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ANALYSIS OF THE HOT SPOT PROBLEM IN THE MPRE

(Title Unclassified)

M.E. LaVerne

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REACTOR DIVISION

ANALYSIS OF THE HOT SPOT PROBLEM IN THE MPRE

M. E. LaVerne

DECEMBER 1966

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ANALYSIS OF THE HOT SPOT PROBLEM IN THE MPRE

M. E. LaVerne

ABSTRACT

An analysis of the flow distribution in MPRE-type rod bundles has been made in order to assess the extent to which nonuniform vapor generation affects the flows and thus the development of potential hot spots in such bundles. A computer program embodying the analysis has been written and tested. Results of computer runs indicate that the flow channel couplings characteristic of the MPRE-type core greatly diminish the effects of dissymmetry.

INTRODUCTION

The axial and radial power peaks characteristic of reflected reactor cores appear to pose problems for reactors cooled by a boiling liquid as in the MPRE. The resulting nonuniform vapor generation presents the possibility for "dry-channel" operation and attendant burnout. In order to assess the extent to which this nonuniformity affects the flow distribution in MPRE-type rod bundles, an analysis of the flows in such bundles has been made.

The extreme complexity of the boiling flow patterns in an operating rod bundle, such as that used in the Intermediate Water System (IWS) 91-rod water boiler, is quickly revealed by even a cursory visual examination. At the present state-of-the-art, any attempt to compute the detailed structure of such flow patterns would be futile. The present analysis, therefore, assays a substantially less ambitious task.

It is the intent of this report to present an approximate analysis of the flow distributions through MPRE-type cores on the basis of a few physically reasonable simplifying assumptions. The continuous

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character of the flow redistribution will be substantially preserved if the core is axially subdivided into a sufficiently large number of segments, in each of which these assumptions are applied.

The emphasis in this report is on flow distribution rather than hot channel calculation because of a basic difference between a liquid-cooled core and a core cooled by a boiling liquid with net vapor generation. In the liquid-cooled case, high power in a channel leads to an elevated temperature, i.e., a "hot channel". In contrast, the temperature in a core with net vapor generation is set by the saturation temperature associated with the operating pressure. A high-power channel, then, simply generates more vapor at the same temperature as adjacent channels. As a result, the problem attacked here is limited to determining whether the vapor is redistributed in such a manner as to prevent dry-channel operation with its consequent overheating.

Three basic assumptions were used in deriving the MPRE flow distribution model presented herein. First, the expression used in the analog report adequately correlates the core two-phase pressure drop.[1] Second, any transverse cross section of the core is a surface of constant pressure. Finally, as a consequence of the combined effects of wetting, surface tension, and momentum, liquid is not interchanged between channels. This last assumption is not inconsistent with the interchange of vapor. These assumptions are discussed in some detail in the analysis section of this report.

ANALYSIS

Basic Assumptions

The basic assumptions made for the derivation of the MPRE flow distribution model are three in number:

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[1]A. R. Barbin and M. M. Yarosh, An Analog Study of a Single-Loop Rankine Cycle System, USAEC Report ORNL-TM-1369, Oak Ridge National Laboratory, January 1966.

1. The core pressure drop is adequately correlated by the expression used in the analog report;[1]

2. The pressure is constant across any transverse cross section of the core;

3. There is no interchange of liquid between adjacent channels.

The validity of the first assumption is indicated in Fig. 1, where the quantity $W^2\Delta X$ has been plotted against ΔP for the IWS rod bundle. The ordinate in Fig. 1 is directly proportional to the expression used in Ref. 1 for computing boiler two-phase pressure drop. As will be seen, use of the analog expression is also attractive in that it leads to a set of linear algebraic equations in the unknown vapor flows within the core.

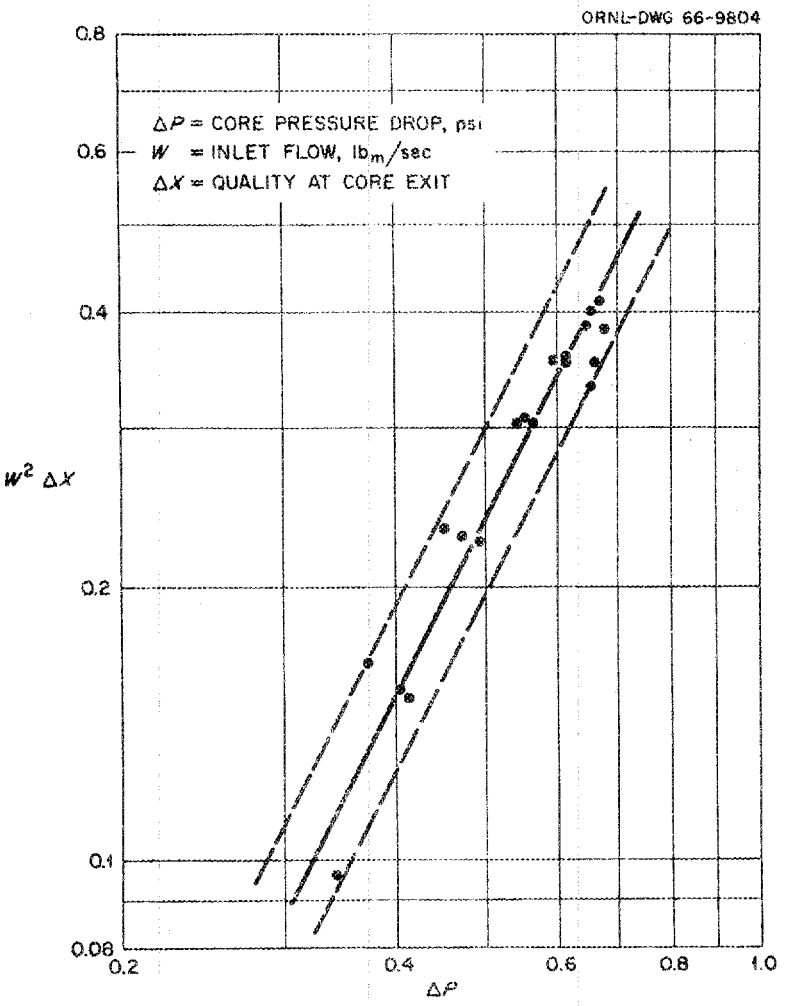

Fig. 1. Correlation of Core Pressure Drop for IWS.

The second assumption certainly would be valid at the ends of the core. Away from the edges of the core, both axially and radially, its plausibility is less clear. However, because of the high connectivity of adjacent channels (even for the close-packed MPRE core, the radial-to-axial equivalent-diameter-ratio is 5:8), the discrepancy should be small even there. In any event, one would expect to wash out a large fraction of the transverse pressure variation that would obtain were there no vapor interchange between channels. In the absence of better information, then, this large fraction has been assumed to be one.

The final assumption arises primarily from the experimental observation that the liquid tends to flow as a film straight up the heater rods. This tendency is a consequence of wetting and surface tension effects. Thus, assumptions two and three are compatible in that there is no lateral force impelling the liquid sidewise. Further, any drag forces on the liquid arising from lateral diffusion of vapor will be small because of the small transverse vapor velocities. This, coupled with the large liquid-to-vapor density ratio and the consequently strong momentum effects tending to maintain axial flow of any liquid droplets, leads to a negligible lateral transport of liquid. Note that interchange of vapor between adjacent channels is not inconsistent with the notion of negligible crossflow of liquid.

Input Restrictions

In addition to the above assumptions, several restrictions have been placed on the input parameters to the computer program. As a result, the problem has been reduced from three- to two-dimensional with little loss in generality. The savings, however, both in problem preparation and in volume of output, are considerable.

For geometric regularity, fuel (or heater) rods may be added only in complete hexagonal rings. Further the core container wall is considered to be formed as if it consisted of partial rods, as shown in Fig. 2, a one-sixth cross section of a typical core. These restrictions result in a core wherein all flow channels are alike in size and shape.

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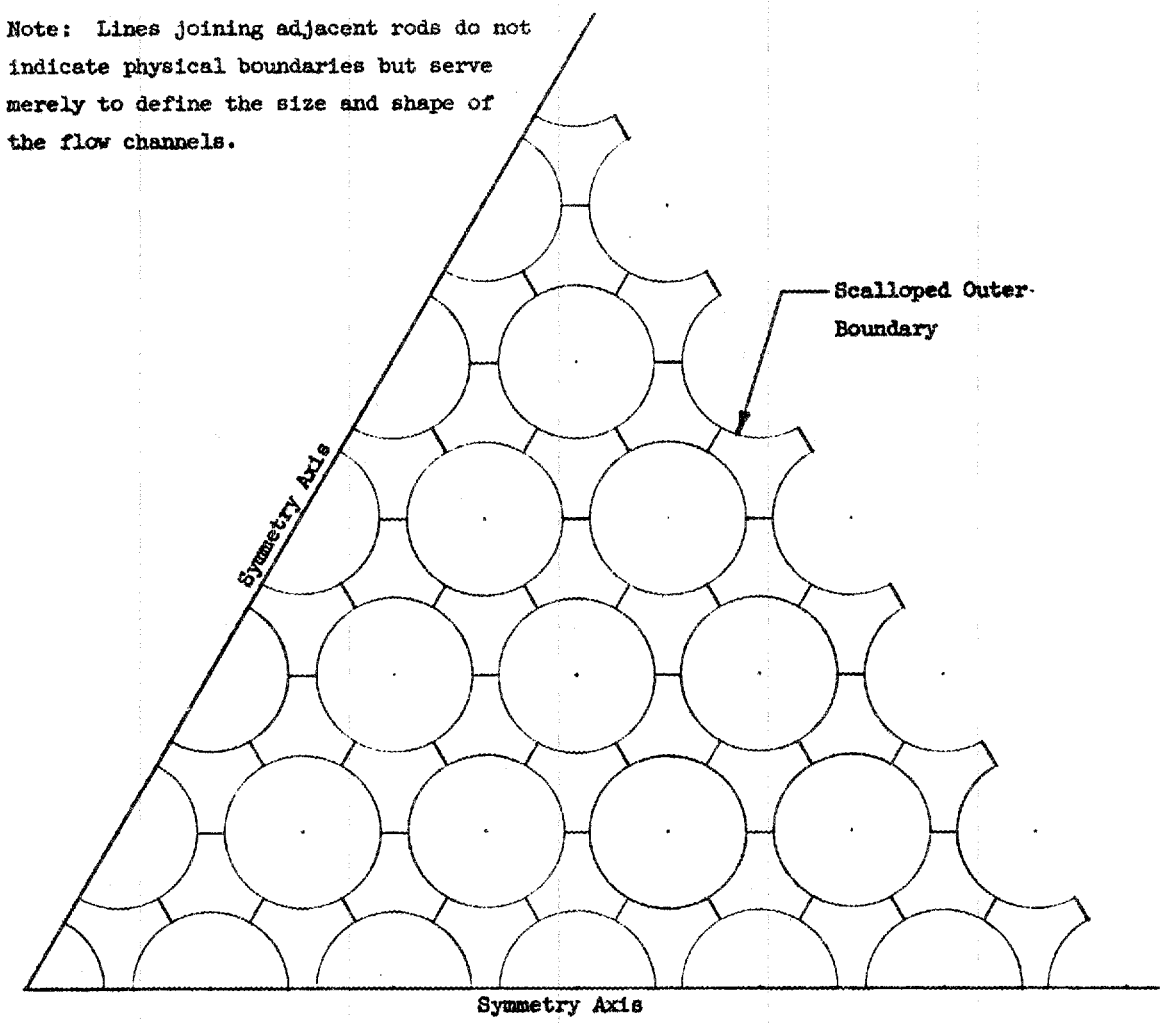

Fig. 2. One-Sixth Cross-Section Through Typical Rod Matrix. Equilateral triangular pitch.

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Essentially arbitrary power distributions are allowed, subject to the limitations that radial variations must occur row-wise and that axial variations must have the same shape for all rods in the core. The first limitation simply means that each rod in a given hexagonal ring must have the same power output, although the variation from ring to ring may be completely arbitrary. The second requirement is equivalent to saying that at a given axial location in the core a differential length of any rod emits the same fraction of that rod's total power.

Finally, the flows at the core inlet are allowed to vary only with radial location of the channels and not with circumferential position.

The net effect of all the above restrictions is to impose circumferential symmetry on the problem, thus reducing it to two dimensions.

Vapor Flow Equations

Figure 1 shows that, for segment I of channel j,

$$W^2_{I,j}\Delta X_{I,j} = f(\Delta P) \quad . \tag{1}$$

Equating the pressure drops for adjacent channels then gives

$$W^2_{I,j}\Delta X_{I,j} = W^2_{I,j+1}\Delta X_{I,j+1} \quad . \tag{2}$$

Expressing the quality change as

$$\Delta X_{I,j} = (G_{I+1,j} - G_{I,j})/W_{I,j} \tag{3}$$

finally yields

$$\begin{aligned} W_{I,j}G_{I+1,j} - W_{I,j+1}G_{I+1,j+1} &= W_{I,j}G_{I,j} - W_{I,j+1}G_{I,j+1} \\ &= C_j \end{aligned} \tag{4}$$

for $1 \leqslant j < N_c$. Equations (4) consist in $N_c - 1$ equations relating the N_c unknown vapor flows.

The remaining equation needed is obtained by imposing continuity on the vapor flows. For any longitudinal segment of the core we have the mass balance,

$$\begin{bmatrix}\text{Total vapor}\\ \text{flow out of}\\ \text{the segment}\end{bmatrix} = \begin{bmatrix}\text{Total vapor}\\ \text{flow into}\\ \text{the segment}\end{bmatrix} + \begin{bmatrix}\text{Total vapor}\\ \text{generated in}\\ \text{the segment}\end{bmatrix} . \tag{5}$$

If we apply this definition, recursively, to each segment back to the core entrance, the right-hand side becomes simply the total vapor generated, through the current segment. The vapor flow into any segment is, of course, the vapor flow out of the previous segment. The left-hand side is the appropriately weighted sum of the individual channel flows, so that we have

$$\begin{aligned} &6G_{I+1,1} + 6G_{I+1,2} + 12G_{I+1,3} + 12G_{I+1,4} + \cdots + \\ &\quad 3(N_c-1)G_{I+1,N_c-2} + 3(N_c-1)G_{I+1,N_c-1} + 3(N_c+1)G_{I+1,N_c} = \sum_{i=1}^{I} \Delta G_i \\ &\qquad\qquad\qquad

where the C's are constants defined by Eqs. (4) and (6). These constants are completely determined by the vapor generation rates, vapor flows, and liquid flows of the previous segment.

Vapor Generation in a Segment

As may be seen by reference to Fig. 2, any pair of adjacent rows of rods defines two distinct types of channel, which will be designated as inner and outer channels. An inner channel is defined by two rods from the inner row and one rod from the outer row of a pair of rows, while an outer channel is defined by two rods from the outer row and one rod from the inner row. With these definitions we have

$$\Delta G_{I,j} = f_I(k_1 q_{I,r} + k_2 q_{I,r+1})/h_{fg} \tag{8}$$

where

$$k_1 = 2.0 \text{ and } k_2 = 1.0 \text{ for an inner channel} \tag{9}$$

and

$$k_1 = 1.0 \text{ and } k_2 = 2.0 \text{ for an outer channel.} \tag{10}$$

The total vapor generated in segment i is, then,

$$\Delta G_i = \sum_{j=1}^{N_c} \Delta G_{i,j} \quad . \tag{11}$$

Liquid and Total Flow Equations

The third basic assumption states, in effect, that the liquid flows in adjacent channels are uncoupled, so that

$$F_{I+1,j} = F_{I,j} - \Delta G_{I,j} \quad . \qquad 1 \leqslant j \leqslant N_c \tag{12}$$

By definition, the total flow at any point is the sum of the vapor and liquid flows. Hence,

$$W_{I,j} = F_{I,j} + G_{I,j} \quad . \qquad 1 \leqslant j \leqslant N_c \tag{13}$$

Solution of the Vapor Flow Equations

The first and last of Eqs. (7) may be combined to give a new last equation free of the first channel vapor flow, $G_{I+1,1}$. Similarly, the second of Eqs. (7) and the new last equation yield a new equation free of both $G_{I+1,1}$ and $G_{I+1,2}$. Proceeding in this fashion, in a radially outward direction, one eventually obtains an equation containing only G_{I+1,N_c} as unknown. This final equation may be solved explicitly for G_{I+1,N_c}, giving

$$G_{I+1,N_c} = \frac{C_{N_c} - \sum_{j=1}^{N_c-1} C_j \sum_{k=1}^{j} B_k/W_{I,k}}{W_{I,N_c} \sum_{j=1}^{N_c} B_j/W_{I,j}} \tag{14}$$

where B_j has been written for the coefficient of $G_{I+1,j}$ in the last of Eqs. (7). Back substitution then yields, in succession, the remaining vapor flows, proceeding in a radially outward direction. Thus, we have

$$G_{I+1,j} = (C_j + W_{I,j+1}G_{I+1,j+1})/W_{I,j} \tag{15}$$

for $1 \leqslant j < N_c$.

Initial Conditions

In order to start the calculation, initial values are required for vapor and liquid flows and for vapor quality. At the beginning of the heated length, no vapor has yet been generated and the liquid flow is equal to the total flow specified as program input. Hence, we have, for $1 \leqslant j \leqslant N_c$,

$$G_{1,j} = X_{1,j} = 0.0 \quad \text{and}$$
$$F_{1,j} = W_{1,j} \quad . \tag{16}$$

COMPUTER RESULTS AND DISCUSSION

Effect of Number of Axial Segments

Inter-channel mixing in the physical core occurs continuously; in the computational model, the mixing occurs at the ends of discrete segments. It is to be expected, therefore, that the number of axial segments used in a calculation will affect the results. A series of calculations was therefore made to assess this effect for both a 7-rod and a 91-rod core having uniform power distributions. Figure 3 shows the effect on channel exit quality of varying the number of segments into which the heated length of the core was divided. It is apparent from the figure that the major portion of the quality variation has been accounted for by the time ten segments have been used. Beyond twenty segments, the change is negligible. Subsequent calculations have used twenty-five segments.

Radial Variation in Boiler Exit Quality

An interesting abstraction from Fig. 3 is the observed quality decrease as the outer edge of the core is approached, despite the uniform power distribution. This decrease can be explained on a purely geometric basis. As Fig. 2 shows, each flow channel is defined by three curved wall sections. In the outermost channel, only one of these sections is heated. The next channel in has two heated walls, while the third has three heated walls. Thus, the relative power inputs to these three channels are as 1:2:3, respectively. In the absence of inter-channel mixing, then, one would expect the qualities to vary in the same proportions. The observed reduction to a variation below 30% results from the cross-channel coupling characteristic of the MPRE-type core.

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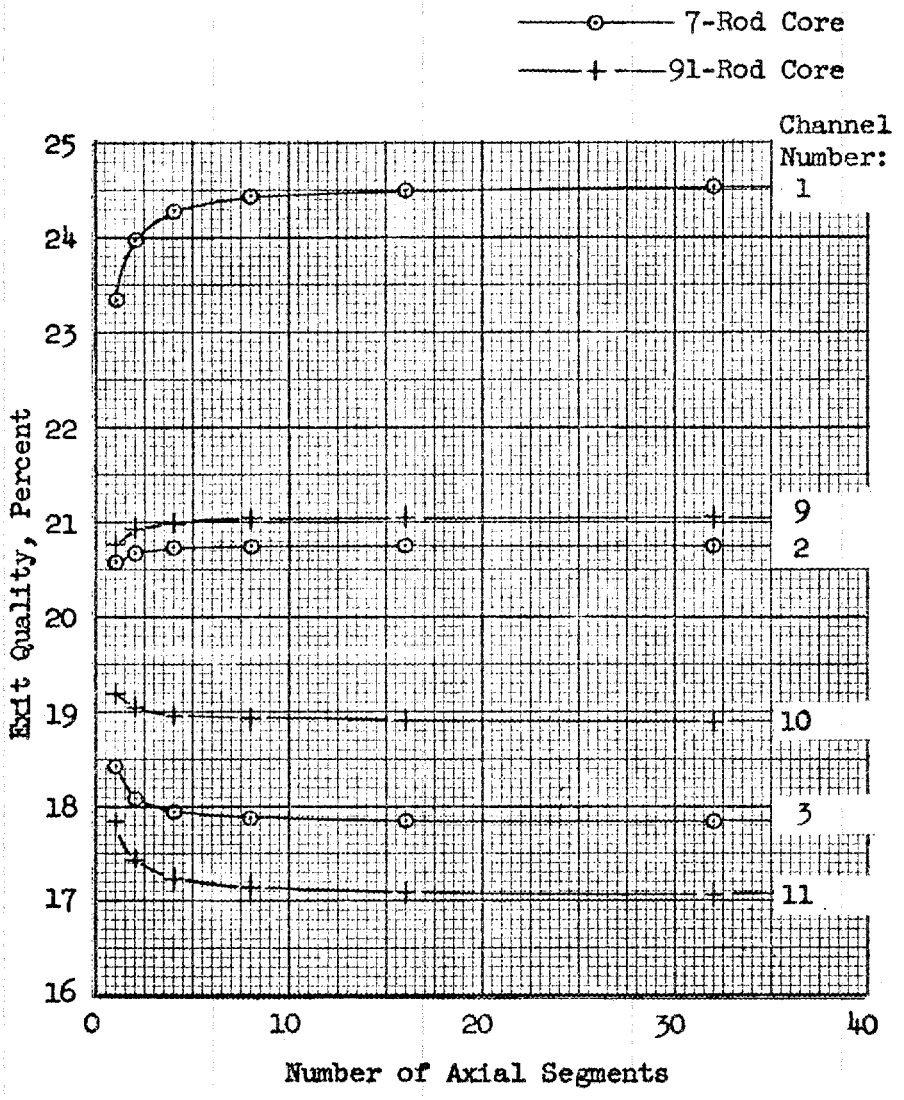

Fig. 3. Effect of Core Axial Subdivision on Calculated Exit Quality Distribution. Uniform power, 3 Kw/Rod.

Comparison Between Calculation and Experiment

In an effort to assess the validity of the computational model, "burnout" experiments were carried out in the IWS for two widely different radial power distributions,[2] i.e., a uniform distribution, and one in which the outer row of rods operated at twice the power level in the remainder of the core. While a direct and detailed comparison between calculation and experiment could not be made, the indirect evidence obtained was consistent with the effects predicted by the calculations.

For each of the two experiments performed, the desired boiler power distribution was set and the system allowed to come to equilibrium at a quality comfortably away from the burnout condition. The recirculation flow to the boiler was then throttled at constant power, thus raising the exit quality, until transient temperature spikes displayed on the monitoring equipment indicated incipient burnout. In each case, the experiment was terminated before the temperature spikes became severe enough to result in a system scram. This was done in order to avoid the difficulties inherent in attempting to duplicate operating conditions after a forced shutdown.

Rather surprisingly, the experiments indicated that burnout conditions were reached for the same mean exit quality, despite the considerable difference in the radial power distributions. That this should be so is indicated by Fig. 4, which shows the predicted exit quality distributions for calculations designed to match the operating conditions of the IWS experiments. Note that near the core center, where internal rod temperature fluctuations indicated incipient burnout in both experiments, the calculated quality difference is quite small. A small error in power or flow measurement could easily accommodate this discrepancy.

Note that the effectiveness of the flow channel coupling in reducing the effects of power dissymmetry is again apparent. The quality peak occurs away from the edge of the core as a result of the geometric effect previously explained. As may be seen from Fig. 2, high power in the outermost row of rods yields a maximum channel power input for the third channel in from the core edge, where the quality peak is observed to occur.

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[2] M. M. Yarosh, Oak Ridge National Laboratory, private communication.

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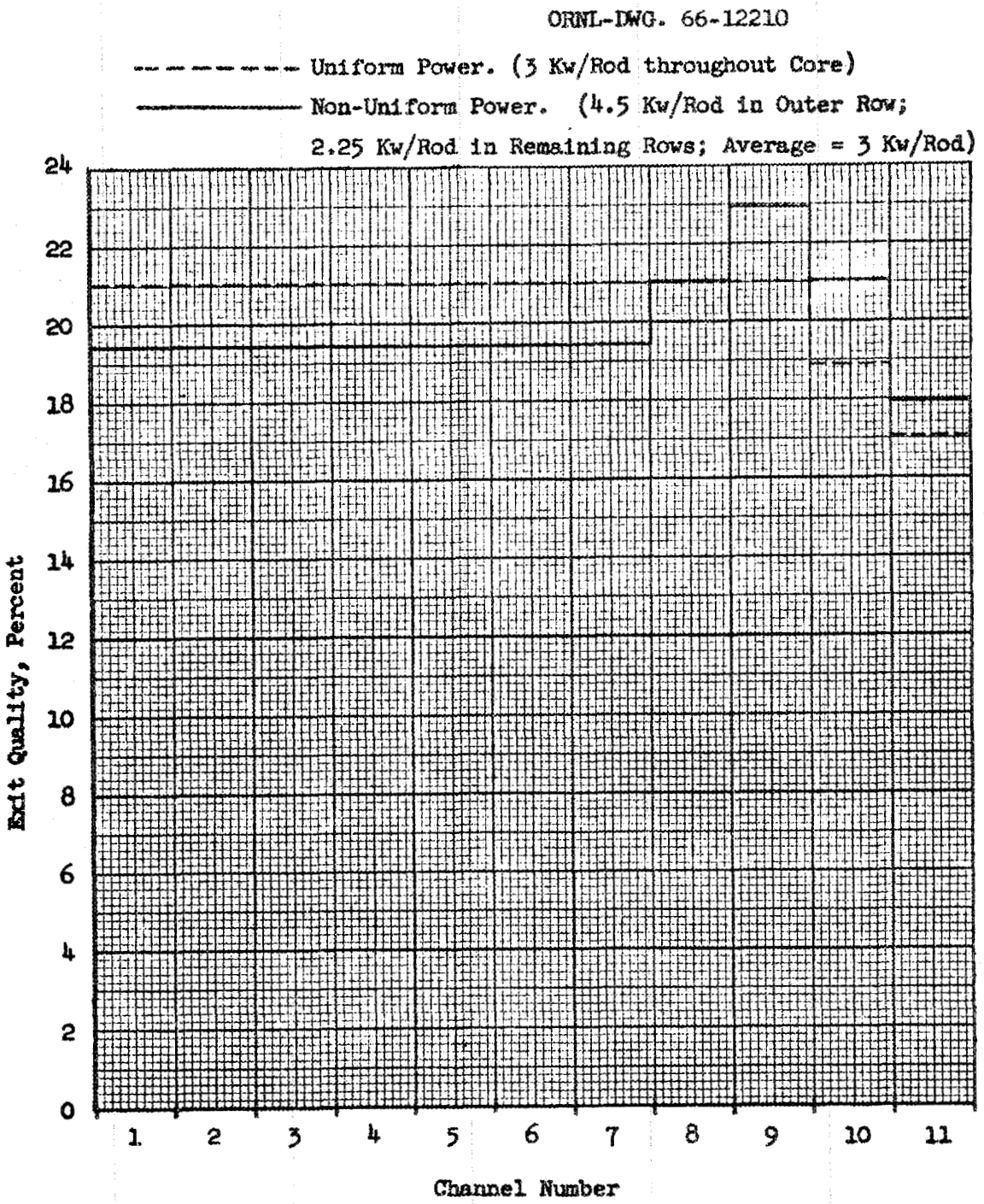

Fig. 4. Comparison of Exit Quality Distributions for Uniform and Non-Uniform Radial Power Distributions. 91-rod core.

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Operational experience with potassium systems has also indicated the same smoothing of the effects of nonuniform power distributions. Because of internal electrical failures in heater rods, some systems have been operated with a number of inactive rods, yielding a rather patchy power distribution. For example, a seven-rod potassium boiler has operated with as few as four active heater rods and the Intermediate Potassium System (IPS) has operated with as many as half the rods in the core inactive. There was no discernible effect on system functioning save for the obvious one of the reduced vapor generation resulting from the large number of inactive heaters.

Quality Distributions in the MPRE Core

Quality distributions have been calculated for the MPRE core as functions of both radial and axial position in the core. Power distributions obtained from Ref. 3 are shown in Figs. 5 and 6. For use in the computer program, these continuous distributions were integrated over the nine rings of fuel rods and 25 axial segments to obtain the lumped parameters required.

Figure 7 shows the radial quality distributions at five axial locations in the MPRE core. The core power is one megawatt; the mean exit quality is 20%. Again it is apparent that the flow channel coupling is quite effective in reducing the effects of power nonuniformity. What may not be so obvious is the reason for the drop in quality at the edge of the core, where the radial power distribution peaks. The explanation is two-fold. First, the power spike of Fig. 5 has been integrated over the last row of fuel rods and the resultant mean power assumed to be uniformly rejected around the rod periphery. Calculations by Jung show that, although the peripheral heat rejection does vary, the thermal conduction within a fuel rod reduces the variation much below that of the

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[3]A. M. Perry, O. L. Smith, and J. V. Wilson, Revision and Further Study of Reference Reactor, pp. 38-39, Space Power Program Semiann. Progr. Rept. June 30, 1964, USAEC Report ORNL-3683, Oak Ridge National Laboratory.

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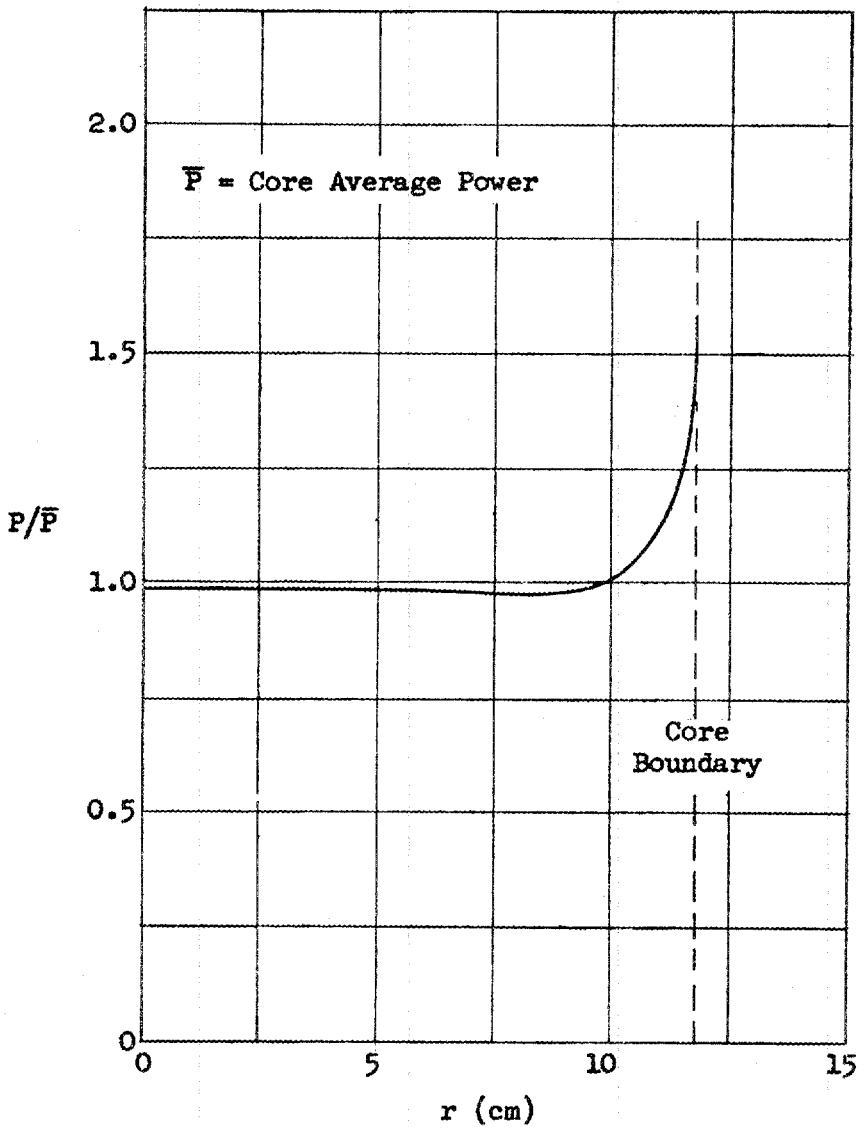

Fig. 5. Relative Radial Power Distribution at Midplane of MPRE Core.

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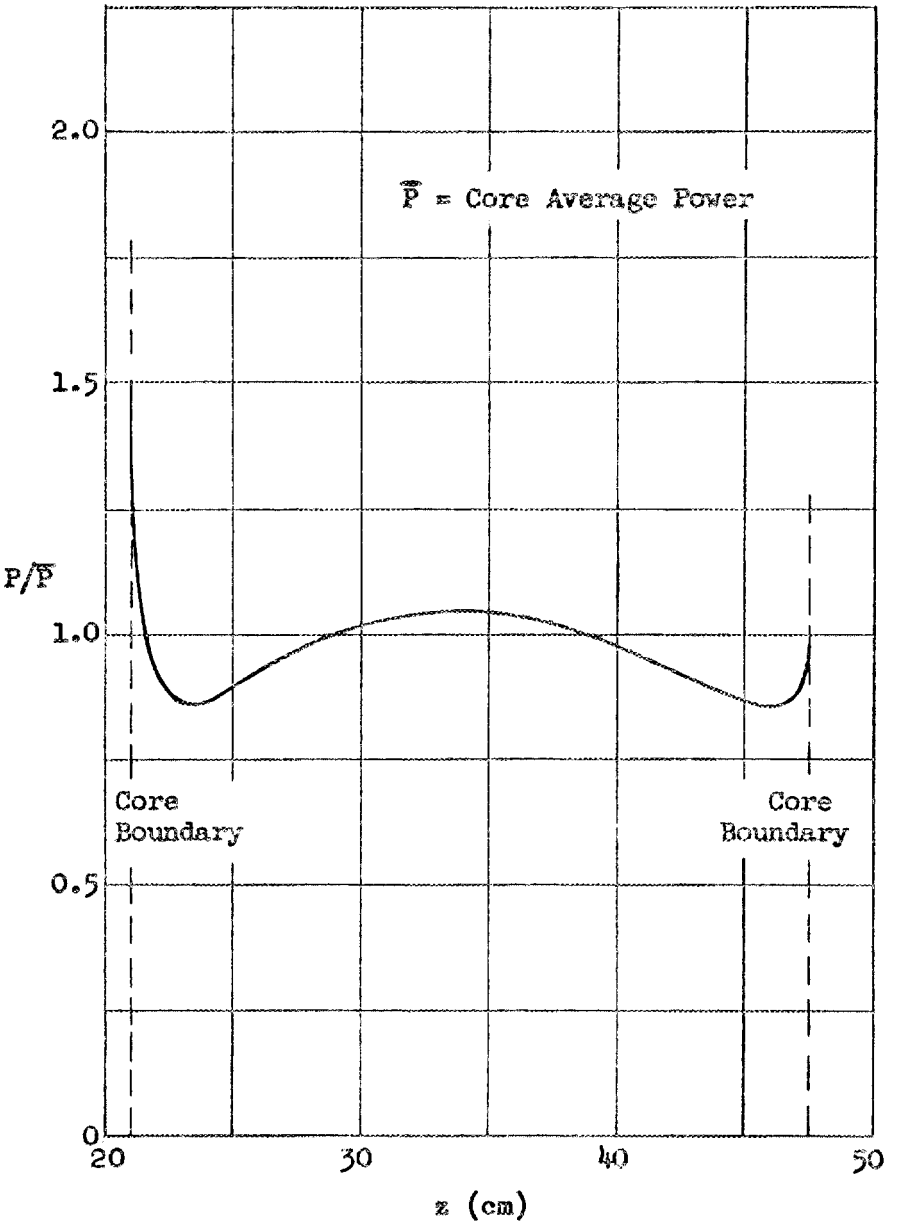

Fig. 6. Relative Axial Power Distribution Near Centerline of MPRE Core.

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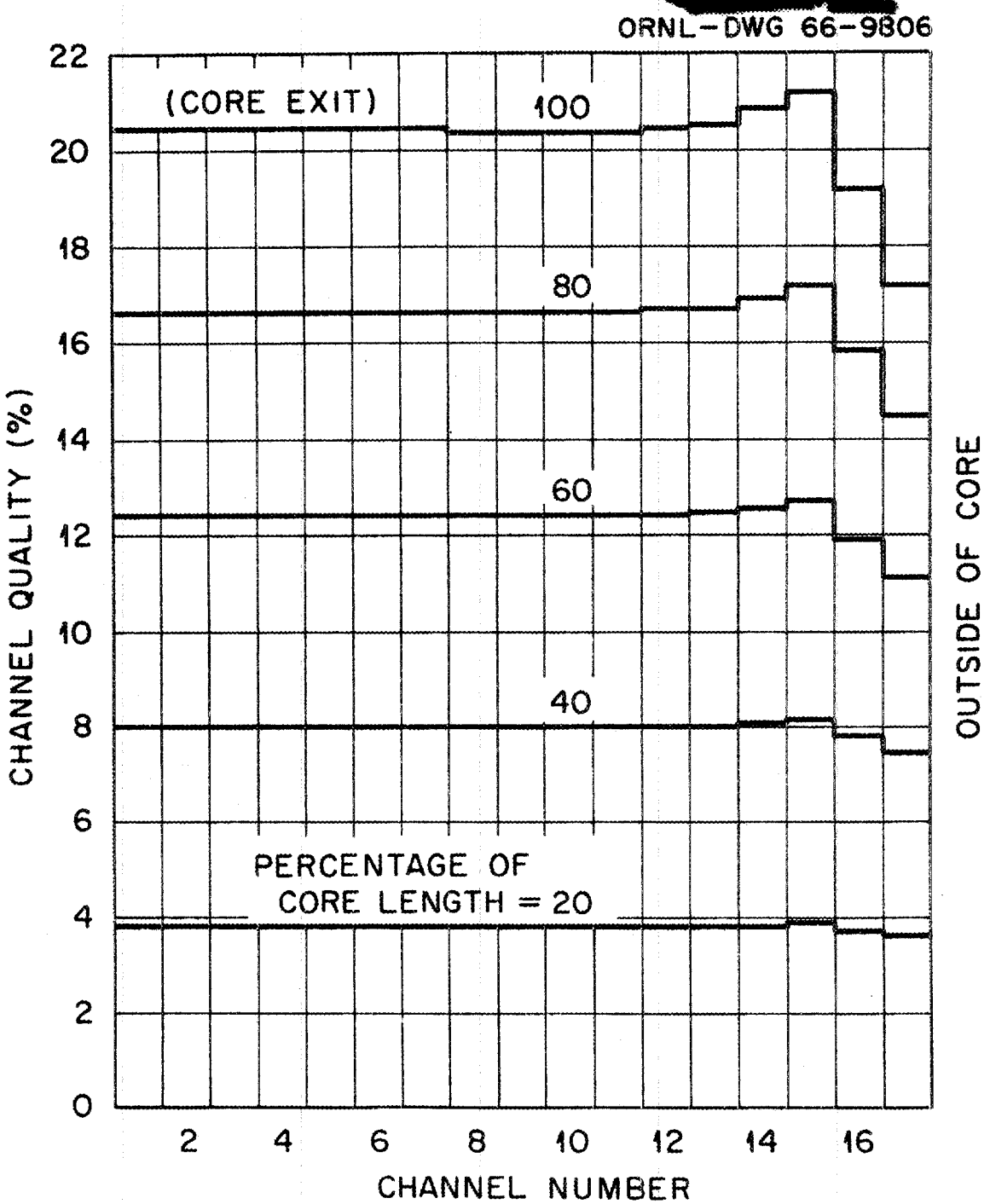

Fig. 7. Radial Quality Distribution at Several Axial Positions in the MPRE Core. Power = one Mw. Mean exit quality = 20%.

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power generation across the same rod.[4] To a first approximation, then, this variation has been assumed negligible. Second, the geometric effect of the unheated outer perimeter (as explained above with reference to Fig. 3) then comes into play, resulting in the observed quality decrease in the outermost channels.

A more nearly precise calculation would allow peripheral variation in the output of individual rods. Radial power peaking would thus give more nearly uniform heat inputs to the outer channels, resulting in a lessened quality variation. It may be concluded, then, that the present calculation actually gives a somewhat pessimistic estimate of the radial variation in quality.

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[4]J. K. T. Jung, Temperature Distribution in Fuel Rods Near Core-Reflector Interface, pp. 10-12, Space Power Program Semiann. Progr. Rept. June 30, 1963, USAEC Report ORNL-3489, Oak Ridge National Laboratory.

NOMENCLATURE

(Any consistent set of units)

Quantity	Definition
C	Constant defined by Eqs. (4) or (6)
f	Axial fraction of rod heat output
F	Channel liquid weight flow
G	Channel vapor weight flow
ΔG	Generated vapor increment
h_{fg}	Latent heat of vaporization
k	Constant defined in Eqs. (9) and (10)
N_c	Total number of channels
P	Pressure
ΔP	Pressure drop
q	Rod heat output to channel
W	Channel total weight flow
X	Channel quality
ΔX	Channel quality increment

Subscripts	Definition
I	Current segment number
i	General segment number
j, k	General channel numbers

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