1.7798	0.00501	0.08459	0.01065
		2	0.9480	0.00385	0.07872	0.00214
		3	0.5480	0.03831	0.05929	0.03148
		4	0.2045	0.22990	-	0.39654

b. 49-fuel-rod Boiler, 489°F, No Boric Acid, Homogenized over 3.375 in. sq.

		1	1.9654	0.00491	0.07246	0.01054
		2	1.0561	0.00384	0.06220	0.00214
		3	0.6149	0.03738	0.04405	0.03070
		4	0.2935	0.18369	-	0.31787

APPENDIX F

Four-group Homogenized-fuel-region Constants from PDQ-3 for Axial
Control-rod-worth Calculations, Superheaters Drained, 68°F

1. No Boric Acida. Control Rods In

Group	D	Σ_a	Σ_r	$\nu\Sigma_f$	B_r^2
1	2.0141	0.00369	0.08139	0.00769	0.03670
2	1.0612	0.00286	0.08363	0.00182	0.02620
3	0.5850	0.03199	0.06858	0.02766	0.00420
4	0.2045	0.18876	-	0.31888	-0.27427

b. Control Rods Out

1	2.0294	0.00367	0.08080	0.00765	0.03820
2	1.0679	0.00285	0.08300	0.00183	0.02591
3	0.5865	0.03208	0.06811	0.02788	-0.01298
4	0.2068	0.19132	-	0.32343	-0.38438

2. 5 g(H₃BO₃)/gal(H₂O)a. Control Rods In

1	2.0160	0.00369	0.08131	0.00768	0.03660
2	1.0620	0.00286	0.08355	0.00182	0.02611
3	0.5849	0.03223	0.06853	0.02768	0.00411
4	0.2051	0.19301	-	0.31814	-0.27056

b. Control Rods Out

1	2.0287	0.00367	0.08082	0.00765	0.03800
2	1.0676	0.00286	0.08302	0.00183	0.02759
3	0.5862	0.03230	0.06813	0.02787	-0.01298
4	0.2071	0.19507	-	0.32187	-0.37805

3. 10 g(H₃BO₃)/gal(H₂O)a. Control Rods In

1	2.0177	0.00369	0.08124	0.00768	0.03657
2	1.0627	0.00287	0.08347	0.00182	0.02606
3	0.5849	0.03247	0.06847	0.02771	0.00404
4	0.2057	0.19720	-	0.31732	-0.26807

b. Control Rods Out

1	2.0286	0.00367	0.08082	0.00765	0.03789
2	1.0675	0.00286	0.08302	0.00183	0.02572
3	0.5860	0.03254	0.06812	0.02788	-0.01299
4	0.2073	0.19893	-	0.32051	-0.37333

4. $15 \text{ g(H}_3\text{BO}_3\text{)}/\text{gal(H}_2\text{O)}$ a. Control Rods In

Group	D	Σ_a	Σ_r	$\nu\Sigma_f$	B_r^2
1	2.0197	0.00368	0.08116	0.00767	0.03662
2	1.0635	0.00287	0.08339	0.00182	0.02602
3	0.5849	0.03272	0.06840	0.02775	0.00430
4	0.2063	0.20133	-	0.31676	-0.26833

b. Control Rods Out

1	2.0291	0.00367	0.08080	0.00765	0.03787
2	1.0677	0.00287	0.08300	0.00183	0.02565
3	0.5858	0.03277	0.06810	0.02789	-0.01263
4	0.2077	0.20280	-	0.31950	-0.37124

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