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PHYSICS PERFORMANCE OF THE EBWR
IN ITS OPERATION FROM ZERO TO 100 MWt

by

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May 1965

Operated by The University of Chicago
under
Contract W-31-109-eng-38
with the
U. S. Atomic Energy Commission

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I. INTRODUCTION

The Argonne Experimental Boiling Water Reactor (EBWR) achieved a power level of 20 MWt on December 28, 1956. Experiments conducted in 1957 and 1958 affirmed that the reactor was capable of operations at power levels up to 60 MWt. The reactivity of the operating core, Core 1, would not, however, permit prolonged operation at a power level substantially above 60 MWt. Core 1A, a modification of Core 1, was designed for operation near 100 MWt. Resulting changes in the reactor system have been described in Reference 1. (See Tables I and II for physical and nuclear constants.)

Table I
VOLUME FRACTIONS AND ATOMIC DENSITIES IN 12.25 x 12.25-in (31.115 x 31.115-cm) CELL
AT ROOM TEMPERATURE

Fuel Element Type Material	Thin Elements				Thick Elements				Spikes (S)	
	Enriched (ET)		Natural (T)		Enriched (EH)		Natural (H)		Volume Fraction	Atomic Density (x 10 ²⁴)
	Volume Fraction	Atomic Density (x 10 ²⁴)	Volume Fraction	Atomic Density (x 10 ²⁴)	Volume Fraction	Atomic Density (x 10 ²⁴)	Volume Fraction	Atomic Density (x 10 ²⁴)		
U ²³⁵	0.00253	0.0001196	0.001265	0.0000598	0.00353	0.000167	0.001765	0.00008454	0.00378	0.0001789
U ²³⁸	0.1735	0.00819	0.1747	0.00825	0.24164	0.01143	0.24341	0.011513	0.000285	0.00001345
U	0.176	0.0083096	0.176	0.0083096	0.245	0.0011597	0.245	0.0011597	0.00407	0.00019235
H ₂ O	0.683	0.02287	0.683	0.02287	0.596	0.01995	0.596	0.01995	0.589	0.01973
Zr	0.135	0.005742	0.135	0.005742	0.151	0.006386	0.151	0.006386	0.262	0.01107
Nb	0.00626	0.0003414	0.00626	0.0003414	0.00881	0.00480	0.00881	0.00480	0	0
Ca									0.040	0.000922
O in Spike Meat										0.00802

Notes: In the spikes, the meat is in the form of ZrO₂-UO₂ and Ca O (with a slight excess of O). The number densities in the meat are (x 10²⁴) U, 0.000818; Zr, 0.016233, Ca, 0.003924; O, 0.038048. The volume fraction of the meat in the cell is 0.2352

Table II
VOLUME FRACTIONS AND ATOMIC DENSITIES IN 12.75 x 12.75-in (32.385 x 32.385-cm) CELL
AT ROOM TEMPERATURE

Fuel Element Type Material	Thin Elements				Thick Elements				Spikes (S)	
	Enriched (ET)		Natural (T)		Enriched (EH)		Natural (H)		Volume Fraction	Atomic Density (x 10 ²⁴)
	Volume Fraction	Atomic Density (x 10 ²⁴)	Volume Fraction	Atomic Density (x 10 ²⁴)	Volume Fraction	Atomic Density (x 10 ²⁴)	Volume Fraction	Atomic Density (x 10 ²⁴)		
U ²³⁵	0.00244	0.0001156	0.001276	0.0000604	0.00336	0.0001592	0.001739	0.0000823	0.0036	0.0001702
U ²³⁸	0.1598	0.00756	0.1610	0.007615	0.2230	0.01055	0.22474	0.01063	0.000262	0.0000124
U	0.1623	0.007675	0.1623	0.007675	0.2264	0.01071	0.2264	0.01071	0.003862	0.0001826
H ₂ O	0.668	0.02239	0.668	0.02239	0.588	0.01970	0.588	0.01970	0.582	0.01950
Zr	0.134	0.005650	0.134	0.005650	0.148	0.006245	0.148	0.006245	0.250	0.01057
Nb	0.00578	0.0003151	0.00578	0.0003151	0.00813	0.0004431	0.00813	0.0004431		
Ca									0.0365	0.0008511
O in Spike Meat										0.00757
Fe	0.0302	0.00256	0.0302	0.00256	0.0302	0.00256	0.0302	0.00256	0.0302	0.00256

Notes: The rod follower has a volume fraction of 0.0302; in the follower N(U²³⁵) = 0.0001737 x 10²⁴, N(Fe) = 0.0848 x 10²⁴. The control rod has the same volume fraction as the follower: in the rod N(Fe) = 0.07605 x 10²⁴, N(B) = 0.00875 x 10²⁴. U²³⁵ in the rod follower is included with U²³⁵ in the cell.

Fig. 1. Fuel Distribution in Core 1A

The physics analysis of Core 1A was made⁽²⁾ to determine the static characteristics of the core, and to check calculations with experimental data. Most of the physics measurements have already been reported.^(3,4,5) The purpose of this report is to give a more detailed, and in some cases, improved, analysis of calculated results. Comparisons are also made with some previous⁽²⁾ calculations.

Although the EBWR was not an experimental arrangement for making accurate physics measurements, efforts to make detailed calculations proved fruitful in understanding the behavior of the reactor during its zero to 100-MWt operation.

II. COMPLETION OF LOADING 1A AND INITIAL OPERATION OF STRIPPING SPIKE FUEL ELEMENTS

As previously reported,⁽²⁾ Core 1A (Fig. 1) was composed mainly of fuel elements consisting of thin (ET) and thick (EH), slightly enriched, fuel plates, and fully enriched, spike (S) elements. In addition, a few plate-type elements contained natural uranium. The spike elements were provided with removable, borated stainless-steel strips, attached to the sides of the elements for additional flexibility in increasing the core reactivity and to overcome losses due to burnup and steam voids at high reactor powers.

It had been predicted,⁽²⁾ on the basis of physics-hydrodynamic iterations, that an increment of ~ 0.054 in multiplication factor Δk_{eff} would be required for 100-MWt operation.

To obtain this reactivity, the average number of borated stainless-steel strips was reduced to 1.57 per spike. The procedures outlined in Reference 2 were followed in this operation, and care was taken to meet the requirements of Reference 1 for a nine-rod cold shutdown without H_3BO_3 , and an eight-rod cold shutdown with H_3BO_3 .

Before the power operations of the core, the control-rod system was calibrated and the void coefficients of the core with H_3BO_3 were obtained.

III. CALIBRATION OF CONTROL-ROD SYSTEM

A cold calibration of the bank of nine rods was obtained from a series of period runs in terms of the reactivity worths of H_3BO_3 .

The method of calibration consisted of obtaining the differential worths, in dollars ($\Delta\rho/\beta_{\text{eff}}$), of the bank of nine rods from period runs, for

positions of the rods from 19.05 cm (7.5 in.) up to 55.88 cm (22 in.), and from 106.68 cm (42 in.) to the out position of the rods (Fig. 2). The reactor was critical at a bank position of 19.05 cm (7.5 in.), with no H_3BO_3 in the core.

Fig. 2. Bank Calibration of Rods Nos. 1-9;
Differential Worths for Bank
Positions of 7.5 to 24 in.

To determine the bank worth of rods Nos. 1-9 from zero to the 19.05-cm (7.5-in.) position, the usual "rod drive" or "rod drop" methods were not suitable, due mainly to relatively high uncertainties in the time scale, and limitations of instrumentation.

A method of estimating the worth of the bank of rods Nos. 1-9 below the 19.05-cm (7.5-in.) position was afforded from the differential-worth data of the bank of rods Nos. 1-8, with the No. 9 rod out (see Fig. 3). With

Fig. 3
Calibration of Bank of
Rods Nos. 1-8 and 1-9 for
Positions of Zero to 10 in.

rod No. 9 out, the bank of rods Nos. 1-8 was lowered down to the 5.08-cm (2-in.) position for criticality, where the differential worth of the bank was measured to be \$0.104/in.

Figure 3 shows a partial calibration of the banks of rods Nos. 1-9 and rods Nos. 1-8 (with rod No. 9 out). The worths of these two banks were equal at the 18.54-cm (7.3-in.) and 22.98-cm (9.05-in.) positions, and again at the 31.37-cm (12.35-in.) and 32.89-cm (12.95-in.) positions.

From an observation of the calibration of the rod banks Nos. 1-8 and 1-9, the worth of the bank of rods Nos. 1-9 from zero to the 19.05-cm (7.5-in.) position was estimated to be \$1.10.

The integrated worths of the rods were then obtained up to the 55.88-cm (22.01-in.) position. Worths of the rods, from a bank position of 55.88 cm to that of 106.68 cm (42 in.), were obtained in terms of the worth of H_3BO_3 ; the latter was calculated to be 1.14% ρ/g of H_3BO_3 in a gallon of cold water (or 77 ppm of H_3BO_3 in H_2O).

The reactivity worth of H_3BO_3 was obtained from

$$\Delta\rho_{\text{H}_3\text{BO}_3} = \frac{\int_{\text{core}} \Sigma_a^B \phi_{\text{H}_2\text{O}} dv}{\int_{\text{core}} \Sigma_a^B \phi_{\text{H}_2\text{O}} dV + \int_{\text{core}} \Sigma_a^{\text{core}} \phi_{\text{core}} dV}.$$

Although the expression above is a ratio of total absorptions, only thermal absorption was considered in this evaluation. Error resulting from this limitation was considered to be within the experimental uncertainties. Details of the calculations of the reactivity worth of H_3BO_3 are presented in Appendix A.

The worths of the rods in dollars may be converted to reactivities by multiplying by β_{eff} .

IV. SEMIEMPIRICAL DETERMINATION OF β_{eff}

The value of β_{eff} was determined semiempirically and also calculated as explained in Appendix B. It was found that

$$\beta_{\text{eff}}(\text{calculated}) = 0.0060; \quad \beta_{\text{eff}}(\text{semiempirically}) = 0.0058.$$

The bank calibration of the control-rod system, obtained near the conclusion of the reactor experimental program, is shown in Fig. 4. This measured bank worth of the rods of ~11.3% is in agreement with the results of previous⁽²⁾ control-rod worth calculations (see Appendix C).

Fig. 4. Bank Calibration of Rods Nos. 1-9

The differential worths of the bank of rods Nos. 1-9 for two settings of the rods, at 167°C (333°F) and 249°C (480°F), were obtained, to be compared with measurements at room temperature. The results are as follows:

$$\begin{array}{lcl}
 (\Delta\rho/\text{in.}) & \text{Control Rods} & \\
 & \text{at} & \\
 & 17.2 \text{ in.} & \left. \begin{array}{l} 0.545\% \rho \text{ at } 167^\circ\text{C} \\ (0.43\% \rho \text{ at room temp}), \\ \text{Ratio } (0.545/0.43) = 1.27; \end{array} \right\}
 \end{array}$$

$$\begin{array}{lcl}
 (\Delta\rho/\text{in.}) & \text{Control Rods} & \\
 & \text{at} & \\
 & 19.2 \text{ in.} & \left. \begin{array}{l} 0.475\% \rho \text{ at } 250^\circ\text{C} \\ (0.32\% \rho \text{ at room temp}), \\ \text{Ratio } (0.475/0.32) = 1.48. \end{array} \right\}
 \end{array}$$

The reactivity worths of the rods in a hot unvoided core were obtained by multiplying their worths in the cold reactor by the above-obtained experimental ratio of $0.475/0.32 = 1.48$.

An evaluation of control-rod worths by Henry's simplified cell analysis for cross-rods⁽⁶⁾

$$\left(\Delta\rho_{\text{CR}} = \frac{\Sigma_a^{\text{P}}}{\Sigma_a^{\text{P}} + \Sigma_a} = \left(\frac{2\ell}{m^2 - 2a\ell + a^2} \right) \left[e\Sigma + \frac{1}{L} \coth\left(\frac{m-a}{2L}\right) \right]^{-1} \right)$$

gave

$$\frac{\Delta\rho(250^{\circ}\text{C})}{\Delta\rho(\text{room temp})} = 1.44; \quad \frac{\Delta\rho(167^{\circ}\text{C})}{\Delta\rho(\text{room temp})} = 1.27.$$

The agreement between measured and calculated values of these ratios may be considered to be fair, since the above formula is based on a cell calculation, whereas the bank of rods is not totally inserted.

Henry's formula was also used to determine the effects of steam voids on rod worth, for the tabulation of data associated with the power runs. The formula proved adequate for these calculations.

V. VOID COEFFICIENT MEASUREMENTS

Measurements were made to determine the void coefficients in the EBWR for varying concentrations of H_3BO_3 at room temperature.

The test facility consisted of four "void simulator" subassemblies, which could be fitted in the ET elements of the core and produce 70% voids therein.

The reactivity effects of these void simulators in a region were measured with the aid of a single rod located furthest from this region, in order to minimize the effect of the simulator voids on the calibration of the rod. These measurements were made in two regions for two concentrations of H_3BO_3 , i.e., 0.4 and 3.37 g of H_3BO_3 per gallon of water.

The results of these measurements are assembled in Table III, and the simulator locations are shown in Fig. 5. Calculations of void coefficient were obtained from the data of Table IV.

Table III

DETERMINATION OF VOID COEFFICIENT BY THE USE OF VOID SIMULATORS; REACTIVITY LOSSES DUE TO VOIDS IN ET ELEMENTS

Concentration of H_3BO_3 , g/gal	0	0.4	3.37	3.37
Number of simulators used	3	4	3	4
Void per simulator	70	70	70	70
Reactor average void $\Delta v = \frac{\text{No. of simulators}}{147} \times 70\%$	1.43	1.90	1.43	1.90
$-\Delta\rho/\beta_{\text{eff}}$, dollars	0.114	0.160	0.081	0.113
$\Delta\rho$, %	0.0684	0.096	0.0486	0.0678
$\Delta\rho/\Delta v$	0.0480	0.0505	0.034	0.0356

Fig. 5

Use of Void Simulators for
Void-coefficient Measurements
of the Cold Reactor

Table IV

CALCULATION OF VOID COEFFICIENT OF COLD CORE
CONSISTING ENTIRELY OF ET, EH, OR SPIKE ELEMENTS

$$\frac{\Delta k_{eff}}{k_{eff}} = \frac{\Delta f}{f} + \frac{\Delta p}{p} + \frac{\Delta \epsilon}{\epsilon} + \left(- \frac{\Delta \Lambda}{\Lambda} \right)$$

Type of Element	Concentration of H_3BO_3 , g/gal	$\frac{1}{f} \frac{\partial f}{\partial v}$	$\frac{1}{\epsilon} \frac{\partial \epsilon}{\partial v}$	$\frac{1}{p} \frac{\partial p}{\partial v}$	$\frac{1}{\Lambda} \frac{\partial \Lambda}{\partial v}$	$\frac{1}{k_{eff}} \frac{\Delta k_{eff}}{\Delta v}$
ET	Zero	0.121	0.0106	-0.152	-0.115	-0.137
	0.4	0.124	0.0106	-0.152	-0.115	-0.133
	3.37	0.152	0.0106	-0.152	-0.115	-0.105
EH	Zero	0.086	0.0133	-0.146	-0.115	-0.162
	0.4	0.089	0.0133	-0.146	-0.115	-0.159
	3.37	0.110	0.0133	-0.146	-0.115	-0.138
Spike	Zero	0.094			-0.115	-0.021
	0.4	0.097			-0.115	-0.018
	3.37	0.118			-0.115	+0.003
$\int_{54 \text{ ET's}} \phi dv = 54 \times 55; \quad \int_{52 \text{ EH's}} \phi dv = 52 \times 20; \quad \int_{28 \text{ Spikes}} \phi dv = 28 \times 43.$						
		Core of ET's only			Core 1A	
$\frac{1}{k_{eff}} \frac{\Delta k_{eff}}{\Delta v} \Big _{\text{Zero } H_3BO_3}$		-0.137%			-0.114%	
$\frac{1}{k_{eff}} \frac{\Delta k_{eff}}{\Delta v} \Big _{\text{Concentration of } H_3BO_3 \text{ 0.4 g/gal}}$		-0.133%			-0.111%	
$\frac{1}{k_{eff}} \frac{\Delta k_{eff}}{\Delta v} \Big _{\text{Concentration of } H_3BO_3 \text{ 3.37 g/gal}}$		-0.105%			-0.086%	

An extrapolation of $\Delta k_{\text{eff}}/\Delta v$ obtained from the data of Table III indicated that the latter would remain negative for H_3BO_3 concentrations up to 10 g/gal. Figure 6 also shows the calculated void coefficient for a core made entirely of ET elements and for Core 1A. From these data, it is readily seen that the Core 1A should have a negative void coefficient for H_3BO_3 concentrations of ≤ 10 g/gal (see Fig. 6). There is some cross-streaming of neutron between simulators, as revealed by data corresponding to three and four simulators (see Table III).

Fig. 6. Void Coefficient vs Concentration of H_3BO_3 in Cold Reactor

VI. POWER RUNS

A. Zero to 60 MWt

To study the behavior of the reactor in reaching the high estimated powers, power-coefficient data were taken. Evaluation of $\Delta k_{\text{eff}}/\Delta p$ involved a knowledge of steam voids in the core. In our initial study, these were assumed to be as originally dictated by physics-hydrodynamic iterations.⁽²⁾

Power-coefficient calculations involved the reactivity worths of the rods and of the H_3BO_3 poison in the reactor, both of which are dependent on steam-void concentrations in the core.

In the original calculations of power coefficients for powers of up to 40 MW, the effects of steam voids on control-rod worth were neglected. These effects (when accounted for) result in a correction of 1-2% on the averaged values of the power coefficient as shown below. (See also Tables V and VI.)

Table V.

CALCULATION OF POWER-COEFFICIENT CHARACTERISTIC WITH NO ALLOWANCE FOR "CARRYUNDER" OF STEAM

Time	Reactor Power MWt	Steam Void Fraction	Bank Position(a) Rod Nos 1-9 in	Concentration of H ₃ BO ₃ (Hot) g/gal		Δ[α(1 a)] ^(b) g/gal	① Δρ(H ₃ BO ₃) ^(b)	② Control Rods (CR)				② Δρ _{CR} ^(b)		③ Δρ _{Xe} ^(b)	① + ② + ③ Δρ _{Total} ^(b)		Δρ _{Total} ΔP x 100 ^(b)		
				α Not Voided	α(1 a) Voided			Cold	Hot No Void	Void Correction Factor	Hot Voided	Hot No Void ^(c)	Hot Voided		Hot No Void ^(c)	Hot Voided	Hot No Void ^(c)	Hot Voided	
-	<1	Small	23 6	3 88	3 88	0 080 -0 028 0 070 0 124	0 00091 -0 00032 0 00080 0 00141	0 0312	0 046	1 0	0 046	0 0075 0 0133 0 0067 0 0060	0 0069 0 0123 0 0067 0 0061	Small 0 0002 0 0003 0 0003	0 0084 0 0128 0 0072 0 0071	0 0078 0 0118 0 0072 0 0072	0 145 0 0805 0 0888 0 0700	0 134 0 0742 0 0888 0 0706	
-	5 8	0 03	25 7	3 92	3 80			0 0260	0 0385	1 023	0 0391								
-	21 7	0 073	29 8	4 13	3 828			0 0170	0 0252	1 066	0 026								
-	29 8	0 090	32 8	4 13	3 758			0 0125	0 0185	1 090	0 0194								
-	40 0	0 12	36 6	4 13	3 634			0 0085	0 0125	1 113	0 0132								
								Hot No Void ^(c)		Hot Voided									
								(Δρ/ΔP) 40 MW 5 8 MW		0 0798% 0 0779%									
								(Δρ/ΔP) 40 MW 0		0 0960% 0 0919%									
1520	35 1	0 10	0	3 624	3 261	2 026 1 404 1 076 1 666	-0 0231 -0 0160 -0 0123 -0 0190	0	0	0	0	0	0	+0 0024 +0 0021 +0 0014 +0 0018	0	+0 0255 +0 0181 +0 0137 +0 0211	0	0 1080 0 1077 0 1046 0 1185	
1300	58 7	0 20	0	1 544	1 235			0	0	0	0								
1334	41 9	0 125	0	3 016	2 639			0	0	0	0								
1300	58 7	0 20	0	1 544	1 235			0	0	0	0								
1405	45 6	0 13	0	2 656	2 311			0	0	0	0								
1300	58 7	0 20	0	1 544	1 235	1 666	-0 0190	0	0	0	0	0	0	+0 0018	0	+0 0211	0	0 1185	
1405	45 6	0 13	0	2 656	2 311			0	0	0	0								
1230	63 4	0 21	0	0 816	0 645			0	0	0	0								
								(Δρ/ΔP) 63 4 MW 35 MW		0 1096%									

(a) Measured from bottom of core

(b) Corresponds to each pair of power readings indicated

(c) Hot no void means effect of steam void on rod worth has been omitted

Table VI

CALCULATION OF POWER COEFFICIENT CHARACTERISTIC WITH ALLOWANCE FOR "CARRYUNDER" OF STEAM

Time	Reactor Power MWt	Steam Void Fraction	Bank Position (a) Rod Nos 1-9 in	Concentration of H ₃ BO ₃ (Hot) g/gal		$\Delta[\alpha(1-\alpha)]^{(b)}$ g/gal	① $\Delta\rho(H_3BO_3)^{(b)}$	ρ Control Rods (CR)				② $\Delta\rho_{CR}^{(b)}$		③ $\Delta\rho_{Xe}^{(b)}$	① + ② + ③ $\Delta\rho_{Total}^{(b)}$		$\frac{\Delta\rho_{Total}}{\Delta P} \times 100^{(b)}$		
				α Not Voided	$\alpha(1-\alpha)$ Voided			Cold	Hot No Void	Void Correction Factor	Hot Voided	Hot No Void(c)	Hot Voided		Hot No Void(c)	Hot Voided	Hot No Void(c)	Hot Voided	
-	<1	Small	23 6	3 88	3 88	0 00113 0 00129 0 00144	0 00129 0 00147 0 00164 0 00188	0 0312	0 0460	1 0	0 0460	0 0075	0 0066	Small	0 00882	0 00792	0 152	0 1370	
-	5 8	0 039	25 7	3 92	3 767			0 0260	0 0385	1 023	0 0394	0 0133	0 0126		0 0002	0 01461	0 01391	0 0919	0 0874
-	21 7	0 119	29 8	4 13	3 638			0 0170	0 0252	1 066	0 0268	0 0067	0 00668		-0 0003	0 00808	0 00806	0 0997	0 0995
-	29 8	0 154	32 8	4 13	3 494			0 0125	0 0185	1 090	0 02012	0 0060	0 00625		-0 0003	0 00763	0 00785	0 0748	0 0770
-	40 0	0 194	36 6	4 13	3 329			0 0085	0 0125	1 113	0 01412								
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(a) Measured from bottom of core

(b) Corresponds to each pair of power readings indicated

(c) Hot no void means effect of steam void on rod worth has been omitted

		Without void effect on rods	With void effect on rods	
$-\left(\frac{\overline{\Delta\rho}}{\Delta P}\right)$	40 MW	0.0798%	0.0779%	when initial void distribution is used
		0.0888%	0.0880%	when void distribution with allowance for carryunder of steam is used.
	5.8 MW			

From the reactivity-versus-power characteristics (Table V and Fig. 7) of the reactor from 0 to 60 MW, the following was noteworthy:

1. Marked changes occurred in $\Delta k_{\text{eff}}/\Delta P$, over the power range of 0 to 60 MW:

$$\left(\frac{\overline{\Delta k_{\text{eff}}}}{\Delta P}\right) \bigg|_0^{5.8 \text{ MW}} = -0.146;$$

$$\left(\frac{\overline{\Delta k_{\text{eff}}}}{\Delta P}\right) \bigg|_{5.8 \text{ MW}}^{40 \text{ MW}} = -0.0798;$$

$$\left(\frac{\overline{\Delta k_{\text{eff}}}}{\Delta P}\right) \bigg|_{40 \text{ MW}}^{60 \text{ MW}} = -0.1015.$$

The high initial value of the power coefficient (-0.146%/MW) was verified from repeated measurements. The reactor power of 5.8 MW was maintained to be accurate within ± 0.2 MW.

2. At 60 MWt the reactivity tied up in steam voids (0.056) was nearly equal to that estimated to occur at the 100-MWt level, on the basis of previous physics-hydrodynamic iterations.⁽²⁾ It appeared as if the core produced sufficient steam to deliver 100 MWt of power; however, this steam could not be drawn from the core. A partial explanation for this discrepancy came when it was found⁽³⁾ that there was appreciable flow of carryunder steam in the downcomer area. With a re-evaluation of steam-void distribution in the core, the reactivity-versus-power characteristic was determined anew (see Table VI and Fig. 7).

Nearly all of the reactivity available in the core having been used up, further removal of borated steel strips became mandatory in order to reach higher powers of ~80 MW.

Fig. 7. Δk_{eff} of Steam Void vs Reactor Power

The number of boron strips per spike was reduced then from 1.57 to 1, taking care that the requirement of nine-rod cold shutdown without H_3BO_3 was met. This resulted in an additional Δk_{eff} of 0.02. Allowing $\Delta k_{eff} \approx 0.005$ for loss of reactivity due to burnup, it was estimated that ~ 80 MWt could be reached.

B. 60-100 MWt

After the addition of $\Delta k_{eff} = 0.02$, by reducing the number of borated steel strips per spike to one, power runs were resumed. Above 60 MWt, the reactor power output became greatly dependent on water level in the pressure vessel. When this level was kept low (~ 1 ft below the top of the riser, or, ~ 6.5 in. above the top of core), the reactivity-loss-versus-power characteristic was quite similar to that at low powers, and only about 73 MWt was obtained. This was the case for the operation of the reactor as a direct-cycle boiling system, and (see Fig. 7)

$$-\left(\frac{\overline{\Delta k_{eff}}}{\Delta P}\right) \bigg|_{60 \text{ MWt}}^{73 \text{ MWt}} = 0.15\%/MWt \text{ was obtained.}$$

At power levels above 60 MWt, as the water level in the pressure vessel was raised by pumping water (at 180°F) through the feed water system into the "downcomer area," without increasing the core reactivity by the usual means (such as removal of H_3BO_3), the reactor power increased. This increase in power was achieved by virtue of the "carryover" of water and accompanying increase in steam being drawn out of the core. This situation (discussed in Reference 3) resulted, in effect, in a dual-cycle operation of the reactor, and a power of 100 MWt.

Summing up, it may be stated that study of physics data had complemented hydrodynamic study in pointing to phenomena of "carryunder of steam" at powers up to 60 MW, and also pointing to a change of hydrodynamic pattern of flow (carryover of core water with associated steam) to account for the high powers of ~100 MWt, without the addition of any reactivity by the usual means (such as removal of H_3BO_3).

VII. IMPROVED CALCULATIONS OF VOID COEFFICIENTS

In the calculations of void coefficients of Core 1A,⁽²⁾ it was found that

$$\overline{\Delta k} \bigg|_{\text{zero void}}^{20.8\% \text{ void}} = 0.0554;$$

hence,

$$\left(\frac{\overline{\Delta k}}{\Delta v} \right) \bigg|_{\text{zero void}}^{20.8\% \text{ void}} = -0.266\%;$$

also,

$$\left(\frac{\overline{\Delta k_{\text{eff}}}}{\Delta v} \right) \bigg|_{\text{zero void}}^{\text{hot no void}} = -0.2636\%.$$

These values of void coefficients became too high when a hydrodynamic re-evaluation of steam voids was made⁽³⁾ that allowed for "carryunder" of steam in the downcomer area, and an average steam void concentration of 27% was to occur at 60 MW. This meant, using the above value of void coefficient, a reactivity loss of ~7.13%, which is considerably higher than the experimental value of ~5.7% ρ .

To explain this situation, cross-section data used for making these calculations⁽²⁾ were studied. It was noted that changes in Dancoff self-shielding factor and in fast effect ϵ with void had been omitted.

When appropriate corrections were made (see Table VII), the following data were obtained from a set of RE-122 problems (see also Fig. 8):

$$\Delta k_{\text{eff}} \left| \begin{array}{l} 10\% \text{ void} \\ \text{zero void} \end{array} \right. = -0.0155, \quad \text{and} \quad \left(\frac{\Delta k_{\text{eff}}}{\Delta \text{void}} \right) \left| \begin{array}{l} 10\% \text{ void} \\ \text{zero void} \end{array} \right. = -0.155\%;$$

$$\Delta k_{\text{eff}} \left| \begin{array}{l} 20.7\% \text{ void} \\ \text{zero void} \end{array} \right. = -0.0368, \quad \text{and} \quad \left(\frac{\Delta k_{\text{eff}}}{\Delta v} \right) \left| \begin{array}{l} 20.7\% \text{ void} \\ \text{zero void} \end{array} \right. = -0.0178\%;$$

$$\Delta k_{\text{eff}} \left| \begin{array}{l} 27\% \text{ void} \\ \text{zero void} \end{array} \right. = -0.0568, \quad \text{and} \quad \left(\frac{\Delta k_{\text{eff}}}{\Delta v} \right) \left| \begin{array}{l} 27\% \text{ void} \\ \text{zero void} \end{array} \right. = -0.21\%.$$

Table VII
CROSS-SECTION SET 153 AND CORRECTIONS MADE TO ALLOW FOR EFFECTS OF CHANGES
OF VOIDS ON DANCOFF SELF-SHIELDING AND FAST-FISSION FACTOR ϵ

Data from Cross-section Set 153 ⁽²⁾												
Group	ET a Zero Void				EH a Zero Void				Spike a Zero Void			
	Σ_a	$3\Sigma_{tr}$	$\nu\Sigma_f$	Σ_{in}	Σ_a	$3\Sigma_{tr}$	$\nu\Sigma_f$	Σ_{in}	Σ_a	$3\Sigma_{tr}$	$\nu\Sigma_{tr}$	Σ_{in}
1	0 0356	0 67024	0	0 0356	0 0319	0 73206	0	0 0319	0 0344	0 54348	0	0 0344
2	0 051726	1 7637	0 004862	0 0382	0 04788	1 9646	0 006272	0 0327	0 043906	1 014	0 00812	0 0384
3	0 07102	3 5997	0 09216	0	0 08324	3 3933	0 1166	0	0 07213	3 1153	0 1247	0
	b 60% Void				b 30% Void				b 60% Void			
	Σ_a	$3\Sigma_{tr}$	$\nu\Sigma_f$	Σ_{in}	Σ_a	$3\Sigma_{tr}$	$\nu\Sigma_f$	Σ_{in}	Σ_a	$3\Sigma_{tr}$	$\nu\Sigma_{tr}$	Σ_{in}
1	0 0144	0 47461	0	0 0144	0 0224	0 64516	0	0 0224	0 0144	0 40502	0	0 0144
2	<u>0 027986</u>	1 23	<u>0 004862</u>	0 0144	<u>0 038031</u>	1 7241	<u>0 006272</u>	0 0222	0 019616	0 54615	0 00812	0 0143
3	0 06542	1 71	<u>0 09406</u>	0	0 08064	2 3998	<u>0 11595</u>	0	0 05965	1 3157	0 10821	0

Note Underlined numbers are correctly shown below

Changes Made in Cross-section Set 153⁽²⁾

	ET (60% Void)		EH (30% Void)	
	Set 153	Present Corrected	Set 153	Present Corrected
Σ_{a2}	0 027986	0 026024	0 038031	0 036602
$\epsilon\nu\Sigma_{f2}$	0 004862	0 005092	0 006272	0 006388
$\epsilon\nu\Sigma_{f3}$	0 09406	0 09678	0 11595	0 11716

Fig. 8

Δk_{eff} of Steam Void vs
Percent of Steam Void

It is seen that the above calculated value of

$$\Delta k_{\text{eff}} \bigg|_{\text{zero void}}^{27\% \text{ void}} = -0.0568$$

is now in good agreement with the experimental value of 5.7% (see Fig. 7).

From the data of Figs. 7 and 8, the reactor power-versus-void distribution curve was drawn (Fig. 9).

Fig. 9. Percent of Steam Void vs Reactor Power

APPENDIX A

Calculation of Reactivity Worth of H_3BO_3

The reactivity worth of H_3BO_3 was calculated from

$$\Delta \rho_{H_3BO_3} = \frac{\int^{\text{core water}} \Sigma_a^B \Phi dV}{\int^{\text{core water}} \Sigma_a^B \Phi dV + \int^{\text{core}} \Sigma_a \Phi dV}$$

$$= \frac{\sum_i N_i \Sigma_{ai}^B(\text{core water}) \Phi_i^{\text{water}}}{(\text{numerator}) + \sum_i N_i \Sigma_{ai} \Phi_i^{\text{fuel}}}$$

In the above summation, N_i refers to 54 ET, 28 spike, and 52 EH elements. These elements have averaged thermal-neutron fluxes proportional to values given in Table A-I. Flux data were obtained from Reference 5.

Table A-I

CONSTANTS USED FOR DETERMINING REACTIVITY WORTH OF H_3BO_3

$\sigma_a^B \left(\begin{smallmatrix} \text{water} \\ \text{in} \\ \text{ET} \end{smallmatrix} \right)$	$\Phi \cdot \text{disF}(\text{ET})$	$\sigma_a^B \left(\begin{smallmatrix} \text{water} \\ \text{in} \\ \text{Sp} \end{smallmatrix} \right)$	$\Phi \cdot \text{disF}(\text{Sp})$	$\sigma_a^B \left(\begin{smallmatrix} \text{water} \\ \text{in} \\ \text{EH} \end{smallmatrix} \right)$	$\Phi \cdot \text{disF}(\text{EH})$
579	55 x 1.10	585	43 x 1.12	545	18 x 1.15

Values of cross sections Σ_{ai}^B and Σ_a and of disadvantage factors were obtained from Reference 2. The above data are assembled in Table A-I.

Carrying out the above numerical calculations resulted in

$$\Delta \rho_{H_3BO_3} = 1.14\% \rho / (\text{g/gal}) \text{ concentration.}$$

APPENDIX B

Semiempirical Determination and Calculated Value of β_{eff} 1. Semiempirical Determination of β_{eff} (Delayed-neutron Fraction)

The "effective delayed neutron" fraction, β_{eff} , of the reactor was evaluated semiempirically as follows. For any paired criticality settings of the bank of rods, the corresponding concentrations of H_3BO_3 and $\Delta\rho_{\Delta(H_3BO_3)}$ and $\Delta\rho_{CR}/k_{eff}$ values are listed in Table B-I. Since $\Delta\rho_{CR} = \Delta\rho_{\Delta(H_3BO_3)}$, β_{eff} may be obtained readily from $\Delta\rho_{CR}/\beta_{eff} = \Delta\rho_{\Delta(H_3BO_3)}/\beta_{eff}$.

The average value of $\beta_{eff} = 0.0058$, with an average deviation of ~ 0.0003 .

Table B-I

SEMIEMPIRICAL DETERMINATION OF β_{eff}

Paired Control-rod Positions	$\frac{\Delta\rho}{\beta_{eff}} \left \frac{2}{1} \right $	H_3BO_3 Concentration	$\Delta(H_3BO_3)$ Concentration	$\Delta\rho_{\Delta(H_3BO_3)},$ (%) ρ	β_{eff}
21.6 18.73	1.68	4.85 4.04	0.81	0.9234	0.0055
18.73 15.5	2.28	4.04 2.8	1.24	1.414	0.0062
15.5 13.91	1.25	2.8 2.18	0.62	0.707	0.0056
13.91 9 86	3.45	2.18 0.35	1.83	2.086	0.0060

Average $\bar{\beta}_{eff} = 0.0058$.

Average deviation = 0.0003.

The data of Table B-I indicate that errors in the computed value of β_{eff} , caused by small changes in the reactivity worth of H_3BO_3 for varying concentration of the acid, should also be small.

2. Calculation of β_{eff}

The value of β_{eff} may be calculated as follows: (7)

$$\beta_{eff} = \bar{\beta} \left\{ (1 - \bar{\beta}) e^{-(\tau_P - \tau_d) B^2} + \bar{\beta} \right\}^{-1}, \quad (B-1)$$

where $\bar{\beta}$ is the average of the core in an infinite system given by

$$\bar{\beta} = \frac{\sum_1^{54ET} \Phi_{ET} \left(\sum_F^{25} \nu^{25} \beta^{25} + \sum_F^{49} \nu^{49} \beta^{49} \right) + \sum_1^{52EH} \Phi_{EH} \left(\sum_F^{25} \nu^{25} \beta^{25} + \sum_F^{49} \nu^{49} \beta^{49} \right) + \sum_1^{28Sp} \Phi_{Sp} \sum_F^{25} \nu^{25} \beta^{25}}{\sum_1^{54ET} \Phi_{ET} \left(\sum_F^{25} \nu^{25} + \sum_F^{49} \nu^{49} \right) + \sum_1^{52EH} \Phi_{EH} \left(\sum_F^{25} \nu^{25} + \sum_F^{49} \nu^{49} \right) + \sum_1^{28Sp} \Phi_{Sp} \sum_F^{25} \nu^{25}}$$

where $\sum_1^{54ET}$ is the summation of quantities indicated above for all 54ET

elements, etc. Values of $\sum_1^{54ET} \Phi_{ET}$, $\sum_1^{52EH} \Phi_{EH}$, and $\sum_1^{28Sp} \Phi_{Sp}$ (summations of integrated flux) were obtained from Reference 5, and are listed in Table B-II (in arbitrary units). The isotopic concentrations of U^{235} and Pu^{239} at the time of these measurements are also listed in Table B-II.

Table B-II
NUCLEAR CONSTANTS USED FOR CALCULATION OF β_{eff}

	N^{25}	N^{49}	Φ_i	β^{25}	β^{49}
54 ET's	0.000,08843	0.000,01468	55	{0.0065	0.0021
52 EH's	0.000,1225	0.000,01381	18		
28 Spikes	0.000,1620	-	43		

From the data of Tables B-I and B-II and the formula for $\bar{\beta}$, we obtain $\bar{\beta} = 0.00573$.

It was calculated [from GAM-I(8)] that $\tau_p - \tau_d \simeq 34$. We have $B^2 \simeq 0.0015$. Hence, we obtain, from Eq. (B-1),

$$\beta_{eff} = 0.0060.$$

This calculated value is in agreement within about 3% with the semi-empirical value of 0.0058, obtained above.

APPENDIX C

Calculation and Measurements of Control-rod Worth

It will be assumed, for simplicity, that when the control rods are down and there is no H_3BO_3 in the core, the reactor is just critical.

1. Calculated Worth of Bank

The calculated worth of the bank of rods is ordinarily defined as

$$k_{\text{eff}}(\text{rods out}) - k_{\text{eff}}(\text{rods in}) = \Delta k_{\text{eff}}(\text{O-I}),$$

where

$$k_{\text{eff}}(\text{O}) = c \frac{\bar{\Sigma}_{\text{FO}}}{\bar{\Sigma}_{\text{a}}},$$

and

$$k_{\text{eff}}(\text{I}) = c \frac{\bar{\Sigma}_{\text{FI}}}{\bar{\Sigma}_{\text{aI}} + \bar{\Sigma}_{\text{a}}^{\text{CR}}}.$$

Hence,

$$\Delta k_{\text{eff}}(\text{O-I}) = k_{\text{eff}}(\text{O}) \left\{ 1 - \frac{\bar{\Sigma}_{\text{F(I)}}/\bar{\Sigma}_{\text{F(O)}}}{(\bar{\Sigma}_{\text{a(O)}} + \bar{\Sigma}_{\text{a}}^{\text{CR}})/\bar{\Sigma}_{\text{a(O)}}} \right\}.$$

Assuming

$$\frac{\bar{\Sigma}_{\text{F(I)}}}{\bar{\Sigma}_{\text{F(O)}}} = \frac{\bar{\Sigma}_{\text{a(I)}}}{\bar{\Sigma}_{\text{a(O)}}} \simeq 1,$$

$\Delta k_{\text{eff}}(\text{O-I})$ becomes

$$\Delta k_{\text{eff}}(\text{O-I}) = k_{\text{eff}}(\text{O}) \frac{\bar{\Sigma}_{\text{a}}^{\text{CR}}}{\bar{\Sigma}_{\text{a}} + \bar{\Sigma}_{\text{a}}^{\text{CR}}}. \quad (\text{C-1})$$

The change in reactivity, when control rods are moved from out to in, is

$$\Delta \rho(\text{O-I}) = \frac{\Delta k_{\text{eff}}(\text{O-I})}{k_{\text{eff}}(\text{O})} = \frac{\bar{\Sigma}_{\text{a}}^{\text{CR}}}{\bar{\Sigma}_{\text{a}} + \bar{\Sigma}_{\text{a}}^{\text{CR}}}. \quad (\text{C-2})$$

2. Measured Worth of Bank

The measured worth of the bank, as obtained from a summation of N differential worths of the bank, all determined from criticality and near-criticality readings, may be expressed as

$$\begin{aligned}\Delta\rho_{(O-I)} &= \Delta k_{\text{eff}(O-I)} = \sum_{i=1}^N \Delta k_{\text{eff}_i} = \frac{\sum_{i=1}^N \Delta \Sigma_a^{\text{CR}_i}}{\bar{\Sigma}_a + \bar{\Sigma}_a^{\text{CR}_i} + \bar{\Sigma}_a^{\text{B}_i}} \\ &= \frac{\bar{\Sigma}_a^{\text{CR}}}{\bar{\Sigma}_a + \bar{\Sigma}_a^{\text{CR}}}.\end{aligned}\tag{C-3}$$

Comparing Eqs. (C-1), (C-2), and (C-3), we note that

$$\Delta\rho_{(O-I)}^{\text{calculated}} \simeq \Delta\rho_{(O-I)}^{\text{measured}},$$

and

$$\Delta k_{\text{eff}}^{\text{calculated}} = k_{\text{eff}(O)} \times \Delta k_{\text{eff}(O-I)}^{\text{measured}};$$

or, calculated worth of bank = $k_{\text{eff}(O)}$ x measured worth of bank.

In previous control-rod evaluations of EBWR,⁽²⁾ it was found for the cold-core loading 1A, that

$$\Delta\rho_{(O-I)} - \frac{\Delta k_{\text{eff}(O-I)}}{k_{\text{eff}(O)}} = \frac{1.1261 - 0.9852}{1.1261} = \frac{0.131}{1.1261} = 0.116.$$

Measurements of control-rod worth (Fig. 4) gave

$$\Delta k_{\text{eff}(O-I)}^{\text{measured}} = 0.113,$$

which agrees with the above reactivity change within ~3%.

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