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A PERFORMANCE ANALYSIS OF THE EBWR
AT VARIOUS POWER LEVELS

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TABLE OF CONTENTS

	<u>Page</u>
NOMENCLATURE	6
I. INTRODUCTION.	7
II. GENERAL PROCEDURE	7
III. CORE LOADING AND GEOMETRY	9
IV. DETERMINATION OF THE POWER DISTRIBUTION FOR EBWR	16
V. RECHOP - PROGRAM.	19
VI. CALCULATION OF SYSTEM PARAMETERS	25
VII. RESULTS AND COMPARISON WITH EXPERIMENTAL DATA.	32
VIII. CONCLUSIONS.	38
BIBLIOGRAPHY.	39
ACKNOWLEDGMENTS	40

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	EBWR Core 1A Configuration	10
2.	Plate-type Fuel Element (Cross Section of a Typical 9-element Cell Composed of Thin Elements)	11
3.	Cross Section of Rod-type Fuel Elements (Spike Element) . . .	11
4.	Schematic of Flow Regions in the EBWR Core Section and Risers	14
5.	Sketch of the EBWR Core Regions for PDQ-Code: 20 MW (Typical Layout, Showing Number of Mesh Points and Assumed Average Voids)	16
6.	EBWR, 20 MW: Radial Power Density Distribution.	17
7.	EBWR, 20 MW: Average Axial Power Density Distribution . .	17
8.	Local Two-phase Friction Factor Versus Quality	21
9.	Average Two-phase Friction Multiplier (Uniform Heat Input) .	21
10.	Correction Factors Based on α from SHER: Slip = 1.0	22
11.	Westinghouse Two-phase Pressure-drop Data	22
12.	Typical RECHOP Output Diagram: 20 MW (Inlet Velocity, Exit Quality, and Exit Void Fraction as a Function of Power) .	24
13.	Entrance Section of a Typical Channel	25
14.	Entrance Section of Control Rod	25
15.	EBWR, 20 MW: Radial Velocity Distribution with Friction Factor as a Parameter	32
16.	EBWR, 20 MW: Radial Exit Quality Distribution with Fric- tion Factor as a Parameter	32
17.	EBWR, 20 MW: Radial Exit Void Distribution with Friction Factor as a Parameter	33

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
18.	EBWR: Radial Velocity Distribution for Various Powers. . . .	34
19.	EBWR: Radial Exit Quality Distribution for Various Powers .	34
20.	EBWR: Radial Exit Void Distribution for Various Powers . . .	35
21.	Total Flow Rate W_T Versus Power	36
22.	Riser-3 Voids Versus Power	36
23.	Carryunder Versus Power	36
24.	Subcooling Versus Power	37

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Compilation of EBWR Geometrical Dimensions (Core, Riser and Downcomer).	12
II.	Total Energy Released and Power Density in EBWR Core for Various Power Levels.	18
III.	Comparison of Assumed and Calculated EBWR Core Exit Void Fractions.	18
IV.	Typical RECHOP Output Sheet	24
V.	EBWR Average Velocities, Flow Rates, and Riser Voids for Various Power Levels.	35

NOMENCLATURE

NOMENCLATURE

A	Flow area, ft ²	<u>Greek Letters</u>	
a	Parameter discussed in text	α	Steam volume fraction, ft ³ steam/ft ³ mixture
b	Parameter discussed in text	Λ	Density ratio
c	Parameter discussed in text	$\lambda = x_D/x$	Weight per cent carryunder
D	Equivalent diameter, ft	ρ	Density, lb/ft ³
F _a	Parameter discussed in text	σ	Area ratio
F _r	Froude Number	<u>Subscripts</u>	
f	Friction factor	B	Boiling section of the channel
G	Mass velocity, lb/sec-ft ²	BPC	Bypass central region
g _c	Gravitational force per unit mass, 322 lb-ft/lb-sec ²	BPO	Bypass outer region
H	Contraction loss in risers (RECHOP)	BPP	Bypass peripheral region
h	Enthalpy, Btu/lb	bfp	Below fuel plates
h _{fg}	Heat of vaporization, Btu/lb	C	Core section
Δh	Subcooling, Btu/lb	CR	Bypass control rod guide regions
K _L	Inlet loss coefficient (RECHOP)	D	Downcomer
K _n	Mass flow correction factor for two-phase pressure drop	e	Exit conditions
k _c	Loss coefficient for sudden contraction	g	Gaseous phase
k _e	Loss coefficient for sudden expansion	in	Inlet of a channel
L	Length, ft	KO	thick outer region
N _{ref}	Reynolds Number	l	Liquid phase
P	Pressure, psi	LP	Lower plenum
Q _T	Total heat input, Btu/hr	m	Makeup water
Q"	Average heat flux, Btu/ft ² -hr	NB	Nonboiling section of a channel
Q'''	Average power density, kw/l _{coolant}	ri	Risers, i = 1, 2, 3
R	Two-phase friction factor multiplier	S	Spike region
S = C _g /C _l	Slip ratio in upflow	Sr	Shroud
T	Temperature, °F	sub	Subcooled
ΔT_{sub}	Subcooling, °F	T	Total
V ₀	Velocity, ft/sec	TC	Thin central region
(V _g /V _l) _{DF}	Slip ratio in downflow	TO	Thin outer region
W	Mass flow rate, lb/hr		
x	Quality, lb steam/lb mixture		

A PERFORMANCE ANALYSIS OF THE EBWR AT VARIOUS POWER LEVELS

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I. INTRODUCTION

This study is an attempt to predict the operating performance of EBWR (Experimental Boiling Water Reactor) at various power levels. It was done at the same time that EBWR was raised in power up to 100 MW, and so an excellent possibility was given to check the validity of the used performance analysis.

Basically, the treatment follows a previous analysis done at Argonne National Laboratory,⁽¹⁾ but includes some refinements. An IBM-704 Code (RECHOP) for calculating the recirculating velocity, was necessary to simplify the reactor geometry somewhat in order to clarify flow patterns and specify the unheated flow (bypass flow) through the core. An attempt was made to take into account the effect of steam carryunder. The structure of RECHOP did not allow consideration of steam carryover, which becomes quite significant in EBWR at high power operation; therefore, the experimental values of subcooling were used as independent parameters in order to make a comparison with the experimental results.

Rather than giving a general and complete outline of the analysis or establishing a new approach, the study outlines and specifies the numerous practical problems involved in this analysis, and tries to explain the discrepancies between predicted and experimental results.

II. GENERAL PROCEDURE

EBWR, a boiling water reactor, represents a natural-circulation system in which fluid flow is derived through a density potential in the system. The density differential is caused and maintained by the energy released in the reactor core, where boiling takes place.

The analysis of such a system is complicated by many interrelationships. Calculations of the heat transfer and fluid flow are linked closely with the physics of the reactor. Because of the dependence of the steam void of the various neutron cross sections, calculation of the neutron flux or power distribution requires information about the average void distribution in the reactor core, and vice versa. A further complication is due to the existing interdependence between various parameters such as steam void fraction and steam quality fraction, recirculation rate, subcooling, and

carryunder. In addition to the somewhat inadequate information about two-phase flow parameters, such as slip correlations, two-phase pressure drop, two-phase friction factor and its dependency upon mass velocity, and carryunder correlation, the geometry of the EBWR is quite complex, so that it is somewhat difficult to define flow paths, flow areas, and hydraulic diameters.

Briefly, the procedure used for calculating the performance of the EBWR was as follows:

In order to bypass the time-consuming iteration process between the hydro- and thermodynamic calculations and the physics calculation, the neutron-flux distribution was calculated by means of a PDQ code for a number of assumed average void distributions in the core. As a basis for the guesses regarding voids, previous calculations were used. For a specific power level, a certain average void content was assigned. This not very correct way was chosen after realizing that the complexity of the reactor and the lack of information in two-phase flow will introduce a much more significant error than the fact that assumed and actual void distribution, for the physics calculation, did not agree exactly. Having established the power distribution for various operating powers, an IBM-704 code (RECHOP) was used to calculate the circulation velocity. RECHOP is a modified IBM-650 code (CHOP) which calculates the recirculation velocity for a single channel by an iterative procedure. Since the EBWR is far from being a single-channel loop, it is obvious that some very simplifying assumptions have to be made in order to apply RECHOP to calculations about EBWR performance.

An attempt was made to consider carryunder and also to specify the bypass flow (unheated flow) through the core. Because of the extraordinary performance characteristics of EBWR at high power levels (carryover becomes quite significant and introduces an increase of subcooling with increasing power), the experimental values of subcooling were used as an input. This was necessary because RECHOP has no way of taking into account carryover and would predict zero subcooling at 100 MW due to carryunder of steam in the downcomer. Of course, this lessens the value of the entire analysis, but was the only way of comparing the hydrodynamic calculations with the experimental data.

A short outline of the general procedure, without going into too many details, reads as follows:

1. Specify the total reactor power, operating pressure, and makeup water temperature.
2. Assume a total mass flow rate and determine the average void content in the various sections of the core, which have been determined by physical and hydrodynamic considerations.

3. Estimate control rod position and calculate homogenized cross sections for the various core regions.
4. Calculate neutron-flux distribution by an IBM-704 PDQ code and determine the energy released in the various core sections, which will be treated as a single channel.
5. Assume a radial circulation velocity profile and calculate all the parameters which are necessary as RECHOP input for the various regions:
 - riser voids;
 - inlet loss coefficients (K-term);
 - contraction losses in the riser (H-term);
 - downcomer density (carryunder analysis).
6. Use RECHOP to calculate the circulation velocity and average power densities as a function of the exit void fraction for the various radial regions of the core.
7. With the calculated power densities from step 4 and the output of step 6, determine the circulation velocity for each "channel" (region).
8. Check the new velocity profile against the one assumed in step 5 and repeat until agreement is reached.
9. If the velocity profiles agree, calculate the average void content in the core and compare with that determined in step 2. If the new profile differs substantially from the assumed profile, the procedure is repeated, beginning at step 2*.
10. After velocity profile and average void content in the core have been brought into agreement, the radial profiles of existing qualities, void fractions, and flow rates, as well as total flow rate and percentage carryunder, can be calculated in a straightforward manner.

The entire procedure was repeated for power levels from 20 MW up to 100 MW, and the results are given as dependent upon the power.

III. CORE LOADING AND GEOMETRY

One of the main difficulties was to establish the geometry of the core, riser, and downcomer flow regions.

The basic design of EBWR is given in Ref. 2. The modifications made for higher power operation are described in Ref. 3.

*Because the original guesses of the void profile were based on experimental data and previous calculations, the agreement was good enough and no iterations on the physical calculations were done.

For both physics as well as thermo- and hydrodynamic calculations, it was necessary to divide the core in certain regions or channels according either to common physical parameters or similar geometry dimensions.

Figure 1 shows the core loading of the EBWR Core 1A as it was used during high-power operation. Basically, the core consists of a central region of thin enriched plate elements (see Fig. 2) surrounded by rod-type, "spiked" fuel assemblies (see Fig. 3) arranged in a square pattern and followed by an incomplete ring of outer thin elements. The rest of the outer region of the core contains, mainly, thick enriched plate elements with a few "natural" plate elements as well as spike elements, adding up to a total of 147 elements.

Fig. 1. EBWR Core 1A Configuration

Fig. 2

Plate-type Fuel Element (Cross Section of a Typical 9-element Cell Composed of Thin Elements)

Fig. 3
Cross Section of Rod-type Fuel Elements (Spike Element)

NOTE: ALL DIMENSIONS IN INCHES

For the analysis, the loading scheme was simplified and the core radially divided in four main regions of flow:

Region No. 1, thin central region	TC:	36 elements;
Region No. 7, spike region	S:	28 elements;
Region No. 4, thin outer region	TO:	21 elements;
Region No. 5, thick outer region	KO:	62 elements.

By viewing at a cross section of a typical plate element (see Fig. 2), it appears that not all of the flow going through the element will come in contact with heated surfaces. Furthermore, the peripheral flow between the shroud structure and the outer fuel elements, as well as the flow through the control rod guides, will not contribute significantly to the removal of

heat released in the core. Therefore, in addition to the four main or heated flow regions, four bypass flow regions were defined:

Region No. 2:	bypass central thin region	BPC;
Region No. 3:	bypass control rod guide region	CR;
Region No. 6:	bypass outer region	BPO;
Region No. 8:	bypass peripheral region	BPP.

The bypass regions 2 and 6 are defined as the flow area between the element side plates (see Fig. 2). The bypass region 3 consists of the flow area inside of the control rod guides (see Fig. 2), whereas the peripheral bypass region 8 is represented by the gap between core and shroud structure (see Fig. 1). The fuel rods in the spike elements are fully enclosed in the fuel element can; therefore, all flow going through those elements can be considered as "heated flow," and no bypass region for the spikes were defined. Flow areas, equivalent diameters, and heights of those flow regions are listed in Table I.

Table I
COMPILATION OF EBWR GEOMETRICAL DIMENSIONS
(CORE, RISER, AND DOWNCOMER)

(All dimensions are given in ft)

[illegible]

A schematic of the simplified flow paths of core and riser sections of EBWR as used in the analysis is shown in Fig. 4. For each of the defined flow regions up to three risers were specified. In all cases the riser one represents, in fact, actual flow channels and is well defined, whereas for the risers two and three (common riser) the riser areas which are common for more than one "channel" had to be divided artificially. This was necessary in order to be able to apply the RECHOP program - which treats only a single channel - to the multichannel program of the EBWR. The definitions of these riser areas were done by weighting the actual area according to the mass flow rate of the participating channels and making some adjustments of the equivalent diameter. Starting with flow rates derived from the assumed velocity distribution, the riser flow areas were corrected during the iteration process.

Riser 1 is defined as the inactive length of the fuel plates for all plate-type fuel elements (regions 1, 4, and 5). For the corresponding bypass regions 2 and 6 there is no change in area in this section of the channel, and therefore no Riser 1 was specified. This portion of the channel is included in the core section. In the case of the spike elements (region 7), Riser 1 is defined as the distance from the top of fuel rods to the top of the fuel element cans.

Riser 2 is defined for all flow regions as the distance from the top of fuel cans to the top of the control-rod guides. As mentioned before, establishing the proper flow areas and hydraulic diameters proved to be somewhat problematic. Generally, there are two main portions of Riser 2 in both of which more than one fuel element discharges. The central part is common for regions 1 and 2. The outer part of Riser 2 is common to the remaining regions. Due to mixing and the fact that those riser areas and hydraulic diameters are used in RECHOP for calculating both the friction loss and expansion losses, the determination of these "geometric" parameters required some adjustments.

As mentioned before, the Riser 2 areas are used in RECHOP to calculate expansion losses and frictional losses. For the outer regions (TO, KO, BPO, and S), the proper area for calculating expansion losses would be A_{36} (see Fig. 4), which had to be weighted by the mass flow rates of the discharging channels. The frictional loss in the two-phase region is calculated in RECHOP by use of the Martinelli friction factor multiplier:

$$\Delta P = R_f \frac{G^2 L}{2 g_c \rho D} = R_f \frac{W^2}{2 g_c \rho} \left(\frac{L}{D A^2} \right) \quad (III-1)$$

Since there is a change in area over the length L of Riser 2, the correct expression would be

$$\Delta P = R_f \frac{W^2}{2 g_c \rho} \left(\frac{L_{33}}{D_{33} A_{33}^2} + \frac{L_{34}}{D_{34} A_{34}^2} + \frac{L_{36}}{D_{36} A_{36}^2} \right) \quad (III-2)$$

Fig. 4. Schematic of Flow Regions in the EBWR Core Section and Risers

where $\bar{A}_{33}$ is an average value of the conical end section of Riser 2. Equations (III-1) and (III-2) yield the relationship

$$(\bar{D}\bar{A}^2)_{R2} = \frac{L_{R2}}{\left[(L_{33}/D_{33}A_{33}^2) + (L_{34}/D_{34}A_{34}^2) + (L_{36}/D_{36}A_{36}^2) \right]} \quad , \quad (III-3)$$

where

$$L_{R2} = L_{33} + L_{34} + L_{36} \quad . \quad (III-4)$$

By using $\bar{A} = A_{36}$ for correct evaluation of the expansion losses, one had to adjust the value for the equivalent diameter $\bar{D}$. Since the riser areas A_{33} , A_{34} , and A_{36} will be weighted with different factors according to the mass flow rates of the participating channels, the equivalent diameter $\bar{D}_i$ has to be calculated for each channel separately. Then $\bar{D}_i$ together with the mass flow-weighted area $(A_{36})_i$ will give the proper value for the friction losses. Thus, for example, for the TO region the areas used for evaluation of the equivalent diameter $\bar{D}_{TO}$ are given by

$$A_{33}^{TO} = A_{33} \frac{W_4}{W_4 + W_5 + W_6 + W_7 + W_8} \quad ; \quad (III-5)$$

$$A_{34}^{TO} = A_{34} \frac{W_4}{W_4 + W_5 + W_6} \quad ; \quad (III-6)$$

$$A_{36}^{TO} = A_{36} \frac{W_4}{W_4 + W_5 + W_6 + W_7} \quad . \quad (III-7)$$

By substitution of Eqs. (III-5), (III-6), and (III-7) into Eq. (III-3), and setting $\bar{A}_{R2} = A_{36}^{TO}$, the equivalent diameter $\bar{D}_{TO}$ for the TO region can be calculated. Riser 2 flow areas and equivalent diameters for the other flow regions can be determined in a similar way.

Riser 3, the common riser, is defined for all flow channels as the distance from the top of control-rod guides to the top of the shroud. Again, the specific riser areas for the various channels as used in RECHOP were determined by weighting the common riser flow area according to the mass flow rates of the channels involved.

The downcomer flow areas are again the averaged geometrical downcomer area weighted according to the mass flow rates.

During the iteration process, some readjustments of both the riser and downcomer areas were made. Flow areas, hydraulic diameters, and lengths of the core section risers and downcomer used in the final stage of the analysis (20 MW) are shown in Table I.

IV. DETERMINATION OF THE POWER DISTRIBUTION FOR EBWR

The power distribution for EBWR was calculated by use of a PDQ Code⁽⁴⁾ in R-2 geometry. Three-group diffusion theory was applied with the following group limits:

group 1: $\infty \rightarrow 180$ keV

group 2: $180 \text{ keV} \rightarrow 0.625 \text{ keV}$

group 3: $0.625 \text{ keV} \rightarrow 0$,

it being assumed that all fission neutrons are born in group 1. The reactor was divided in 14 regions according to physical and hydrodynamic considerations. Following the flow "channel" set-up for the hydrodynamic calculation, four radial regions were defined:

thin enriched elements, central;

spike elements;

thin enriched elements, outer;

thick enriched elements.

The vertical subdivisions were found by estimating the control-rod position and the nonboiling length of the channels. From previous calculations, a power distribution was estimated, and for a certain power level, the energy released in the channel was calculated. With an assumed velocity profile and subcooling value, average steam volume voids for the various regions were calculated. Figure 5 gives a typical layout, showing the number of mesh points and assumed average voids for the 20-MW calculation.

Fig. 5

Sketch of the EBWR Core Regions for PDQ-Code: 20 MW (Typical Layout, Showing Number of Mesh Points and Assumed Average Voids)

Having established the subregions, the same procedure was followed as outlined in detail in Ref. 5. Void-dependent cross sections were calculated, and for regions 3 and 6 corrections for the control rod were made accordingly.⁽⁶⁾ To account for the poisoning effect of the boron-stainless steel strips, fastened to the sides of the spike elements, homogeneous equivalent poison cross sections were added to the spike element cross sections (see Ref. 5). No corrections were made for burnup. Figures 6 and 7 give the average radial and axial power density distribution for the 20-MW case. Table II shows the final results for the various power levels.

Fig. 6. EBWR, 20 MW: Radial Power Density Distribution

Fig. 7. EBWR, 20 MW: Average Axial Power Density Distribution

Table II

TOTAL ENERGY RELEASED AND POWER DENSITY IN EBWR CORE
FOR VARIOUS POWER LEVELS

Power Level, MW	TC		S		TO		KO	
	Total Energy	PD	Total Energy	PD	Total Energy	PD	Total Energy	PD
20	6.456	21.60	5.042	27.02	2.637	15.20	5.864	13.50
40	12.912	46.084	10.084	56.962	5.275	32.299	11.729	28.555
60	21.032	75.063	15.126	85.443	7.913	48.447	17.593	42.831
80	25.824	92.168	20.168	113.924	10.550	64.597	23.457	57.108
100	32.280	115.211	25.211	142.405	13.188	80.746	29.322	71.386

As mentioned previously, an iteration process is necessary between the physics and thermodynamic calculations for an exact analysis. For-

unately, in this study, because the original guesses of void content were based on previous calculations and partly on experimental data, assumed and calculated voids agreed in most cases quite well. Table III shows quite fair agreement of assumed and calculated values for the 20-MW core.

Table III

COMPARISON OF ASSUMED AND
CALCULATED EBWR CORE
EXIT VOID FRACTIONS

	Assumed for PDQ α_e	Result from RECHOP α_e
TC	0.18	0.20
S	0.27	0.30
TO	0.16	0.15
KO	0.15	0.17

Furthermore, by assuming that the radial exit void distribution $\alpha_e(r)$ changes only its amplitude but has approximately the same shape for each power level, the assumption that the radial power distribution will also increase only its magnitude but not change

the profile will not introduce a very significant error.

V. RECHOP PROGRAM

RECHOP is an IBM-704 Code to calculate the circulation velocity V_0 , average power density Q''' , and average heat flux Q'' for a single channel. A detailed description of the program is given in Ref. 7. The program calculates the circulation velocity V_0 from the following equation:

$$V_0 = 8.04 \sqrt{\frac{(1/\rho_L) \left\{ \sum_i (\bar{\rho}_D - \rho_{ri}) L_{ri} + L_B (\bar{\rho}_{NB} - \bar{\rho}_B) + L_C (\bar{\rho}_D - \bar{\rho}_{NB}) \right\}}{\sum_i \left[f_{ri} R_{ri} \left(\frac{A_C}{A_{ri}} \right)^2 \frac{L_{ri}}{D_{ri}} \right] + f_D \frac{\rho_L}{\rho_D} \left[\left(\frac{A_C}{A_D} \right)^2 \left(\frac{L_C + L_{ri}}{D_D} \right) \right] + f_C \left[\bar{R} \frac{L_B}{D_C} + \frac{\rho_L}{\rho_{NB}} \left(\frac{L_C - L_B}{D_C} \right) \right] + 2 \frac{(1-x_e)^2}{1-\alpha_e} + \frac{x_e^2}{\alpha_e} \frac{\rho_L}{\rho_g} + \frac{\rho_L}{\rho_D} (K_L - 1) + 2F_a + H}} \quad (V-1a)$$

with

$$F_a = \sum_i \left(\frac{A_C}{A_{ri}} \right) (n_{9i} = n_{9i-1}) \quad (V-1b)$$

$$n_i = \frac{A_C}{A_{ri}} \left[\frac{(1-x_e)^2}{(1-\alpha_{ri})} + \left(\frac{\rho_L}{\rho_g} \right) \left(\frac{x_e^2}{\alpha_{ri}} \right) \right], \quad (V-1c)$$

where the i^{th} term is equal to zero if $A_{ri-1}/A_{ri} \geq 1$, $i = 1, 2, 3$. Since several terms in Eq. (V-1a) are directly or indirectly related to V_0 , an iterative process is required. Once V_0 is calculated to the specified accuracy (change in V_0 from one iteration to the next is less than 1%), the power density Q''' and heat flux Q'' are calculated in a straightforward manner from the Eqs. (V-2) and (V-3):

$$Q''' = 0.03725 V_0 \left(\frac{C_g}{C_\ell} \right) \rho_g (1-x_e) \left(\frac{h_{fg}}{L_B} \right) \left(\frac{\alpha_e}{1-\alpha_e} \right); \quad (V-2)$$

$$Q'' = 24240 D_C Q''' \quad (V-3)$$

Basically, Eqs. (V-1a), (V-2), and (V-3) are composed of three groups of quantities: independent parameters, physical properties of the fluid, and quantities which are functions of the circulation velocity V_0 . The independent parameters, such as

- pressure P ;
- makeup water temperature T_m ;
- channel length L ;
- equivalent diameter D ;
- flow area A ;
- downcomer density $\bar{\rho}_D$;
- undefined losses H ;
- contraction term K_L ;
- exit void fraction α_e

are given as an input. It should be noted that flow areas A , downcomer density $\bar{\rho}_D$, exit void fraction α_e , and the loss terms H and K_L are only in RECHOP assumed to be independent of the circulation velocity V_0 . It will be shown later on that these parameters had to be recalculated for each "outside" iteration. In addition, void fractions for up to three risers can be specified. There is also a possibility to introduce subcooling and specific heat as an input.

The contraction term K_L is used to take care of the entrance losses which must be calculated by hand and given as an input, since the program does not account for any sudden contractions. The H -term gives a possibility to account for further losses, e.g., contraction losses in the two-phase region (riser).

The thermodynamic properties of steam, such as density, enthalpy, saturation temperature, are calculated in the program by a set of subroutines developed by General Electric.⁽¹⁵⁾

The velocity-dependent terms, such as Reynolds Number, friction factor f , two-phase friction multiplier R , correction factors K_{ni} , slip correlations $S = C_g/C_l$, and exit quality x_e , are recalculated in each iteration step based upon V_0 from the preceding iteration. The isothermal friction factor f for core section, riser, and downcomer, respectively, are based on data from C. F. Moody.⁽⁹⁾ For a chosen relative roughness, the friction factors were expressed by

$$\text{core: } f_c = A + \frac{B}{(N_{ref})^C} \quad (V-4a)$$

$$\text{riser: } f_{ri} = A + \frac{B}{[(A_C/A_{ri})(D_{ri}/D_C)N_{ref}]^C}, \quad (V-4c)$$

where the constants A , B , and C have to be evaluated according to the assumed relative roughness.

Since RECHOP uses uniform heat input along the channel, the two-phase frictional pressure-drop computations are based on the original Martinelli-Nelson model, which uses the concept of a friction factor multiplier. Local and average two-phase friction multipliers R and $\bar{R}$ (see Figs. 8 and 9) are tabulated as a function of exit quality x_e and pressure (see Ref. 8). In order to account for the effect of mass flow rate on two-phase pressure drop, a correction factor K_{ni} is applied. This mass flow correction factor K_{ni} (see Figs. 10 and 11) is computed from

$$K_{ni} = 1 + x_e^2 \ln (G_{ri} \times 10^{-6}) + 2 \sqrt{x_e} \left[\frac{1 - (G_{ri} \times 10^{-6})}{(G_{ri} \times 10^{-6})^{1.1}} \right] \quad (V-5)$$

Fig. 8
Local Two-phase Friction
Factor Versus Quality

Fig. 9
Average Two-phase
Friction Multiplier
(Uniform Heat Input)

Fig. 10

Correction Factors
Based on α from
SHER: Slip = 1.0

Fig. 11

Westinghouse Two-phase
Pressure-drop Data

with the limits

$$x_e \leq 0.45 - 0.02(G_{ri} \times 10^{-6}) \quad (V-5a)$$

and

$$(G_{ri} \times 10^{-6}) \geq 0.06 \quad (V-5b)$$

The slip correlation $S = C_g/C_\ell$ used is an empirical correlation developed at Argonne National Laboratory.⁽¹⁰⁾ The empirical correlation

$$\frac{C_g}{C_\ell} = S = [1.89 + 5.70x_e] \left(\frac{1000}{P} \right)^{0.0794} \left(\frac{2.2}{V} \right)^{0.2} \quad (V-6)$$

and the well-known expression for the slip ratio

$$S = \left(\frac{x}{1-x} \right) \left(\frac{1-\alpha}{\alpha} \right) \left(\frac{\rho_f}{\rho_g} \right) \quad (V-7)$$

were combined and by eliminating the quality term, the following relationship was derived:

$$S = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad , \quad (V-8)$$

where

$$a = 1 \quad ; \quad (V-8a)$$

$$b = \left(\frac{1 - \alpha_e}{\alpha_e} \right) \left(\frac{\rho_L}{\rho_g} \right) - 7.59 \left(\frac{1000}{P} \right)^{0.0794} \left(\frac{V_{0j+1}}{2.2} \right)^{-0.2} \quad ; \quad (V-8b)$$

$$c = -1.89 \left(\frac{1 - \alpha_e}{\alpha_e} \right) \left(\frac{\rho_L}{\rho_g} \right) \left(\frac{1000}{P} \right)^{0.0794} \left(\frac{V_{0j+1}}{2.2} \right)^{-0.2} \quad . \quad (V-8a)$$

This correlation holds only for pressures up to 600 psi.

A simple carryunder analysis was carried out, by hand, leading to an average downcomer density. This density $\bar{\rho}_D$ was introduced into the program as an independent parameter.

Starting with the initial conditions:

$$V_{0j} = 1 \quad ; \quad N_{ref} = 2 \times 10^5 \quad ; \quad K_{ni} = 1 \quad ; \quad C_g/C_\ell = 1 \quad ,$$

an iteration process is followed until

$$\frac{|V_{0j+1} - V_{0j}|}{V_{0j}} \leq 0.01 \quad .$$

Then, Eqs. (V-2) and (V-3) are computed with the values obtained from the final iteration for V_0 .

Table IV shows a typical output sheet of RECHOP. For each channel a range of exit void fraction was specified, and so a relation between the circulation velocity V_0 and the power density PD obtained. From the known distribution of power density, a velocity profile can be determined. This procedure was followed also for exit quality x_e and exit void fraction α_e (see Fig. 12).

Table IV

TYPICAL RECHOP OUTPUT SHEET

RE 160 COMPUTATIONS FOR .27012 TO

PAGE 1

PROBLEM NUMBER 1

GENERAL PARAMETERS

PRESSURE	6.14700E 02	TEMPERATURE	1.30000E 02
UNDEFD LOSSES	1.68820E 01	CONTRACTION	9.67000E-01
GAMMA	0.	ALPHA E	10.00000E-02

REGIONAL PARAMETERS

	AREA	DIAMETER	LENGTH
DOWNCOMER	2.14500E 00	1.70000E 00	
CORE	1.44100E 00	6.48000E-02	4.25000E 00
RISER 1	1.44100E 00	6.48000E-02	1.25000E-01
RISER 2	2.95100E 00	9.32000E-01	3.86000E 00
RISER 3	1.50300E 00	3.83000E 00	3.76000E 00

OPTIONAL PARAMETERS

ALPHA R 2	2.03800E-01
ALPHA R 3	2.00800E-01
DELTA T	1.90000E 00
SPEC. HEAT	1.17000E 00

RESULTS

VELOCITY	2.10276E 00	L SUB B	2.81676E 00
AVG POWER DENS	6.01326E 00	K SUB T	1.64892E 00
AVG HEAT FLUX	3.44534E 03	F ZERO SUB F	3.10711E-02
SLIP RATIO	2.01816E 00	R BAR	1.72305E 00
EXIT QUALITY	5.99919E-03	DELTA T	1.90000E 00

AVG DENSITIES

BOILING	4.70083E 01	DOWNCOMER	4.86400E 01
NON-BOILING	4.95844E 01	SAT - TEST	1.61919E 00

	F	DENSITY	ALPHA
RISER 1	1.63608E 00	4.46798E 01	10.00000E-02
RISER 2	2.22832E 00	3.96804E 01	2.03800E-01
RISER 3	1.71689E 00	3.98249E 01	2.00800E-01

Fig. 12

Typical RECHOP Output Diagram:
20 MW (Inlet Velocity, Exit Quality,
and Exit Void Fraction as a Func-
tion of Power).

VI. CALCULATION OF SYSTEM PARAMETERS

In Section V are listed the independent system parameters which serve as an input for the RECHOP program. Some of these general parameters, such as pressure, makeup water temperature, and geometrical dimensions of the core section, are independent of power level, whereas the terms undefined losses H , contraction K_L , and downcomer density $\bar{\rho}_D$ will vary with power. Since the flow areas and equivalent diameters of the risers and downcomer, not being material realities, are determined as a function of the mass flow rates, these, too, will be a function of power.

1. K_L -terms

Coming from the lower plenum (beneath the grid plate), the recirculation flow apportions itself and undergoes sudden contractions and expansions (single phase) by entering the individual channels. The K_L -terms give a possibility to account for these entrance losses. Simplified views of the entrance section which are typical of all heated channels and bypass channels are shown in Figs. 13 and 14. For single-phase flow, from a simple pressure balance across the change in area, neglecting the hydrostatic head

Fig. 13. Entrance Section of a Typical Channel

Fig. 14. Entrance Section of Control Rod

and the friction losses, one can write the pressure difference in terms of the number of velocity heads. Assuming no change in density, one gets

$$K_L = \frac{P_1 - P_6}{(1/2\rho)(V_0^2/g_c)} = [1 - (\sigma_{2-1})^2 + k_{C1}] \left(\frac{V_2}{V_0}\right)^2 + [(\sigma_{3-4})^2 - 1 + k_{e3}] \left(\frac{V_2}{V_0}\right)^2 + [1 - (\sigma_{5-4})^2 + k_{C4}] \quad , \quad (VI-1)$$

where

$$V_2 = W_T/A_2 \text{ and } V_5 = V_0 \quad .$$

It has been shown that $k_{e3} = (1 - \sigma_{3-4})^2$ exactly (Ref. 9), and so Eq. (VI-1) can be rewritten as

$$K_L = \left(\frac{V_2}{V_0}\right)^2 \{ [1 - (\sigma_{2-1})^2 + k_{C1}] - 2\sigma_{3-4}(1 - \sigma_{3-4}) \} + [1 - (\sigma_{5-4})^2 + k_{C4}] \quad . \quad (VI-2)$$

The values given by Weissbach⁽⁸⁾ are used as loss coefficients (k_{C1} and k_{C4}) for a sudden contraction.

The quantities σ represent area ratios, namely,

$$\sigma_{2-1} = A_2/A_1 = A_{in}/A_{LP} \quad ; \quad (VI-3a)$$

$$\sigma_{3-4} = A_3/A_4 = A_{in}/A_{bfp} \quad ; \quad (VI-3b)$$

$$\sigma_{5-4} = A_5/A_4 = A_f/A_{bfp}^* \quad . \quad (VI-3c)$$

$A_f = A_C$ are the flow areas of the core section of the various regions and are listed in Table I. A_{in} denotes the flow area of the cylindrical end sections of the channels, which are identical for all fuel elements. A_{bfp} stands for "flow area below fuel plates," i.e., the total area inside the fuel element cans (see Figs. 2 and 3).

The areas A_{LP} and A_{bfp}^* are prorated areas weighted according to the mass flow rates of the participating flow channels. For the first contraction 1-2, regions 1 and 2 (TC and BPC) can be treated at once, and the corresponding A_{LP} (lower plenum) is given by

$$A_{LP}^{1,2} = A_{Sr} \frac{W_1 + W_2}{W_T} \quad , \quad (VI-4a)$$

where A_{Sr} is the total flow area inside the shroud. It is assumed that the entire peripheral bypass BPP (region 8) stems only from the region 5 (KO), whereas the outer bypass BPO (region 6) is split up between regions TO

and KO according to the number of fuel elements present in those regions. Thus, the areas A_{LP} for TO and KO are calculated as

$$A_{LP}^{4,6} = A_{Sr} \frac{W_4 + (21/83) W_6}{W_T} ; \quad (VI-4b)$$

$$A_{LP}^{5,6,8} = A_{Sr} \frac{W_5 + (62/83) W_6 + W_8}{W_T} . \quad (VI-4c)$$

Before undergoing the second contraction 4-5, heated and bypass flow are assumed to be completely separated, and the areas A_{bfp}^* are calculated as follows

$${}_1A_{bfp}^* = A_{bfp}^{1,2} \frac{W_1}{W_1 + W_2} ; \quad (VI-5a)$$

$${}_2A_{bfp}^* = A_{bfp}^{1,2} \frac{W_1}{W_1 + W_2} ; \quad (VI-5b)$$

$${}_4A_{bfp}^* = A_{bfp}^{4,6} \frac{W_4}{W_4 + (21/83) W_6} ; \quad (VI-5c)$$

$${}_5A_{bfp}^* = A_{bfp}^{5,6,8} \frac{W_5}{W_5 + (62/83) W_6 + W_8} ; \quad (VI-5d)$$

The outer bypass flow area is now split up into two parts, bypass outer TO and bypass outer KO:

$${}_6A_{bfp}^* = A_{bfp}^{4,6} \frac{(21/83) W_6}{W_5 + (21/83) W_6} ; \quad (VI-5e)$$

$${}_6A_{bfp}^* = A_{bfp}^{5,6,8} \frac{(62/83) W_6}{W_5 + (62/83) W_6 + W_8} ;$$

$${}_8A_{bfp}^* = A_{bfp}^{5,6,8} \frac{W_8}{W_5 + (62/83) W_6 + W_8} . \quad (VI-5f)$$

Since the spike region has no bypass,

$$A_{LP}^7 = A_{Sr} \frac{W_7}{W_T} \quad (VI-4d)$$

and

$${}_7A_{bfp}^* = A_{bfp}^7 . \quad (VI-5g)$$

The geometry of the bypass channel is identical for both the TO and KO regions, and therefore the bypass is combined and treated in RECHOP as one flow region, BPO. The entrance loss term K_L^6 for the region is calculated by combining the two K_L values obtained from the TO and KO dependent parts in a way that it leads to the same mass flow:

$$V_6 = \frac{V_6^{TO} A_6^{TO} + V_6^{KO} A_6^{KO}}{A_6} \quad (\text{VI-6})$$

where V_6^{TO} and V_6^{KO} are expressed in terms of K_L as

$$V_6^{TO} = \sqrt{\Delta p \cdot 2g_c / K_L^{TO} \rho} \quad ; \quad (\text{VI-7a})$$

$$V_6^{KO} = \sqrt{\Delta p \cdot 2g_c / K_L^{KO} \rho} \quad . \quad (\text{VI-7b})$$

If the same pressure drop may be assumed for combined and separated flows, the expression for K_L^6 becomes

$$K_L^6 = \frac{\Delta P}{\rho} \frac{2g_c}{(V_6)^2} = \left(\frac{A_6}{\left(A_6^{TO} / \sqrt{K_L^{TO}} \right) + \left(A_6^{KO} / \sqrt{K_L^{KO}} \right)} \right)^2, \quad (\text{VI-8})$$

where A_6^{TO} and A_6^{KO} are prorated areas.

The entrance loss for the bypass control-rod guide channel CR (Region 3) is calculated in a similar way, except that there is no sudden expansion (see Fig. 14). The corresponding mass-flow-rate-dependent areas are given by

$$A_{LP}^3 = A_{Sr} \frac{W_3}{W_T} \quad (\text{VI-4e})$$

and

$${}_3A_{bfp}^* = A_{bfp}^3 = A_{in}^3 \quad . \quad (\text{VI-5h})$$

Since the entrance losses are mass-flow-dependent, all the K_L values are recalculated for each "outside" iteration, i.e., with the velocity profile obtained from RECHOP, all the general input parameter and flow rates were recalculated for the next iteration step.

2. H-term

Since the flow area in Riser 3 (common riser) is less than that of Riser 2, the contraction loss in the two-phase flow region must be calculated.

If a gradual contraction (see Fig. 4) may be assumed to occur, i.e., $k_c = 0$, an energy balance yields

$$H = \left(\frac{V_{R2}}{V_0} \right)^2 \frac{1}{1 + x_{R2}(\Lambda - 1)} \left\{ x_{R2} \Lambda^2 \left[\left(\frac{x_{R3}}{\alpha_{R3}} \right)^2 \left(\frac{V_{R3}}{V_{R2}} \right)^2 - \left(\frac{x_{R2}}{\alpha_{R2}} \right)^2 \right] + (1 - x_{R2}) \left[\left(\frac{1 - x_{R3}}{1 - \alpha_{R3}} \right)^2 \left(\frac{V_{R3}}{V_{R2}} \right)^2 - \left(\frac{1 - x_{R2}}{1 - \alpha_{R2}} \right)^2 \right] \right\} \quad (VI-9)$$

For small qualities x , Eq. (VI-9) reduces to

$$H = \left(\frac{V_{R2}}{V_0} \right)^2 \frac{1}{1 + x_{R2}(\Lambda - 1)} \left[\left(\frac{1}{1 - \alpha_{R3}} \right)^2 \left(\frac{V_{R3}}{V_{R2}} \right)^2 - \left(\frac{1}{1 - \alpha_{R2}} \right)^2 \right] \quad (VI-10)$$

where

V_0 circulation velocity at the core inlet

V_{R2} velocity in Riser 2;

V_{R3} velocity in Riser 3;

Λ density ratio ρ_f/ρ_g ;

x_{R2} , α_{R2} , and α_{R3} qualities and voids in Risers 2 and 3, respectively.

3. Carryunder

Due to incomplete steam separation in the reactor dome, some steam will be carried under in the downcomer, and this affects strongly the subcooling ΔT_{sub} . In EBWR a further complication occurs due to the excessive carryover effect at higher power levels, which introduces an erratic subcooling pattern.

Since the RECHOP program has no way of taking into account this effect, experimental values for subcooling ΔT_{sub} were used. Experiments have shown that the subcooling is strongly effected by the water level. Therefore, the subcooling values used in this analysis are characteristic for a certain water level in the reactor.

A heat balance on the downcomer yields

$$W_m h_m + W_\ell h_\ell + W_g h_g = W_T h_m \quad (VI-11)$$

By substituting

$$W_m = (1 - \lambda) \bar{x}_e W_T \quad (VI-12a)$$

$$W_{\ell} = (1 - \bar{x}_e) W_T \quad , \quad (\text{VI-12b})$$

$$W_g = \lambda \bar{x}_e W_T \quad , \quad (\text{VI-12c})$$

and

$$\bar{x}_e = \frac{Q_T}{W_T(1 - \lambda)(h_g - h_m)} \quad , \quad (\text{VI-13})$$

where $\lambda = x_D/x_C$, the weight per cent carryunder, one can derive the following equation:

$$\Delta h_{\text{sub}} = \frac{Q_T}{W_T} \left[1 - \frac{h_{fg}}{(h_g - h_m)(1 - \lambda)} \right] \quad . \quad (\text{VI-14})$$

If solved for percentage carryunder, Eq. (VI-14) yields

$$\lambda = 1 - \frac{h_{fg}}{\left[(h_g - h_m) \left(1 - \frac{W_T \Delta h_{\text{sub}}}{Q_T} \right) \right]} \quad . \quad (\text{VI-15})$$

Knowing x_R from a heat balance in the reactor, the quality at the top of the downcomer is given by

$$x_D = \lambda x_R \quad . \quad (\text{VI-16})$$

By use of a downflow slip correlation (see Ref. 12), the void fraction at the top of the downcomer can be calculated. The slip correlation, developed at Argonne, is

$$\left(\frac{V_g}{V_{\ell}} \right)_{\text{DF}} = 0.63 (F_r)^{0.4} \left(\frac{x_D}{1 - x_D} \frac{\rho_{\ell}}{\rho_g} \right)^{0.2} \quad . \quad (\text{VI-17})$$

For a channel diameter greater than 3 in., the Froude Number F_r in this correlation is evaluated with $D = 3$ in. (see Ref. 12 and 13). The carryunder value is then used to calculate the density at the top of the downcomer.

The downcomer density $\bar{\rho}_D$ depends not only on λ , but also on void profile in the downcomer and the rate at which the steam bubbles collapse in the subcooled liquid. Since no reliable model for the collapse rate of steam bubbles was available and experiments showed that collapsing takes place over a short distance below the feedwater ring, a crude approximation was made. First, it was assumed that all entrained steam bubbles collapse in a 3-ft distance below the feedwater ring. Secondly, the void profile was assumed to vary linearly from the value α_D at the top of the downcomer to zero at 3 ft below. At the top of the downcomer the density

is given by $\rho_D = \alpha_D \rho_g + (1 - \alpha) \rho_\ell$. The density in the lower part of the downcomer, ρ_{D2} , is governed by the temperature of the subcooled liquid. The average density in the upper portion of the downcomer ρ_{D1} is calculated as the arithmetic average of the density at the top and the density in the downcomer where all bubbles have been collapsed, since void distribution is assumed to vary linearly.

To evaluate the hydrostatic head term in the flow equation, it is necessary to determine an average density for the entire downcomer. This average density is defined by weighting the average densities in the upper and lower sections of the downcomer according to the lengths of these sections:

$$\bar{\rho}_D = \rho_{D1} \frac{L_{D1}}{L_D} + \rho_{D2} \frac{L_{D2}}{L_D} \quad . \quad (\text{VI-18})$$

VII. RESULTS AND COMPARISON WITH EXPERIMENTAL DATA

The results obtained from this analysis are presented in a series of graphs and tables. Basically, two ways of presenting the results were chosen:

1. For every power level the calculated radial profiles of inlet velocity V_0 , exit steam quality, and exit steam void fraction are given. In addition, flow rates for the various core regions, ΔT_{sub} , riser voids, etc., are tabulated for the various power levels.

2. For comparison with the experimental data,⁽¹⁴⁾ total flow rate, steam void fraction, carryunder, and subcooling are plotted versus power.

Figures 15 to 17 show the very strong influence of the Moody friction factors. Originally, a friction factor for smooth tubes, approximately 0.017, was used, which is for the range of Reynolds Number in question. This led to the prediction of much too high flow rates, of the order of 10×10^6 lb/hr at 20 MW. The use of friction factors of the order of 0.03 and 0.05 lowered the flow rates quite significantly.

Fig. 15
EBWR, 20 MW: Radial
Velocity Distribution
with Friction Factor
as a Parameter

Fig. 16
EBWR, 20 MW: Radial
Exit Quality Distribu-
tion with Friction Fac-
tor as a Parameter

Fig. 17

EBWR, 20 MW: Radial Exit Void Distribution with Friction Factor as a Parameter

At the time there was no way to determine the accurate values of the friction factor of the various fuel assemblies. Scale has been found on the fuel element of EBWR, varying in thickness up to 8 mils. The scale flakes off and builds up intermittently during reactor operation. The flaking process is believed due to the temperature cycling which occurs during normal reactor operation. Therefore, the assumption of a smooth tube surface on the EBWR element is false, since a degree of roughness most probably exists.

For the final calculations, a friction factor of approximately 0.03 was chosen. The corresponding formulas (V-4a, V-4b, and V-4c) used in the RECHOP are

$$f_c = 0.03 + \frac{15.90}{(N_{ref})^{0.84}} ; \quad (VII-1)$$

$$f_{ri} = 0.03 + \frac{15.90}{[(A_c/A_n)(D_{ri}/D_c)\bar{N}_{ref}]^{0.84}} ; \quad (VII-2)$$

$$f_D = 0.03 + \frac{15.90}{[(A_c/A_D)(D_D/D_c)\bar{N}_{ref}]^{0.84}} . \quad (VII-3)$$

As the results show, these values for the friction factors are apparently still too low.

In Fig. 18 the radial inlet velocity distribution for all power levels calculated are presented. Although at low power the velocity profile across the core is rather flat, the dependency upon power becomes more and more effective at higher power levels. The opposite trend for the spike region,

where velocity decreases with increasing power, should be noticed. This stems mainly from the smaller equivalent diameter, which increases the frictional component of the pressure drop, and partially from the super-

Fig. 18. EBWR: Radial Velocity Distribution for Various Powers

ficial way of the assigning areas and voids for the riser of the spike region. Since the spikes, with a much higher exit quality, discharge in the common outer Riser 2 (see Fig. 4) where the riser voids are governed by TO, KO, and BPO regions with a lower exit quality, the two-phase friction effect in the core region of the spikes overcomes the only slightly increased driving head from the common outer riser. The velocities in the outer regions increase with higher power much more than the velocities

in the inner regions as the voids in Riser 2 do, and so the influence from the total flow rate of the outer regions becomes more and more significant with increasing power.

Figures 19 and 20 show the radial distributions of exit quality and exit voids in the four core regions for all power levels calculated. Again, the deviation from the rather flat profiles at 20 MW with increasing power is quite apparent.

Fig. 19
EBWR: Radial Exit
Quality Distribution
for Various Powers

Fig. 20
EBWR: Radial Exit
Void Distribution for
Various Powers

Table V gives a compilation of the final results. Average velocities, flow rates (including the total flow rate W_T), average riser voids, percentage carryunder, and subcooling are listed for each region and power levels separately. For the comparison with experimental data, total flow rate, average void fraction in the common Riser 3, carryunder and subcooling are plotted versus power (in Figs. 21-24). Also plotted on these figures are curves of the measured values of the parameters as reported in Ref. 14.

Table V
AVERAGE VELOCITIES, FLOW RATES, AND RISER VOIDS
FOR VARIOUS POWER LEVELS

	Power Level				
	20 MW	40 MW	60 MW	80 MW	100 MW
$\bar{V}_1$ ft/sec	4.33	4.74	4.86	4.88	4.85
$\bar{V}_2$	3.21	3.73	4.11	4.31	4.38
$\bar{V}_3$	1.13	1.15	1.17	1.14	1.26
$\bar{V}_4$	4.30	4.83	5.13	5.30	5.30
$\bar{V}_5$	3.32	3.98	4.11	4.30	4.30
$\bar{V}_6$	2.90	3.38	3.66	3.94	3.94
$\bar{V}_7$	3.49	3.57	3.48	3.20	3.00
$\bar{V}_8$	1.80	1.92	2.03	1.72	1.85
$W_1 \times 10^{-6}$ lb/hr	1.916	2.095	2.151	2.159	2.146
W_2	0.144	0.167	0.184	0.193	0.196
W_3	0.083	0.085	0.086	0.083	0.093
W_4	1.109	1.246	1.323	1.367	1.367
W_5	2.154	2.582	2.666	2.789	2.789
W_6	0.404	0.471	0.510	0.549	0.549
W_7	0.974	0.997	0.973	0.895	0.839
W_8	0.971	1.072	1.093	0.927	0.997
$W_T \times 10^{-6}$ lb/hr	7.754	8.715	8.985	8.963	8.976
$\alpha_{R2\ 1,2}$	0.22	0.33	0.41	0.45	0.39
$\alpha_{R2\ 4,5,6}$	0.19	0.28	0.36	0.42	0.37
$\alpha_{R2\ 7}$	0.20	0.30	0.37	0.43	0.38
$\alpha_{R2\ 8}$	0.19	0.28	0.36	0.42	0.37
α_{R3}	0.20	0.29	0.37	0.43	0.38
λ	0.118	0.214	0.284	0.280	0.221
ΔT_{sub} °F	1.9	2.25	1.55	2.20	5.00

Fig. 21
Total Flow Rate
 W_T Versus Power

Fig. 22
Riser-3 Voids Versus
Power

Fig. 23. Carryunder Versus Power

Fig. 24
Subcooling Versus Power

It should be noted again that the measured subcooling values corresponding to an interface height of $725 \text{ ft} \pm 3 \text{ in.}$ was used as input to the RECHOP Program. The subcooling curve used is shown in Fig. 24. As can be seen, the calculated flow rates are substantially higher than the measured values (see Fig. 21). However, the trends versus power are quite similar. Likewise, in Fig. 22 the measured riser void fractions are somewhat higher than the calculated values, but again there is a very close agreement in the trends with power. The sharp deviation in the measured versus calculated values of the steam carryunder beyond 60 MW (see Fig. 23) is due to the occurrence of liquid carryover. The subroutine introduced into the RECHOP Program for computing the carryunder by a simple heat balance did not include provisions for an excess of cold feed water to be introduced due to the occurrence of carryover. As a result, when the subcooling curve was fed in as input, the subroutine computed decreasing values of carryunder as the subcooling increased beyond 60 MW.

For the unheated portion of the flow - bypass regions 2, 3, 6, and 8 - it was assumed that at the exit of the core section no voids are present. This assumption is somewhat questionable, since bypass and heated flow are not completely separated and, therefore, mixing will take place to a certain extent.

By specifying an exit void fraction for the bypass region of the magnitude of 50% of the exit voids α_e of the corresponding heated channels, a remarkable decrease of the recirculation velocity of the bypass channels could be achieved. This would decrease the bypass flow from 20% of the total flow rate at zero exit voids to approximately 10% of the total flow rate, which is almost in the measured range. Because of lack of information about the mixing effect, no data about the exit voids in the various bypass channels were available, and the results are presented without this unverified correction.

VIII. CONCLUSIONS

At a first glance, the results obtained from this analysis appear to be quite poor, and the agreement between experimental data and analytical results can hardly be called excellent. This is basically true; however, by realizing how difficult it is to define such basic parameters as flow areas for EBWR and that RECHOP was originally written for a single channel using uniform heat input along the channel, etc., the results obtained are rather amazing. Furthermore, as has been shown previously, the simple fact of evaluating the proper Moody friction factor will bring the results even closer. Another thing which had to be taken into account in judging the validity of the analysis is the simple fact that EBWR originally was designed for a maximum operating power of 20 MW. Modification as outlined in ANL-6552⁽³⁾ made it possible to raise power to more than 100 MW.

Carryover became very significant at higher powers and changed the characteristic of the reactor completely. The rather sharp and unexpected increase in subcooling beyond a certain power level as shown by the experimental data⁽¹⁴⁾ made it necessary to feed ΔT_{sub} as an independent input (experimental results) into RECHOP. This certainly simplified the analysis (carryunder calculations) but lessened the completeness of the analysis. This means, in fact, that it was not possible to accomplish the original hope that it would be possible to predict the performance of EBWR without using experimental results.

In general, the conclusion of this analysis is that this highly simplified approach to predict the thermodynamic performance of the EBWR proved to be able to show the general trend of the major parameters, except the influence of carryover, and can be used for preliminary predictions. However, in order to obtain more accurate answers, major changes in RECHOP would be necessary (nonuniform heat input, specification of power as input rather than exit quality, etc.) and also a complete iteration between physics and hydrodynamic calculations are required.

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