MASTER

CALCULATION OF DEPARTURE FROM NUCLEATE BOILING CONDITIONS
FOR THE SPERT III REACTOR IN THE HIGH PRESSURE REGION

J. Dugone

PHILLIPS
PETROLEUM
COMPANY

ATOMIC ENERGY DIVISION

NATIONAL REACTOR TESTING STATION
US ATOMIC ENERGY COMMISSION

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

PRICE \$1.50

Available from the
Office of Technical Services
U. S. Department of Commerce
Washington 25, D. C.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Printed in USA

IDO-16774
AEC Research and Development Report
Reactor Technology
TID-4500 (17th Ed.)
Issued: April 18, 1962

CALCULATION OF DEPARTURE FROM NUCLEATE BOILING CONDITIONS
FOR THE SPERT III REACTOR IN THE HIGH PRESSURE REGION

By
J. Dugone

PHILLIPS
PETROLEUM
COMPANY

Atomic Energy Division

Contract AT(10-1)-205

Idaho Operations Office

U. S. ATOMIC ENERGY COMMISSION

ACKNOWLEDGMENT

The author wishes to acknowledge the help of
R. J. Wagner in developing the computer program.

CALCULATION OF DEPARTURE FROM NUCLEATE BOILING CONDITIONS
FOR THE SPERT III REACTOR IN THE HIGH PRESSURE REGION

by

J. Dugone

ABSTRACT

Calculations are made to determine the safe steady-state power operating limits of the Spert III reactor from the viewpoint of fuel plate burnout. A computer program is developed for the IBM 704 to aid in these calculations. The Bettis design departure from nucleate boiling (DNB) equation is used in conjunction with the LeTourneau and Grimble method of "hot channel" analysis in the development of the calculations. For cases where DNB occurs in the bulk boiling region, a modified Martinelli-Nelson two-phase flow correlation and some experimental single-phase pressure drop data are employed.

DNB for a typical operating condition of 550°F inlet temperature and 2500 psig is computed to check the code.

The results of the sample calculation show that at a steady-state power level of 60 Mw (maximum design power) the minimum flow rate required to prevent DNB is approximately 8000 gpm.

CALCULATION OF DEPARTURE FROM NUCLEATE BOILING CONDITIONS
FOR THE SPERT III REACTOR IN THE HIGH PRESSURE REGION

CONTENTS

ABSTRACT	111
I. INTRODUCTION	1
II. CALCULATION OF HOT CHANNEL FACTORS	3
A. Hot Channel Factors	3
B. Considerations in Evaluation of Hot Channel Factors. . .	4
III. DEPARTURE FROM NUCLEATE BOILING CORRELATIONS	9
IV. THE BETTIS DESIGN EQUATIONS.	14
A. Bulk Temperature Rise.	14
B. Bulk Enthalpy Rise	15
C. Bettis Design DNB Correlations	15
V. PRESSURE DROP IN TWO-PHASE FLOW.	16
A. Pressure Drop in Straight Section - Single-Phase Flow. .	16
B. Pressure Drop for Sudden Expansion - Single-Phase Flow .	16
C. Pressure Drop for Sudden Contraction - Single-Phase Flow	16
D. Pressure Drop in Straight Section - Two-Phase Flow . . .	16
E. Pressure Drop for Sudden Expansion - Two-Phase Flow . .	17
F. Pressure Drop for Sudden Contraction - Two-Phase Flow .	17
G. Total Pressure Drop Through the Core as a Function of Flow - Single-Phase Flow	17
VI. METHOD OF CALCULATIONS	19
A. DNB Heat Flux	19
B. Two-Phase Flow Effects	19
C. Total Flow Through the Core.	22
VII. DNB CODE FOR SPERT III	23
A. Input Format	27
B. Output Format	33
C. Operating Instructions	34
VIII. RESULTS OF SAMPLE CALCULATION	35
IX. REFERENCES	36
X. APPENDIX I	39
A. Nomenclature	39
B. Symbol Table	43
XI. APPENDIX II	48

XII. APPENDIX III	55
A. Input Data	55
B. Output Data	58

FIGURES

Fig. 1 Curve illustrating the regimes of boiling	10
Fig. 2 Ratio ΔP_{TPF} to ΔP as a function of exit quality and absolute pressure	17
Fig. 3 Friction pressure drop correction for mass flow rate.	17
Fig. 4 Multiplier r versus quality for various absolute pressures.	17
Fig. 5 Sketch of Spert type C 2-S fuel assembly.	19
Fig. 6 Cross section of Spert type C 2-S fuel assembly	20
Fig. 7 Flow chart of the DNB code - main loop.	24
Fig. 8 Flow chart of DNB code - "Are Conditions Safe" test (*1).	25
Fig. 9 Flow chart of DNB code - "Find Total Flow" calculation #2	26
Fig. 10 Flow chart of the DNB code - "Find Channel Flow" (*3).	27
Fig. 11 Reactor DNB power versus total flow rate.	35

TABLES

I. Estimated hot channel factors - 60-Mw thermal power, 20,000-gpm flow, 560°F temperature	8
II. DNB correlations	12

CALCULATION OF DEPARTURE FROM NUCLEATE BOILING CONDITIONS FOR THE SPERT III REACTOR IN THE HIGH PRESSURE REGION

I. INTRODUCTION

The Spert III reactor is a heterogeneous, pressurized-water, research reactor which was constructed to provide a facility for conducting investigations of reactor kinetic behavior and safety. The investigations are designed to provide information for the advancement of pressurized-water reactor technology and safety. The operating parameters of pressure, temperature, coolant flow rate and power vary from ambient to 2500 psig, room temperature to 650°F; 200 to 20,000 gpm, and steady-state power up to 60 Mw thermal, respectively.

Since the experimental program for this reactor will include tests in which the reactor is operated for short periods of time at high steady-state power levels (~ 60 Mw), for a variety of temperature, pressure, and flow conditions, it is important to determine the safe steady-state operating limits from the point of view of fuel plate burnout. This report describes the calculations used to determine these safe limits and also describes the computer code which was developed to aid in the calculations.

To establish operational limits for the steady power experimental program, departure from nucleate boiling (DNB)* heat flux calculations are made. Since the operating conditions of this reactor are extremely wide, no single correlation equation is best suited for all points. However, for the present purpose, the high temperature and pressure range is of primary interest, and the initial calculations are made using the Bettis design DNB equation (1,2). The Bettis correlation was chosen since it was derived from data from out-of-pile experiments conducted on rectangular channels with environmental conditions of temperature, pressure and flow rates similar to those of the Spert III reactor system. The design equation is considered conservative and is used because a safe value rather than a best-estimate of DNB heat flux is desired. From the Bettis experimental data, it appears that a calculated DNB heat flux obtained by use of the design equation will be less than actual burnout heat flux 99 percent of the time(2).

Since the Spert III core is a plate-type, water-moderated core which consists of a large number of parallel rectangular coolant channels, it is necessary to consider the effect of small deviations from the nominal channel geometry and ideal flow conditions, as well as the effect of non-uniform volumetric heat generation, on the thermal and hydraulic design of the reactor core. To account for these

*Note: Departure from nucleate boiling (DNB) heat flux, "burnout" heat flux, and "critical" heat flux are used by many authors to denote the maximum heat flux (see Fig. 1). Current literature indicates that DNB is the preferred notation.

deviations a "hot channel factor" analysis is made using the method of the LeTourneau and Grimble⁽³⁾.

DNB occurs in the bulk boiling region for some cases. Therefore, calculations using the modified Martinelli-Nelson two-phase flow correlation⁽⁴⁾ and experimental single-phase pressure data⁽⁶⁾ are employed to better evaluate the DNB conditions in the boiling region.

A program is coded for the IBM 704 to set the operating limits of the Spert III reactor, and a sample problem is solved for conditions of 550°F and 2500 psig to check the code. The results of the sample problem show that at a steady-state power level of 60 Mw (maximum design power) the flow rate below which DNB will occur is approximately 8000 gpm.

The results of the calculation are conservative for several reasons. First, the design DNB equation which is considered conservative is used in the calculations. Second, the "hot channel factors" are used. Third, the code neglects the effect of voids that would probably reduce the peak power density at the DNB point during bulk boiling. Fourth, it is assumed that there is only one hot channel. If there is more than one hot channel, the flow through the hot channel would be higher than predicted because of the flow redistribution. For a given total flow, more fluid would be forced through the normal channels which would increase the pressure drop across the core. The increased pressure drop would, in turn, increase the flow through the hot channel. This would result in an increase in the DNB heat flux.

II. CALCULATION OF HOT CHANNEL FACTORS

The core of the Spert III reactor consists of a large number of parallel rectangular coolant channels. These coolant channels are not of uniform channel geometry or heat generation. It is, therefore, necessary to account for the effects of deviations from nominal channel geometry and ideal flow conditions and the effects of non-uniform volumetric heat generation. The "hot channel factor" method of approach, as developed by LeTourneau and Grimble⁽³⁾, is utilized to account for these effects.

A. Hot Channel Factors

The enthalpy rise, film temperature difference, and heat flux will not be constant throughout the reactor core; therefore, hot channel factors are defined for each of these three thermal parameters. They are defined as follows:

$$F_H^T = \frac{\Delta H_{\max}}{\Delta H_{\text{nom ave}}} = \text{hot channel factor for enthalpy rise}$$

$$F_\theta^T = \frac{\theta_{\max \text{ local}}}{\theta_{\text{nom ave}}} = \text{hot channel factor for film temperature difference}$$

$$F_Q^T = \frac{Q/A_{\max \text{ local}}}{Q/A_{\text{nom ave}}} = \text{hot channel factor for heat flux}$$

The symbol F is used for the hot channel factors with subscript H, θ , or Q depending on the thermal parameter to which the factor is applicable. The superscript T refers to the total hot channel factor which is the summation of the individual factors resulting from both nuclear and engineering deviations from the ideal case.

Each of the three total factors described above account for deviations from the ideal case and are composed of contributions from both nuclear and engineering considerations. The following individual factors, as defined by LeTourneau and Grimble⁽³⁾, are considered pertinent to this analysis:

1. Nuclear Factors

- a. Neutron flux distribution perpendicular to the coolant flow.
- b. Neutron flux distribution parallel to the coolant flow.
- c. Local neutron flux peaking.

* Symbols defined in Table of Nomenclature in Appendix I.

2. Engineering Flow Factors

- a. Fuel element inlet plenum chamber effects, called the plenum factor.
- b. Deviations from the nominal channel design dimensions, called the channel tolerance factor.
- c. Material distortion due to irradiation, the irradiation factor.
- d. Fuel element surface finish variations, the roughness factor.
- e. Enthalpy variations across the coolant channel cross-section, the mixing factor.
- f. Local or bulk boiling, the boiling factor.

3. Engineering Heat Flux Factors

- a. Deviation from the nominal design dimensions of heat generating material, called the fuel element tolerance factor.
- b. Variations of fissionable atom concentrations, the fuel density factor.
- c. Variations in cladding thicknesses, the eccentricity factor.

B. Considerations in Evaluation of Hot Channel Factors

1. Nuclear Factors

In application of the nuclear factors, the spatial distribution of the volumetric heat generation rate is assumed to vary directly as the thermal neutron flux. These factors are temperature dependent and will have to be evaluated at the desired temperature.

To illustrate the application, a typical reactor operating condition of 60 Mw thermal power at 560°F temperature, 2500 psig pressure and 20,000 gpm flow is chosen, and the hot channel factors determined.

For the neutron flux distribution perpendicular to the coolant flow a maximum to average neutron flux ratio of 1.83 is estimated at 560°F.

Since experimental flux data are at present not available for this environmental condition, the value is obtained in the following way: The peak to average values of the horizontal flux for the control rods withdrawn and fully inserted are determined from unpublished IBM 704 calculations. These data are extrapolated to determine the peak to average value of the flux with the control rods inserted 16.8 in. of

the 36 in. (experimental critical control rod position at a bulk water temperature of 560°F).

The neutron flux distribution parallel to the coolant flow is estimated from calculated flux curves for a 48 assembly core⁽⁵⁾. These curves are adjusted to the operational 52 assembly core by weighting according to the experimental critical rod position. The maximum to average flux ratio is found to be 2.04 at 560°F.

Prior to steady-state power operation, experimental flux data will be obtained and these data used in the code to determine the actual DNB operating limits.

The factor for local flux peaking is estimated to be 1.20.

2. Engineering Flow Factors

a. Plenum Factor

The plenum chamber flow factor is evaluated from data of flow tests of a dummy Spert III fuel element. The average to minimum channel flow distribution variation measured is 1.24⁽⁶⁾. The average to minimum flow is used because a minimum flow will give the highest enthalpy rise in the channel. This will result in a low DNB heat flux.

$$F_H = \frac{W_{ave}}{W_{min}} = 1.24$$

Employing the turbulent flow single-phase heat transfer correlation (Colburn, Sieder-Tate, Dittus-Boelter).

$$h \propto (W)^{0.8}$$

$$F_\theta = \frac{h_{ave}}{h_{min}} = \left(\frac{W_{ave}}{W_{min}} \right)^{0.8} = 1.19$$

b. Channel Tolerance Factor

The channel tolerance factor is determined from equations derived by LeTourneau and Grimble⁽³⁾, where:

$$F_H = \left(\frac{S_{nom}}{S_{min ave}} \right)^{5/3}$$

$$F_\theta = \left(\frac{S_{max local in min ave}}{S_{min ave}} \right) \left(\frac{S_{nom}}{S_{min ave}} \right)^{1/3}$$

For the Spert III reactor:

$$S_{nom} = 0.128 \text{ in.}$$

$$S_{min ave} = 0.120 \text{ in.}$$

$$S_{\text{max local in min ave}} = 0.025 \text{ in.}$$

$$\text{then } F_H = 1.12 \text{ and } F_\theta = 1.07$$

c. Irradiation, Roughness, and Mixing Factors

At this stage of reactor development, it is not possible to properly analyze irradiations, roughness, and mixing factors. The mixing factor will be less than unity⁽³⁾. The product of all three is assumed here to be unity. This assumption appears warranted because of the conservation method employed for determination of the channel tolerance factor.

d. Boiling Factor

An investigation has shown that under some conditions, bulk boiling occurs in the hot channel. Calculations are made to determine the pressure drop in two phase flow and the flow distribution in the core due to bulk boiling in the hot channel. Because the results of these calculations are applied in the cases where bulk boiling occurs, the boiling factor is considered unity.

3. Engineering Heat Flux Factors

a. Fuel Element Tolerance Factor

The fuel element tolerances specify the meat thickness is to be held to ± 0.001 in. from the nominal 0.020 in. The hot channel is assumed to be flanked by two plates with maximum fuel density.

$$\text{Then } F_\theta = F_Q = \frac{b_{\text{max local}}}{b_{\text{nom}}} = 1.05$$

$$\text{and } F_H = \frac{b_{\text{max ave}}}{b_{\text{nom}}} = 1.00$$

where b = Fuel plate meat half-thickness.

b. Fuel Density Factor

Each Spert III fuel plate (2-S) contains a nominal mass of U^{235} of 13.8 grams $\pm 5\%$ and the fuel density per unit area within any plate may not deviate from the average fuel density for that plate by more than $\pm 5\%$. Again, assuming the hot channel to be flanked by two plates with maximum fuel density:

$$F_H = \frac{(\rho_F)_{\text{max ave}}}{(\rho_F)_{\text{nom}}} = 1.05$$

$$\text{and } F_\theta = F_Q = \frac{(\rho_F)_{\text{max local}}}{(\rho_F)_{\text{nom}}} = 1.10$$

c. Eccentricity Factor

The eccentricity factor is evaluated from the derivations of LeTourneau and Grimble⁽³⁾:

$$F_H = 1 + \frac{(a_{\text{max ave}} - a_{\text{nom}})}{\frac{k_c}{k_m} b + a_{\text{nom}} + \frac{k_c}{h}}$$

$$F_\theta = F_Q = 1 + \frac{(a_{\text{max local}} - a_{\text{nom}})}{\frac{k_c}{k_m} b + a_{\text{nom}} + \frac{k_c}{h}}$$

Values for k_c and k_m are obtained by Bondel for stainless-steel clad stainless steel-UO₂ meat fuel elements⁽⁷⁾.

$$k_c = 0.000274 \text{ Btu/in.}^\circ\text{F sec (at 600}^\circ\text{F)}$$

$$k_m = 0.000205 \text{ Btu/in.}^\circ\text{F sec (at 600}^\circ\text{F)}$$

Based on previous Spert III flow studies⁽⁶⁾ and rated flow velocity, 16.9 ft/sec,

$$h = 0.0147 \text{ Btu/in.}^2 \text{ }^\circ\text{F sec. (Modified Colburn Equation)}^{(8)}$$

According to the Spert III specifications, clad thickness is to be held to ± 0.001 in. from the nominal 0.005 in. No average deviation for the plate is specified. Then for the worst condition, $a_{\text{max ave}} = a_{\text{max local}}$, and $F_H = F_\theta = F_Q$.

$$\text{Then } F_H = F_\theta = F_Q = 1.028 \text{ say } 1.03.$$

Eccentricity is also calculated by a somewhat dissimilar method given by Bondel⁽⁷⁾ as follows:

$$F_H = F_\theta = F_Q = \frac{t_m + 2k_m \alpha}{t_m + k_m \beta}$$

$$\text{Where } \alpha = \frac{t_{co}}{k_c} + \frac{1}{h}$$

$$\beta = \frac{t_{co}}{k_c} + \frac{t_{ch}}{k_c} = \frac{2}{h}$$

$$\text{Then } F_H = F_\theta = F_Q = 1.03.$$

4. Total Hot Channel Factors

A tabulation of the individual hot channel factors and the resultant total hot channel factors is presented in Table I.

TABLE I
ESTIMATED HOT CHANNEL FACTORS
60-Mw THERMAL POWER, 20,000-GPM FLOW, 560°F TEMPERATURE

Hot Channel Factor Cause	Thermal Parameter Affected		
	Enthalpy Rise (ΔH)	Film Temperature (θ)	Heat Flux (ΔQ)
Neutron Flux Distribution Perpendicular to Coolant Flow(a)	1.83	1.83	1.83
Neutron Flux Distribution Parallel to Coolant Flow-Hot Channel ^a	1.00	2.04	2.04
Local Neutron Flux Peaking	1.00	1.20	1.20
Combined Nuclear Factor	1.83	4.48	4.48
Plenum Chamber Flow	1.24	1.19	1.00
Channel Tolerances	1.12	1.07	1.00
Irradiation	1.00	1.00	1.00
Roughness	1.00	1.00	1.00
Mixing	1.00	1.00	1.00
Boiling	1.00	1.00	1.00
Combined Engineering Flow Factor	1.39	1.27	1.00
Fuel Element Tolerances	1.00	1.05	1.05
Fuel Density Tolerances	1.05	1.10	1.10
Eccentricity	1.03	1.03	1.03
Combined Engineering Heat Flux Factor	1.08	1.19	1.19
Combined Engineering Factor	1.50	1.51	1.19
Total Hot Channel Factors Due to All Causes	2.74	6.78	5.33

(a) Temperature Dependent

III. DEPARTURE FROM NUCLEATE BOILING CORRELATIONS

The general aspects of boiling heat transfer and DNB may be described by referring to the curve of heat flux as a function of temperature difference between the surface temperature of the solid and the bulk temperature of the liquid shown in Fig. 1. In the range AB, the solid surface temperature is below the fluid saturation temperature, and the heat transfer is by convection. In the range BD, bubbles form at the active nuclei on the heat transfer surface. As the bubbles leave the surface, the laminar boundary layer is destroyed, and the heat flux that can be transferred per increment of wall surface is greatly increased. This is referred to as the nucleate boiling regime. As the surface temperature is increased further, the bubbles become so numerous that their motions interact^(9,10). Under these conditions, the heat flux reaches its peak, and, if the temperature is increased further, a new regime is entered. This regime, DE, is referred to as the partial film boiling regime or transition boiling regime, and the heat flux decreases with an increase in surface temperature. In this range, the solid surface is completely blanketed by a film of vapor, but the film is neither smooth nor stable⁽¹⁰⁾. A stable film boiling regime, EF, is reached when the surface temperature is increased still more. The heat flux increases with an increase of surface temperature but at a slower rate than that during nucleate boiling. The surface is covered by a relatively stable vapor film across which heat is transferred by conduction and radiation^(10,11). Burnout, or departure from nucleate boiling (DNB) occurs when the heat transfer surface becomes blanketed by an unstable, irregular film which is in violent motion⁽¹²⁾. This results in a sharp decrease in the heat transfer coefficient with a rapid increase in surface temperature.

Bettis^(1,2) defines the above discussed regimes in a slightly different manner. The regimes are defined as follows: AB is the nonboiling regime, BC is the nucleate boiling regime, CE is the partial film boiling regime, EF is the stable film boiling regime, and C is the departure from nucleate boiling. The Bettis definition of the DNB as point C is more conservative than the aforementioned definition of DNB as point D since the heat flux at point C is lower than at point D. However, in the Bettis experiments the difference between the point C heat flux and the maximum heat flux, point D, was usually less than 2% and always less than 5%^(1,2).

The effects of various parameters on the DNB flux have been studied, and it was found that disagreement exists among the different experimenters on these effects. A review of the parameters is presented below:

(1) Mass Velocity - H. Susskind⁽¹²⁾ reports that "disagreement exists among the different experiments on the effect of mass velocity. Bettis (and also KAPL) reports an increasing dependence of DNB flux on velocity in all regions, while CE, Sonneman at Bettis, the Russians, Cicchitti, and ANL found that this dependence reversed in the low quality region." Bettis^(1,2) reports "that the burnout heat flux increases with increasing mass velocity for constant pressure, inlet subcooling, and channel geometry." J. F. Wett⁽⁹⁾ concurs with this

Fig. 1 Curve illustrating the regimes of boiling.

a high fraction of the flow area is occupied by vapor.

(2) Inlet Subcooling - Bettis^(1,2) and others⁽⁹⁾ report that the DNB heat flux increases with increasing inlet subcooling at constant pressure, mass velocity, and channel geometry. H. Susskind⁽¹²⁾ reports that there is not enough data available to determine the extent and form of the inlet subcooling effect on the DNB flux.

(3) Pressure - According to theory the DNB flux has a maximum value near one-third of the critical pressure (1060 psia for water) and decreases as the pressure increases or decreases from this point^(1,2,12,15). Jens and Lottes found that the critical flux increased as the pressure was reduced from 2000 to 500 psia for subcooled exit fluid^(12,16). Other ANL work reports the critical heat flux decreases with increasing pressure over the range 1000 to 3000 psi^(12,17). Bettis reported that for constant fluid enthalpy in the quality region, constant inlet subcooling, and channel geometry under forced-circulation conditions the DNB heat flux increases with a decrease in system pressure below 2000 psia^(1,2,9). Other Bettis work reports that the burnout heat flux at 1215 psia is about 30% higher than at either 830 or 2000 psia⁽¹⁸⁾. Later Bettis work "found approximately the same maximum DNB flux values at pressures of 800 to 1200 psia, and for short channels, generally decreasing as the pressure and enthalpy were increased. For long channels (72 in.), however, the maximum DNB flux occurred at higher pressures (i.e., 2000 psia)"⁽¹²⁾.

(4) Channel Geometry - H. Susskind⁽¹²⁾ reports that data have been obtained with test sections of limited size range and configuration; therefore, the geometries may not be generalized enough to develop a suitable correlation. P. Griffith reports the length to channel spacing ratio (L/S) affects the critical flux through a distribution of the two phases at the DNB point^(12,19). Bettis^(1,2,9) reports that the DNB heat flux decreases with an increasing length to diameter ratio (L/D) and the DNB heat flux for round tubes is up to 45% lower than for rectangular channels at the same mass velocity, inlet subcooling, pressure and L/D. Later Bettis⁽¹²⁾ reports that the channel spacing appears to have no significant effect on the DNB flux,

statement. D. W. Bell⁽¹³⁾ reports that "the burnout flux decreases as the mass velocity increases for a constant burnout enthalpy in the quality range. The higher the quality, the stronger is this inverse effect. The opposite is true for subcooled burnout, with the crossover point occurring near the saturated liquid point where mass velocity has a minimum effect on the burnout heat flux". A. F. Pexton⁽¹⁴⁾ reports that it may be assumed that an increase of flow rate will increase the DNB flux at very low mixture qualities but that the inverse occurs when

and that the DNB flux is dependent upon the channel length. D. W. Bell⁽¹³⁾ indicates that channel length and length to diameter ratio has no effect on the DNB heat flux. A. F. Pexton⁽¹⁴⁾ reports that no definite trend exists in the variation of DNB flux with L/D ratio at high qualities but there appears to be a fairly general trend for DNB flux to increase with decreasing equivalent diameter. It has been reported⁽¹⁷⁾ that ANL stated, over the range of channels tested, there was no indication that channel length or L/D ratio affects DNB heat flux but shows an effect of decreasing DNB flux with increasing flow diameter.

(5) Channel Orientation and Flow Direction - There appears to be no effect of orientation or flow direction on the DNB heat flux in forced-circulation systems^(1,2,9).

(6) Material and Surface Finish - ANL reports a significant increase in DNB flux with time, attributed to the possible effect of surface irregularities due to corrosion and corrosion products^(12,17). Other experimenters have reported that neither the type of material⁽²⁰⁾ nor the macroroughness^{*(21,22)} of the surface have an effect on the DNB flux in a forced-circulation system^(1,9). It appears, however that certain arrangements of macroroughness elements can enhance DNB flux, possible without a proportionate increase in pumping power⁽²³⁾. In pool boiling, there is some evidence that aluminum gives a higher DNB flux than other metals^(9,21).

(7) Dissolved Hydrogen Concentration - Hydrogen concentration up to 135 cc/kg in water at 2000 psia showed no effect on the DNB heat flux in tubes of 0.186 in. inside diameter and 12 in. long^(1,9).

(8) Enthalpy at Burnout Point - For constant pressure and channel geometry, the DNB heat flux decreases with increasing enthalpy at the burnout point^(1,2,17).

There are numerous correlations for computing the DNB heat flux which use the parameters discussed above. Some of these correlations are listed in Table II along with the test conditions.

* Consisting of elements smaller than bubble diameters which do not alter the effective heat transfer area.

TABLE II
DNB CORRELATIONS

Proponents	Reference	Correlations	Variable Ranges
DeBortoli, et al	1	$\phi_{DNB} \times 10^{-6} = 0.28 \left(\frac{H_{DNB}}{10^3} \right)^{-2.5} \left(1 + \frac{G}{10^7} \right)^2 e^{-0.0012 L/De}$ -Round Tubes	$P = 1850-2150$ psia $G = 0.2 \times 10^6 - 8.0 \times 10^6$ lbs/hr-ft ² $De = .075-.306$ in.
		$\phi_{DNB} \times 10^{-6} = 0.37 \left(\frac{H_{DNB}}{10^3} \right)^{-2.5} \left(1 + \frac{G}{10^7} \right)^2 e^{-0.0012 L/S}$ -Rectangular	$P = 1850-2150$ psia $G = 1.6 \times 10^6 - 5.0 \times 10^6$ lbs/hr-ft ² $S = .050-.101$ in.
		$\phi_{DNB} \times 10^{-6} = 0.50 \left(\frac{H_{DNB}}{10^3} \right)^{-2.5} e^{-0.0012 L/S}$ -Rectangular	$P = 1850-2150$ psia $G = 0.2 \times 10^6 - 1.6 \times 10^6$ lbs/hr-ft ² $S = .050-.101$ in.
Mislak, Durant, Towell	20	$\phi_{DNB} = 4.79 \times 10^5 (1 + 0.0365V)(1 + 0.00507 \Delta T_{sub})(1 + 0.0131P)$	$P = 25-85$ psia $V = 5-45$ fps $De = 0.21-0.46$ in.
McAdams, Addoms, Kennel	24	$\phi_{DNB} = 4 \times 10^5 V^{1/3} + 4800 \Delta T_{sub} V^{1/3}$	$P = 30-90$ psia $V = 3-12$ fps $De = 0.52$ in.
Gunther	35	$\phi_{DNB} = 7.0 \times 10^3 V^{0.5} \Delta T_{sub}$	$P = 108$ psia $V = 5-40$ fps
Zenkevitch, Subbotin	22	$\phi_{DNB} = 396 G^{0.5} \Delta T_{sub}^{0.33} \left(\frac{\rho_f - \rho_v}{\rho_f} \right)^{1.8}$	$P = 1500-3000$ psia $G > 0.2 \times 10^6$ lbs/hr-ft ² $De = 0.16-0.47$ in.
Bell	13	$\phi_{DNB} = 0.427 \times 10^6 (2.59 + \frac{G}{10^6})^{1.81} \left(\frac{H_v - H_{DNB}}{10^3} \right)^{1.72} \left(\frac{G}{10^6} \right)^{0.406}$	$P = 1850-2150$ psia $G = 0.2 \times 10^6 - 5.0 \times 10^6$ lb/hr-ft ²
		$\phi_{DNB} = 1.37 \times 10^6 \left(1.10 + \frac{G}{10^6} \right)^{1.44} \left(\frac{H_v - H_{DNB}}{10^3} \right)^{1.67} \left(\frac{G}{10^6} \right)^{0.474}$ For quality burnout only. $H_{DNB} \geq 672$ Btu/lb	
Jens, Lottes	16	$\phi_{DNB} \times 10^{-6} = C \left(\frac{G}{10^6} \right)^m \Delta T_{sub}^{0.22}$	UCLA $P = 500, 1000, 2000$ psia $G = 0.96 \times 10^6 - 7.79 \times 10^6$ lb/hr-ft ² $De = 0.226$ in.
		Pressure psia "m" $\frac{C}{10^6}$ (UCLA) $\frac{C}{10^6}$ (Purdue)	Purdue $P = 1000, 2000, 3000$ psia $G = 0.90 \times 10^6 - 7.48 \times 10^6$ lb/hr-ft ² $De = 0.143$ in.
		500 0.16 0.817 --- 1000 0.275 0.626 0.915 2000 0.500 0.445 0.545 3000 0.725 --- 0.300	
Longo	26	$\phi_{DNB} = 1.43 \times 10^{-5} P^{0.113} \Delta T_{sub}^{4.69} (G/10^3)^{1.22(2.38 - \ln \Delta T_{sub})}$	$P = 15-115$ psia $G = 2.2 \times 10^6 - 6.7 \times 10^6$ lb/hr-ft ²
Longo	27	$\phi_{DNB} \times 10^{-6} = 0.447 \left(\frac{H_{DNB}}{10^3} \right)^{-2.39} \left(1 + \frac{G}{10^7} \right)^{0.986} e^{-0.00082L/S}$	$P = 1850-2150$ psia $G < 5.0 \times 10^6$ lb/hr-ft ²
Tramontini, et al	28	$\phi = 520 G^{0.05} (T_s - T_B)^{0.20}$	$P = 2000$ psia $G = 1.0 \times 10^6 - 7.8 \times 10^6$ lb/hr-ft ² $De = 0.226$ in.
McGill, Sibbitt	29	$\phi_{DNB} = 530 G^{0.5} (T_s - T_o)^{0.28}$	$P = 265-3000$ psia $G = 0.9 \times 10^6 - 7.5 \times 10^6$ lb/hr-ft ² $De = 0.143$ in.
Reynolds	30	$\left(\frac{B}{r} \right)^{1.94} = 1.49 \times 10^{-23} \left(\frac{\phi_{DNB} De}{\sigma V} \right) \left(\frac{\rho_f}{\rho_g} \right) \left(\frac{G De}{\mu_f} \right)^{1.5} \left(\frac{H_{fg} g_c}{g De} \right)$ where $\frac{B}{r} = 1 - \sqrt{R_g}$	$P = 500-2000$ psia $G = 0.6 \times 10^6 - 3.6 \times 10^6$ lbs/hr-ft ² $De = .118-.306$ in.

Hoe, Helve	31	$\phi_{DNB} = 53.6 (G)^{0.63}$ for quality region $\phi_{DNB} = 972 (G)^{0.443} (T_s - T_b)^{0.108}$ for subcooled region											
Bernath	21	$\phi_{DNB} = h_{BO} (T_{WDNB} - T_b)$ where $h_{BO} = 5710 \left(\frac{\pi De}{DI} \right)^{0.6} + 48 \frac{V}{De^{0.6}}$ $T_{WBO} = 57 \ln P - 54 \left(\frac{P}{P+15} \right) - \frac{V}{4 \left(\frac{De}{DI} \right)^{0.6}}$	$P = 500-3000$ psia $V = 4.5-54$ fps.										
Griffith	32	$\phi_{DNB} = r^1 [P/P_c] (F^1) \rho_v (H_v - H_b) \left[\frac{g(\rho_\ell - \rho_v)}{\mu_\ell} \left(\frac{k_\ell}{\rho_\ell c_p} \right)^2 \right]^{1/3}$ where $F^1 = 1 + 10^{-6} \left(\frac{V De \rho_\ell}{\mu_\ell} \right) + 0.014 \left[\frac{\rho_\ell c_p (T_s - T_b)}{\rho_v H_{fg}} \right]$ $+ 0.5 \times 10^{-3} \left\{ \left(\frac{V De \rho_\ell}{\mu_\ell} \right) \left[\frac{\rho_\ell c_p (T_s - T_b)}{\rho_v H_{fg}} \right] \right\}^{1/2}$	$P/P_c = .0045-0.97$ $V = 0-110$ fps										
Sonnemann	33	$\phi_{DNB} = \phi_{NB} + \phi^*$ where $T_v = T_s + \left(\frac{60}{e^{P/900}} \right) \left(\frac{\phi_{NB}}{10^6} \right)^{0.25}$ $T_v = T_b + \frac{\phi_{NB}}{h}$ $T_b = T_1 + \frac{\phi_{NB}}{G} \left(\frac{A_1}{A_f} - \frac{1}{e^P} \right)$ $\phi^* = 0.6 \times 10^6 (\alpha) (Re \times 10^{-4})^{0.38}$ for $Re > 35,000$ $\phi^* = 0.366 \times 10^6 (\alpha) (Re \times 10^{-4})^{0.78}$ for $Re < 35,000$ $\frac{1}{\alpha} = Z + 49.5 De (Re \times 10^{-4})^{0.2}$	$P = 2000$ psia $G = 0.157 \times 10^6 - 7.76 \times 10^6$ lbs/hr-ft ² $De = .104-.306$ in.										
Cicchitti	14, 34	$\phi_{DNB} = \frac{K \lambda}{G^n} \frac{1-X}{X + \frac{\rho_g}{\rho_\ell - \rho_g}} 10^6 (n+1)$ where <table><tr><td>n =</td><td>1.2</td><td>1.5</td><td>1.45</td><td>0.6</td></tr><tr><td>P =</td><td>600 psia</td><td>1000 psia</td><td>1500 psia</td><td>2000 psia</td></tr></table> $K = K^1 \left(\frac{De}{12} \right)^{-1/4}$ $K^1 = 1.75 \times 10^{-3}$ @ 500 psia and 0.57×10^{-3} @ 2000 psia	n =	1.2	1.5	1.45	0.6	P =	600 psia	1000 psia	1500 psia	2000 psia	$P = 600, 800, 1200, 2000$ psia $S = .097$ in.
n =	1.2	1.5	1.45	0.6									
P =	600 psia	1000 psia	1500 psia	2000 psia									
Pexton	14	$\phi_{DNB} \times 10^{-6} = \frac{0.085}{X^{1.18} + 0.081}$	$P = 1000$ psia										

IV. THE BETTIS DESIGN EQUATIONS

A discussion of the various parameters which affect the DNB flux and of the numerous correlations for computing the DNB flux is given in Section III. The discussion shows that there is much controversy as to the effects of the parameters and as to the type of equation that should be used to determine the DNB flux. It is beyond the scope of this work to experimentally determine the effect of these parameters and, thus, choose an equation based on the conclusions of the experiment. Therefore, an equation was chosen from the literature that was derived from data of out-of-pile experiments conducted on rectangular channels with environmental conditions of temperature, pressure, and flow rates similar to those of the Spert III reactor system. The equation chosen was the Bettis design equation^(1,2) which correlates the DNB heat flux as a function of the coolant mass velocity, fluid bulk enthalpy at the DNB location and the channel length to width ratio.

It is desirable to have a high degree of confidence that the actual DNB heat flux will be no lower than the calculated values; therefore, design equations somewhat lower than the correlation equations (equations derived as the correlation of the experimental data) are used. Bettis reports that a calculated DNB heat flux which is 65% of the correlation value will be below the actual DNB heat flux 99% of the time^(1,2). These conservative equations are designated as the Bettis design equations and are used, in this report, to calculate the steady-state DNB heat flux for the Spert III facility at high pressure.

In these calculations it is assumed that 90% of the heat is generated in the fuel plates, 5% of the heat is generated in the moderator adjacent to the fuel plates, and 5% of the heat is generated in the reflector and thermal shields⁽³⁵⁾. The average vertical heat flux distribution is estimated from calculated neutron flux curves and adjusted to the Spert III operational core by weighting according to the experimental critical rod positions. The hot channel is found to be in the center section of the core; therefore, burnout calculations are made on the type "C" 2-S assembly.

The equations used to determine the DNB are as follows:

A. Bulk Temperature Rise

$$T_z = T_i + \int_{T_i}^{T_z} dt = T_i + \frac{\int_0^z \phi_z dz}{C_{p(ave)} W}$$

where

$$\int_0^z \phi_z dz = \text{Total heat input to water from channel inlet to } Z, \text{ Btu/hr.}$$

NOTE: Flow tests on the Spert III reactor have shown that approximately 95% of the total flow passes through the active core region. Also it was calculated that

95.4% of the active core flow area lies adjacent to the active fuel.

B. Bulk Enthalpy Rise

$$H_z = H_1 + \int_{T_1}^{T_z} C_p(\text{ave}) dT_z$$

where

$$\int_{T_1}^{T_z} C_p(\text{ave}) dT_z = \text{Total enthalpy input to water from channel inlet to } Z, \text{ Btu/lb.}$$

C. Bettis Design DNB Correlations

$$\text{For } G = 1.6 \times 10^6 - 5.0 \times 10^6 \text{ lb/hr} - \text{ft}^2$$

$$\phi_{\text{DNB}} \times 10^{-6} = 0.24 \left(\frac{H_{\text{DNB}}}{10^3} \right)^{-2.5} \left(1 + \frac{G}{10^7} \right)^2 e^{-0.0012L/S}$$

$$\text{For } G < 1.6 \times 10^6 \text{ lb/hr} - \text{ft}^2$$

$$\phi_{\text{DNB}} \times 10^{-6} = 0.325 \left(\frac{H_{\text{DNB}}}{10^3} \right)^{-2.5} e^{-0.0012L/S}$$

These design equations are applicable for rectangular channels of L/S of 59 to 468 and pressure of 1850 to 2150 psia (L/S ratio for Spert III channel is 281). Use of these equations to predict the DNB heat flux at the high pressures (maximum 2500 psi) does not in all probability result in large errors.

V. PRESSURE DROP IN TWO-PHASE FLOW

DNB occurs in the bulk boiling region for some cases. Bulk boiling reduces the flow in the hot channel, and the reduced flow increases the enthalpy and quality and results in a lower DNB heat flux. The pressure drop in two-phase flow must be evaluated to correct for the effect of bulk boiling in the hot channel. Calculations using the modified Martinelli-Nelson two-phase flow correlation⁽⁴⁾ and experimental single-phase pressure drop data are employed to evaluate the DNB conditions in the boiling region. For the modified Martinelli-Nelson relationship the friction and momentum pressure drops are calculated according to the method of Martinelli and Nelson⁽³⁶⁾. The friction pressure drop is then corrected for the effect of mass flow using the values obtained by Sher⁽³⁷⁾ as recommended by Lottes, Petrick, and Marchaterre⁽⁴⁾.

A summary of the equations involved in determining the two-phase pressure drop in the hot channel and the total flow through the core at burnout conditions is presented:

A. Pressure Drop in Straight Section - Single-Phase Flow

$$\Delta P = \frac{f V_b^2 \rho_b L}{2g De} \quad (38)$$

B. Pressure Drop for Sudden Expansion - Single-Phase Flow

$$\Delta P = K_e \frac{V_1^2}{2g} = 1 - \left(\frac{A_1}{A_2} \right)^2 \left(\frac{V_1^2}{2g} \right) \quad (39)$$

C. Pressure Drop for Sudden Contraction - Single-Phase Flow

$$\Delta P = K_c \frac{V_2^2}{2g} \quad (40)$$

D. Pressure Drop in Straight Section - Two-Phase Flow

$$\Delta P_{TP} = \Delta P \left(\frac{\Delta P_{TPF}}{\Delta P} \right) \frac{\phi_L^2}{\phi_L^2 \text{ at } 10^6} + r G^2/g \quad (36)$$

The ratio $(\Delta P_{TPF}/\Delta P)$ has been determined by Martinelli and Nelson as a function of exit quality and pressure. A graph of the data is shown in Fig. 2. The ratio $\left(\frac{\phi_L^2}{\phi_L^2 \text{ at } 10^6} \right)$ is the correction factor that must be applied to the friction pressure loss due to the effect of mass flow rate. A plot of this correction factor as a function of quality and ratio of mass flow rates is given in Fig. 3. The multiplier r is used to determine the pressure drop due to momentum changes. Fig. 4 is a plot of multiplier r versus exit quality for various pressure.

The two-phase pressure drop equation assumes that a linear relationship exists between the length of the channel and the quality. However, for this application where nonuniform heat generation exists, the friction drop is determined by summing the friction drops for incremental channel lengths. The momentum pressure drop is determined using the exit quality.

E. Pressure Drop for Sudden Expansion - Two-Phase Flow

$$\Delta P = K_e \frac{V_1^2}{2g_c} = 1 - \frac{A_1^2}{A_2^2} \frac{V_1^2}{2g_c} \quad (39)$$

This is the same equation as used for single-phase flow; however, an apparent density of the two-phase fluid ($\rho_{\text{apparent}} = \rho_{\text{steam}} x_{\text{quality}} + \rho_{\text{water}} [1-x]$) is used to calculate the linear velocity.

Fig. 2 Ratio ΔP_{TPF} to ΔP as a function of exit quality and absolute pressure.

Fig. 3 Friction pressure drop correction for mass flow rate.

F. Pressure Drop for Sudden Contraction - Two-Phase Flow

$$\Delta P = K_c \frac{V_2^2}{2g_c} \quad (40)$$

This is the same equation as used for single-phase flow with an apparent density correction applied to the linear velocity.

Fig. 4 Multiplier r versus quality for various absolute pressures.

G. Total Pressure Drop Through the Core as a Function of Flow - Single-Phase Flow

$$\Delta P = C(W)^{1.97}$$

where $C = 1.87 \times 10^{-13}$ at 250°F,
 1.95×10^{-13} at 350°F,
 2.15×10^{-13} at 450°F,
 2.53×10^{-13} at 550°F,
 2.84×10^{-13} at 600°F,
and 3.34×10^{-13} at 650°F,

The previous equations have been determined from experimental curves of core flow rate versus core pressure drop at various temperatures for single-phase isothermal flow⁽⁴¹⁾.

In these calculations, the static head pressure drop is not added in the pressure drop across the core because the experimentally determined correlation between the core flow rate and core pressure drop does not include the head term. This leads to some error at low flows and high exit quality; however, the error is in the direction to make the calculations conservative.

VI. METHOD OF CALCULATIONS

A. DNB Heat Flux

The "hot channel factors" are determined according to the procedure described in Section II. Using these factors where applicable, the bulk temperature and bulk enthalpy are calculated at 2 in. increments up the channel. With the bulk enthalpy established at various power levels and flow rates through the hot channel, the DNB heat flux is calculated using the Bettis design correlations.

B. Two-Phase Flow Effects

Because DNB occurs in the bulk boiling region for some cases, it is necessary to establish a relationship between flow through the hot channel and total flow through the core. A summary of the method of calculation is given as follows:

The pictorial cross-section of the 2-S assembly depicting the expansions, contractions, and straight sections is shown in Fig. 5. As shown in Fig. 6, the flow through the plate section can be divided into three regions: the flow through the channels which have a heat generating surface on both sides of the coolant channel; the flow through the two end channels which have a heat generating surface on one side of the coolant channel; and the flow through two side channels which have no heat generating surfaces.

1. Plate Section

With the mass flow rate and enthalpy of the hot channel established, the two-phase pressure drop is calculated for the plate section.

a. Entrance Loss - Normal Channel

Fig. 5 Sketch of Spert type C 2-S fuel assembly.

Fig. 6 Cross section of Spert type C 2-S fuel assembly.

The fluid enters the plate section as a single phase; therefore, the entrance loss is calculated using the standard equation given in Section V-C.

b. Straight Section Loss - Normal Channel

In some cases, depending on the flow rate and power, the fluid in the hot channel reaches the saturation temperature and bulk boiling occurs. The pressure drop associated with the flow of a two-phase mixture is calculated in a manner described in Section V-D.

c. Exit Loss - Normal Channel

The exit loss for two-phase flow is calculated using the equation given in Section V-E.

A summation of the three pressure drops gives the total pressure drop as a function of the total flow in the normal channels of the plate section.

In addition to the flow in the normal channels, it is necessary to calculate the pressure drop as a function of flow for the end plate annulus and the side plate annulus. Since the plate section is a constant ΔP system, the normal channel flow, end plate annulus flow and side plate annulus flow at constant ΔP can be summed to give the total flow rate as a function of pressure drop.

d. Entrance Loss - End Plate

The fluid enters this section as a single phase, and the pressure drop is calculated from the equation given in Section V-C.

e. Straight Section Loss - End Plate

In this section, it is assumed that heat is transferred from the one fuel plate adjacent to the fluid. Calculation of the bulk temperature rise indicates that the fluid does not reach saturation temperature, and the pressure drop is determined using the equation given in Section V-A.

f. Exit Loss - End Plate Flow

The fluid is in single-phase flow, and the friction pressure drop is calculated using the equation given in Section V-B.

The calculations for the side plate annulus are the same as for the end plate annulus with the exception that it is assumed that no heat

is transferred to the fluid; therefore, the entrance and exit enthalpies are equal.

From the above calculations, the following data needed for the remainder calculations have been established:

- Normal channel flow as a function of ΔP
- Side plate channel flow as a function of ΔP
- End plate channel flow as a function of ΔP
- A summation at constant ΔP to give the total assembly flow
- Exit enthalpy of the inside channel flow
- Exit enthalpy of the end plate channel flow
- Exit enthalpy of the side plate channel flow.

An energy-material balance gives the enthalpy (quality) of the fluid at the exit of the plate section for each flow rate and power level.

2. Upper End Box

a. First Constriction Loss

The quality and flow rate of the fluid is known from the previous calculations. The pressure drop for two-phase flow is calculated with the equation given in Section V-F.

b. Second Constriction Loss

Calculated in a manner similar to that for the first constriction loss.

c. First Straight Section Loss

The two-phase pressure drop is calculated in a manner similar to that described in Section V-D. It is different in that the quality remains constant through the upper end box; therefore, there is no momentum pressure loss and it is unnecessary to calculate the pressure drop at increments up the channel.

d. Third Constriction Loss

Calculated in a manner similar to that for the first constriction loss.

e. Second Straight Section Loss

Calculated in a manner similar to that for the first straight section loss.

f. Exit Loss

The pressure drop for the two-phase flow is calculated using the equation given in Section V-E.

3. Lower End Box

Parallel flow through the bleed holes in the lower grid and the inside of the lower end box occurs in this section. It is assumed that no heat is transferred to the fluid in this section so the fluid is in single-phase flow. The correlation between the pressure drop and mass flow rate for temperatures between 50 and 650°F is as follows:

$$\Delta P = 1.465 \times 10^{-10} (W)^{2.01}$$

The above equation was determined from unpublished calculations of pressure drop through the lower end box as a function of flow rate⁽⁴²⁾.

4. Total Pressure Drop

The total pressure drop is a summation of the head loss through the core and the pressure drops through the lower end box, plate section and upper end box.

C. Total Flow Through the Core

The core is a constant ΔP system. The correlation between mass flow rate and ΔP has been established for the 2-S assembly in two-phase flow at the "just safe power level"*. This establishes the pressure drop through the core. The total flow through the core can be determined from the experimentally determined correlation between the core flow rate and core pressure drop. The equations are listed in Section V-G. It should be noted that these equations were determined under conditions of single-phase isothermal flow; therefore, it is assumed that there is no two-phase flow in the core except in the hot channel.

* The operating limits of a reactor set such that the hot channel of the core does not burn out.

VII. DNB CODE FOR SPERT III

A program has been coded for the IBM 704 to set the operating limits for the Spert III reactor in regard to DNB, using the procedures described in Section VI. For an operating condition of system pressure and inlet temperature of the coolant, the code will determine the relation between the reactor power and the required core flow to prevent DNB.

The method of computing this relation is to find, for a given reactor power, system pressure and inlet temperature, the minimum flow in the hot channel required to prevent DNB according to the Bettis DNB correlations. The minimum flow to prevent DNB is determined by testing increasing hot channel flow rates until DNB does not occur; at this point the hot channel flow is related to the total core flow, and the power and the total core flow are given as output. The power is then increased until DNB occurs, and the testing of flow rates is repeated. This procedure is continued until the maximum core flow is exceeded. The output can be presented as a plot of power versus total core flow for a particular pressure and inlet temperature; any operating point below the curve will be a safe condition.

As stated before in Section VI the flow through the plate section can be divided into three parts. The flow through the channels which have a heat generating surface on both sides of the coolant channel are called normal channels. The hot channel is a normal channel with hot channel factors applied in computing the enthalpy of the coolant and the heat transfer rate.

The hot channel flow is related to the total core flow by applying the results of engineering tests of the Spert III reactor (at zero power) which measured the total core flow as a function of inlet temperature and pressure drop across the core. The pressure drop across the fuel plate section of a fuel element is determined from the conditions in the hot channel. The total flow through the fuel element is obtained by finding the flow through the three different types of coolant channels of the fuel element such that the pressure drop across these channels is the same as that across the hot channel. Since the pressure drop is a non-linear function of the flow, the flow for a particular pressure drop is determined by the method of interpolation with a single interpolation after the required flow had been bracketed. The pressure drops resulting from the total element flow in the upper and lower end boxes is added to the plate section pressure drop to obtain the pressure drop across the core.

To determine the conditions in the coolant channels which have heat generating surfaces, the vertical direction of the channel is divided into equally spaced regions. The enthalpy is determined at each mesh point from the power and the flow by the trapezoidal rule of integration. The test for DNB is made by comparing the DNB heat flux to the hot channel heat flux at each mesh point. In making the DNB test, 95% of the heat in the core region is assumed to be transferred from the plate to the coolant and 5% of the heat in the core

region is assumed to be generated in the coolant. The pressure drop across the plate sections is obtained by summing the pressure drops across each of the regions, using the average conditions in the region to determine the pressure drop across that region.

The flow charts of the DNB code are given in Figs. 7 through 10. The code was programmed using FORTRAN II, and the FORTRAN statements together with a symbol table to facilitate the interpretation of the FORTRAN statements are given in Appendix II. A description of the input and output formats, and the operating instructions are given below. Appendix III contains the input and output of a sample problem for the Spert III reactor at 550°F inlet temperature and 2500-psig pressure.

Fig. 7 Flow chart of the DNB code - main loop.

Fig. 8 Flow chart of DNB code - "Are Conditions Safe" test (*1).

Fig. 9 Flow chart of DNB code - "Find Total Flow" calculation #2.

Fig. 10 Flow chart of the DNB code - "Find Channel Flow" (*3).

A. Input Format

The card format for all the input data is 6 consecutive numerical fields to a card, each field being 12 spaces and the first field starting with the first column of the card. Numbers must be pushed to the extreme right of the field. Positive quantities may be indicated by either a blank or a + (12) punch; minus quantities are indicated by a - (11) punch. Integers are numbers without a decimal point or an exponent field. Floating point quantities are entered in the form XXX...XE+CC, where the X's represent a number containing a decimal point, and the CC is the required power of ten. In the floating point number, either the E or the sign of the exponent, but not both, may be omitted. Thus, examples of how 125.76 could be entered are .12576E3, 1,2576E 02, or 125.76+0. If the decimal point is omitted, it will be assumed to be just before the E or sign punch. Blanks are treated as zeros, and there may be blanks between the decimal and exponent; however, the exponent of the floating point number, and the entire number of an integer quantity must be pushed to the right of the field. In the description of the input data that follows, all quantities are floating point unless indicated otherwise. The system of units are feet-pounds-hour-Btu, unless otherwise stated.

If tape input is desired, these cards may be put on tape with the off line card-to-tape converter.

In the list of input quantities described below, quantities describing the dimensions of a fuel element and the flux distributions in the element will be required. Since the computation is carried out for only one fuel element, flux distributions and dimensions for an element in the peak of the flux distribution should be entered. This will normally be a 2-S element. Since the horizontal and vertical flux peaking is entered with the flux distributions, the hot channel factors should include only the mechanical uncertainties and a factor for possible errors in the flux measurements.

1. Information Cards

Card 1

- Word 1. Temperature of the inlet coolant. Not used in the computation, but is given as output.
- Word 2. Pressure of reactor system. Not used in the computation, but is given as output.
- Word 3. Enthalpy of the inlet coolant.
- Word 4. Enthalpy of the coolant when in liquid phase at the saturation point.
- Word 5. Enthalpy required to evaporate coolant at reactor system pressure.
- Word 6. Enthalpy of the coolant when in the vapor phase at the saturation point.

Card 2

- Word 1. Specific volume of the coolant at the inlet temperature and reactor system pressure.
- Word 2. Specific volume of the coolant when in liquid phase at the saturation point.
- Word 3. Specific volume of the coolant when in the vapor phase at the saturation point.

Card 3

- Word 1. The number of mesh points in the fuel plate, i.e., the number of regions plus one. An integer quantity.
- Word 2. Fuel plate length.

- Word 3. Fuel plate increment. (The number of mesh points minus one times the fuel plate increment should equal the fuel plate length.)
- Word 4. Lowest value of reactor power to be tested. Units are megawatts.
- Word 5. Power increment. Units are megawatts. (Power values equal to the lowest power plus multiples of the power increment will be tested. Generally, the smaller the power increment, the greater the number of operating points given in the output.)
- Word 6. Lowest value of the hot channel mass flow rate (lb/hr-ft²) to be tested.

Card 4

- Word 1. Hot channel mass flow increment (lb/hr-ft²). (The smaller this quantity, the greater the accuracy of the required hot channel mass flow rate and the required total core flow.)
- Word 2. The maximum total core flow (gal/min). (When this quantity is exceeded, the computation for this set of input data is ended.)
- Word 3. The heat transfer area of one region of a fuel plate. The heat transfer area of one region for all the plates in the fuel element are the same. Refer to the Flux Cards description for more information on this quantity.
- Word 4. The water channel thickness of a normal channel. (See Fig. 6)

2. Flux Cards

Word 1 of the first card contains a common scale factor by which the fluxes which follow are multiplied. Values of the flux are punched in the five remaining words of the card and in the six words of as many additional cards as may be needed. The product of the flux values and the common scale factor will give the heat generation rate in units of

$$\frac{\text{Btu}}{(\text{hr.})(\text{ft.}^2 \text{ of heat transfer surface})(\text{Mw of reactor power})}$$

at each mesh point. The flux values are given in order for each mesh point, starting at the bottom. The number of flux values will equal the number entered as Word 1 on Card 3 of the Information Cards. The heat generation rate per square foot of heat transfer surface at each mesh point is given by the product of the reactor power, the common scale factor, and the flux value. The value of the heat transfer rate is 95% of this quantity since it is assumed that 95% of the heat is generated in the plate and 5% is generated in the coolant. The value of the heat transfer surface area should be such that the product of the heat generation rate per square foot of heat transfer surface and the heat transfer area gives the heat generated in the coolant region corresponding to one side of the fuel plate.

3. Fuel Element Description Cards

Card 1

- Word 1. Hot channel factor for enthalpy calculation in the hot channel. (Combined Engineering Factor for Enthalpy Rise.)
- Word 2. Hot channel factor for heat transfer calculation in the hot channel. (Product of the Combined Engineering Factor and Local Neutron Flux Peaking for Heat Flux.)
- Word 3. K_c for normal plate channel entrance loss.
- Word 4. Equivalent diameter for normal plate channel.
- Word 5. K_e for normal plate channel exit loss.
- Word 6. Area of normal plate channel.

Card 2

- Word 1. Number of normal plate channels.
- Word 2. K_c for end plate channel entrance loss.
- Word 3. Equivalent diameter for end plate channel.
- Word 4. K_e for end plate channel exit loss.
- Word 5. Area of end plate channel.
- Word 6. K_c of side plate channel entrance loss.

Card 3

- Word 1. Equivalent diameter for side plate channel.

- Word 2. K_e for side plate channel exit loss.
- Word 3. Area of side plate channel.
- Word 4. Factor in lower end box correlation.
(Must be such that pressure drop is in lb/ft^2 .)
- Word 5. Exponent in lower end box correlation.
- Word 6. K_e for 1st constriction loss in upper end box. (No. 10 of Fig. 5.)

Card 4

- Word 1. Area of 3rd constriction and the 2nd straight section of upper end box.
- Word 2. Equivalent diameter of the 2nd straight section of upper end box. (No. 14 of Fig. 5.)
- Word 3. Length of 2nd straight section of upper end box.
- Word 4. K_e for the exit loss of the fuel element.
(No. 15 of Fig. 5.)
- Word 5. Factor in total core flow vs. pressure drop across core correlation. Units are such that pressure drop is in lb/in^2 .
- Word 6. Exponent in total core flow vs. pressure drop across core correlation.

4. Description of Table Format

The remaining input data consists of tables having an argument and corresponding value of the function. These tables are searched by table lookup subroutines and linear interpolation is performed to obtain the value of the function corresponding to the search argument. The arguments of these tables should have values such that the lowest and highest possible search arguments are bracketed.

The format for all the tables except the ARPHT* table are the same. The argument and the function are entered as pairs, the first number is the argument, the second is the function. At least two pairs must be entered, and the maximum number of pairs is 21.

Card 1

*Symbols defined in the Symbol Table in Appendix II.

Word 1. An integer quantity stating the number of pairs of argument and function will follow.

Word 2. Blank

Words 3
thru 6. Two pairs of numbers.

Remaining Cards - Pairs of numbers, three pairs to a card, are entered on as many cards as needed to enter the number of pairs indicated in the first word of the first card. Due to a peculiarity of the format statement controlling the reading of these cards, if only two pairs of numbers are entered these would require only the first card; an additional blank card is required. The pairs of numbers are to be entered such that the arguments are in ascending numerical order.

5. Table of $\Delta P_{\text{TPF}}/\Delta P$ versus quality. Values of the function appropriate to the reactor pressure should be entered. Format as described in part 4.

6. ARPHT table. This table consists of arguments only, and is used in conjunction with the PHIT table. The function ϕ_L^2/ϕ_L^2 at 10^6 (referred to as Φ hereafter) is a function of quality and mass flow rate. The ARPHT table is a list of the mass flow arguments. The PHIT table is a series of tables, one table for each mass flow argument in a direct correspondence; that is, the first argument in the ARPHT table is associated with the first of the PHIT tables. Each of the tables making up the PHIT table contain pairs of numbers; the first being the argument, quality, the second being the value of Φ at that quality and the corresponding mass flow rate. A subroutine will perform table lookup and interpolation on both arguments.

Card 1

Word 1. An integer quantity stating the number of mass flow arguments. This quantity must be between 2 and 10. The mass flow arguments that follow should have values such that the highest and lowest possible search arguments are bracketed.

Words 2
thru 6. Mass flow arguments in ascending numerical order. If Word 6 is filled, a 2nd card must follow, even if blank.

Card 2

Remaining mass flow arguments, or blank if the number of arguments is 5.

7. PHIT table. A series of tables as described in part 6. Each of the tables corresponding to a mass flow argument has the format described in part 4. There must be one table for each mass flow argument.

8. The table r versus quality. Values appropriate to the reactor pressure should be entered. Format as described in part 4.

9. The table of viscosity versus enthalpy. Values appropriate to the reactor pressure should be entered. Format as described in part 4.

10. Table of the friction factor, f versus Reynolds number for the plate section of the fuel element. Values corresponding to the roughness factor of the fuel plates should be entered. This table should consist only of values in the turbulent flow region since for values of the Reynolds number (R_e) equal to or below 300, f is given by $64.0/R_e$. Format as described in part 4.

11. Table of f versus Reynolds number for the upper end box section of the fuel plate. Values corresponding to the roughness factor of the of the upper end box should be entered. Only values in the turbulent flow region need be entered. Format as described in 4.

12. Table of specific volume versus enthalpy. Values appropriate to the reactor pressure should be entered. Format as described in part 4.

13. This concludes one set of input data. Sets of data may be stacked in the read hopper or on tape.

B. Output Format

For each set of input data the output described below will be given. The output is completely identified and the units are indicated. Output may be either online or offline printer.

1. The first line states, "PROGRAM TO SET OPERATING LIMITS FOR SPERT III IN REGARD TO BURNOUT. INCLUDES TWO-PHASE FLOW".

2. The second line gives the temperature of the inlet coolant, the reactor pressure, the first power tested, and the power increment.

3. The third line gives the initial hot channel mass flow, the mass flow increment, and the maximum total core flow.

4. The fourth line states: "THE FOLLOWING ARE THE OPERATING LIMITS OF THE REACTOR. DECREASE IN FLOW BY THE FLOW INCREMENT WILL CAUSE BURNOUT". The second sentence emphasizes that the channel flow rate is the variable tested to prevent burnout (DNB).

5. The results of the computations are presented in columns, each column headed by a title and the appropriate units. The quantities in one row are the conditions at one operating point.

- a. Total core flow.
 - b. Power.
 - c. Hot spot. The mesh point closest to DNB. The entrance to the plates is mesh point No. 1.
 - d. Pressure drop across the fuel element.
 - e. Hot channel mass flow rate.
 - f. Exit enthalpy from the hot channel.
 - g. Flow through the fuel element.
 - h. Exit enthalpy from the fuel element.
 - i. Exit enthalpy from a normal channel.
 - j. Exit enthalpy from the end channel.
6. The final statement for each set of data is: "MAXIMUM FLOW HAS BEEN EXCEEDED. END OF CALCULATIONS FOR ONE SET OF DATA."

C. Operating Instructions

1. Sense Switches

- 1 through 4: Are not used.
- 5: Down, input will be on tape unit 2; up, input will be on cards.
- 6: Down, output will be on tape unit 10; up, output will be on the "on" line printer.

2, Place data cards (if used) behind program deck, and ready cards in card reader. Clear and load cards. Use 72 column, right hand identification card reader board and the Share No. 2 printer board.

3. Halts. The only stops in addition to the standard FORTRAN object deck stops are those indicating that the search arguments are out of range for the arguments entered in the tables. The stop is HTR with a 1, 2, or 3. After this stop, it is impossible to continue the program. To process the next set of data, the program deck must be reloaded. These stops will occur only when the table lookup routines attempt to search through more than 10 arguments for the ARPHT table, or 21 pairs of numbers for the other tables. These stops will normally be effective only if the unused portions of the tables are zero. If the core was not cleared, or if the second or succeeding sets of data do not have as many table entries as previous problems, it is possible to pick up values not entered with the present set of input data. However, the stops or the picking up of invalid data cannot happen if each table has for its last argument, a value greater than any possible search argument.

4. Print output tape under program control.

VIII. RESULTS OF SAMPLE CALCULATION

The code output data of a sample problem for the Spert III reactor at 550°F inlet temperature and 2500-psig system pressure are given in Appendix III, and the results are shown in Fig. 11. The safe operating region is below and to the right of the graph. The power, as given by the output data shown in Appendix III, is the core power and not the total power of the reactor. In this report, it is assumed that 95% and 5% of the power is generated in the core and thermal shields, respectively; therefore, the core power, given as output data, is 95% of the total power of the reactor.

The results show that at a power level of 60 Mw (maximum design power) the minimum flow rate below which DNB will occur is approximately 8000 gpm. The code is in all probability conservative for several reasons. First, the design DNB equation, which is considered conservative, is used instead of the correlation DNB equation. Second, the "hot channel factors" are used. Third, the code neglects the effect of voids that would probably reduce the peak power density at the DNB point during bulk boiling. Fourth, it is assumed that there is only one hot channel. If there is more than one hot channel, the flow through the hot channel would be higher than predicted because of the flow redistribution. For a given total flow, more fluid would be forced through the normal channels which would increase the pressure drop across the core. The increased pressure drop would, in turn, increase the flow through the hot channel. This would result in an increase in the DNB heat flux.

The final solution of the problem of setting the operating limits of Spert III could be improved in several ways. One method would be to account for the radial heat distribution. This could be done by dividing the core area into regions of approximately equal flux, and repeating the described calculations for each region. The inclusion of the nucleate boiling pressure drop would also improve the solution. Also, the DNB correlations employed are applicable in a limited pressure range (1850 to 2150 psia), and other DNB correlations could be used to extend the pressure range. Use of the Bettis design equations to predict the DNB heat flux in Spert III at the high pressures (maximum 2500 psi) does not, in all probability, result in large errors. Correlations developed for low pressures would have to be used instead of the Bettis design equations to extend these calculations to the low pressure regions.

Fig. 11 Reactor DNB power versus total flow rate.

IX. REFERENCES

1. R. A. DeBortoli, S. J. Green, B. W. Le Tourneau, M. Troy, A. Weiss, "Forced-Convection Heat Transfer Burnout Studies for Water in Rectangular Channels and Round Tubes at Pressure Above 500 psia", WAPD-188 (Oct., 1958).
2. S. J. Green, B. W. Le Tourneau, M. Troy, "Forced Circulation Uniform Flux Burnout Studies for High Pressure Water", Joint ASME-AIChE Heat Transfer Conference, Storrs, Connecticut, August 9-12, 1959, Paper 59-HT-25.
3. B. W. Le Tourneau and R. E. Grimbale, "Engineering Hot Channel Factor", Nuclear Science and Engineering, 1, pp. 359-369 (October, 1956).
4. P. A. Lottes, M. Petrick, J. F. Marchaterre, "Lecture Notes on Heat Extraction from Boiling Water Power Reactors", ANL-6063 (October, 1959).
5. A. H. Spano and D. R. Metcalf, "Quarterly Progress Report, Reactor Projects Branch", April, May, June, 1958, G. O. Bright, Ed., IDO-16489, pp. 56-64 (January 19, 1959).
6. J. F. Koenig, Report to be published.
7. J. O. Brondel, "APPR-1 Hot Channel Factors-Re-evaluation on the Basis of Manufacturing and Zero Power Experiments", APAE Memo. No. 96 (May 6, 1957).
8. Stoever, Chem. and Met. Eng., May, 1944.
9. J. F. Wett, Jr., "Burnout Heat Flux Correlations", Nuclear Safety, 2, pp. 10-13 (March, 1961).
10. "Power Reactor Technology", 1, No. 4, pp. 7-9 (September, 1958).
11. W. H. McAdams, Heat Transmission, pp. 371, McGraw-Hill Book Company, Inc. (1954).
12. H. Susskind, "A Survey of Bulk-Boiling Studies in Pressurized Water Reactor Systems", BNL-636 (August, 1960).
13. D. W. Bell, "Correlation of Burnout Heat-Flux Data at 2000 psia", Nuclear Science and Engineering, 7, pp. 245-251 (1960).
14. A. F. Pexton, "A Review of Data on Burnout Heat Flux for Steam-Water Mixtures in Uniformly Heated Channels", DEG-R203 (March, 1961).
15. C. F. Bonilla, Nuclear Engineering, pp. 423, McGraw-Hill Book Company, Inc. (1957).

16. W. H. Jens and P. A. Lottes, "Analysis of Heat Transfer, Burnout, Pressure Drop and Density Data for High-Pressure Water", ANL-4627 (May 1, 1951).
17. "Power Reactor Technology", 2, No. 4, pp. 36-43 (September, 1959).
18. R. A. DeBortoli, et. al., "Investigation of Burnout Heat Flux," Reactor Heat Transfer Conference, New York City, November 1 and 2, 1956, Paper 33.
19. "Power Reactor Technology", 3, No. 4, pp. 27-28 (September, 1960).
20. S. Mirshak, W. S. Durant, R. H. Towell, "Heat Flux at Burnout", DP-355 (February, 1959).
21. L. Bernath, "A Theory of Local Boiling Burnout and Its Application to Existing Data", Joint ASME-AIChE Heat Transfer Conference, Storrs, Connecticut, August 9-12, 1959, Preprint 110.
22. W. R. Gambill and R. D. Bundy, "HFIR Heat-Transfer Studies of Turbulent Water Flow in Thin Rectangular Channels", ORNL-3079 (June, 1961).
23. W. S. Durant and S. Mirshak, "Roughening of Heat Transfer Surface as a Method of Increasing Heat Flux at Burnout," DP-380 (July, 1959).
24. W. H. McAdams, J. N. Addoms, W. E. Kennel, "Heat Transfer at High Rates to Water With Surface Boiling", ANL-4268 (December, 1948).
25. F. C. Gunther, "Photographic Study of Surface-Boiling Heat Transfer to Water With Forced Convection", Trans. Am. Soc. Mech. Engrs., 73, pp. 115-124 (1951).
26. J. Longo, Jr., "A Statistical Investigation of Subcooled Burnout with Uniform and Locally Peaked Heat Fluxes", KAPL-1744 (October 22, 1957).
27. J. Longo, Jr., "Continuation of KAPL (DIG) Investigation of Burnout". KAPL-M-DIG-TD-2 (June 16, 1958).
28. V. N. Tramontini, et. al., "Final Report on Studies in Boiling Heat Transfer", COO-24 (March, 1951).
29. B. L. McGill and W. L. Sibbitt, "Part I: Heat Transfer and Pressure Drop of Water Flowing in a Small Tube", ANL-4603 (February 15, 1951).
30. J. M. Reynolds, "Burnout in Forced Convection Nucleate Boiling of Water", MIT Tech. Report No. 10, NONR-1848 (39) (July 1, 1957).
31. R. J. Hoe and J. H. Helve, "S3G/S4G Design Criteria and Analysis", KAPL-M-RES-50 (September 12, 1957).

32. P. Griffith, "The Correlation of Nucleate Boiling Burnout Data", Joint ASME-AIChE Heat Transfer Conference, Pennsylvania State University, August 11-15, 1957, Paper 57-HT-21.
33. G. Sonnemann, "A Method of Correlating Burnout Heat Flux Data", Nuclear Science and Engineering, 5, pp. 242-247 (1959).
34. A. Cicchitti, C. Lombardi, M. Silvestri, G. Soldaini, and R. Zavattarelli, "Two-Phase Cooling Experiments: Pressure Drop, Heat Transfer and Burnout Measurements", CISE-71 (1959).
35. S. Glasstone, Principles of Nuclear Reactor Engineering, pp. 638, D. Von Nostrand Company, Inc. (1955).
36. R. C. Martinelli and D. B. Nelson, "Prediction of Pressure Drop During Forced Circulation Boiling of Water", Trans. ASME, 70, pp. 695-702 (1948).
37. N. C. Sher, "Estimation of Boiling and Nonboiling Pressure Drop in Rectangular Channels at 2000 psia", WAPD-TH-300 (March, 1957).
38. The Reactor Handbook, Volume 2, Engineering, AEC D-3646, pp. 58 (May, 1955).
39. Ibid, pp. 64.
40. Ibid, pp. 66.
41. J. F. Koenig, Private Communication.
42. J. A. Norberg, Private Communication.

X. APPENDIX I

A. NOMENCLATURE

The following symbols are used throughout this report. All equations taken from the references are translated into these symbols where necessary.

Roman Symbols

A	Total heat transfer surface of the core, ft^2 .
A_f	Cross-sectional area of flow channel, ft^2 .
A_h	Heat transfer surface area, ft^2 .
A_1/A_2	Ratio of upstream flow area to downstream flow area.
a	Fuel plate clad thickness, ft.
b	Fuel plate meat half-thickness, ft.
C_p	Constant pressure heat capacity of liquid, $\text{Btu/lb-}^\circ\text{F}$.
D_e	Hydraulic diameter, ft.
D_i	Heated perimeter, ft.
F^1	Function defined in Table II, %.
F_H	Hot channel factor for enthalpy rise.
F_θ	Hot channel factor for film temperature difference.
F_Q	Hot channel factor for heat.
f	Friction factor.
f^1	General symbol for function of variable or variables in the brackets following.
G	Mass flow rate, lb/hr-ft^2 .
g	Acceleration due to gravity ($32.2 \text{ ft-lb mass/lb force-sec}^2$).
H_{DNB}	Enthalpy at DNB location, Btu/lb .
H_b	Bulk enthalpy, Btu/lb .
H_{fg}	Latent heat of vaporization, Btu/lb .

H_i	Bulk enthalpy at inlet, Btu/lb.
H_r	Enthalpy of saturated vapor, Btu/lb.
H_z	Bulk enthalpy at point z, Btu/lb.
ΔH	Enthalpy rise through a coolant channel, Btu/lb.
h	Film coefficient of heat transfer, Btu/hr-ft ² -°F.
h_{BO}	Heat transfer coefficient at DNB point, Btu/hr-ft ² -°F.
K_e	The loss coefficient for sudden expansion.
K_c	The loss coefficient for sudden contraction.
k_c	Thermal conductivity of fuel plate clad material, Btu-ft/ft ² -hr-°F.
k_m	Thermal conductivity of fuel plate meat material, Btu-ft/ft ² -hr-°F.
k_l	Thermal conductivity of liquid, Btu-ft/ft ² -hr-°F.
L	Length of heated channel, ft.
P	Pressure, psia.
P_c	Critical pressure, psia.
Pr	Prandtl number.
ΔP	Pressure drop, psia.
ΔP_{TP}	Two-phase flow pressure drop, psi.
ΔP_{TPF}	Two-phase frictional pressure drop, psi.
Q	Thermal power of the reactor core, Btu/hr.
Re	Reynolds number.
R_g	Volume fraction of vapor in fluid.
R_T	Total thermal resistance through the fuel plate half cross-section.
r	Multiplier of G^2/g to calculate the momentum pressure loss in two-phase flow.
S	Channel spacing, ft.

T_B	Bulk temperature at DNB point, °F.
T_b	Fluid bulk temperature, °F.
T_i	Bulk temperature at inlet, °F.
T_{nb}	Temperature at which nucleate boiling starts, °F.
T_o	Bulk temperature at outlet, °F.
T_{pz}	Plate temperature at point z, °F.
T_s	Saturation temperature, °F.
T_w	Temperature of channel wall, °F.
T_{wDNB}	Temperature of wall at DNB point, °F.
T_z	Bulk temperature at point z, °F.
ΔT	Temperature difference through the fuel plate half cross-section, °F.
ΔT_{sub}	Subcooling, °F.
t_{ch}	Minimum clad thickness, ft.
t_{co}	Maximum clad thickness, ft.
t_m	Meat thickness, ft.
V	Velocity of fluid, ft/sec.
V_1	Average linear upstream velocity, ft/sec.
V_2	Average linear downstream velocity, ft/sec.
W	Weight rate of flow, lbs/hr.
X	Steam quality.
Z	Axial distance of point in question from inlet, ft.

Greek Symbols

θ	Film temperature difference (surface temperature minus bulk coolant temperature).
μ_f	Viscosity of saturated liquid, lb/ft-hr.
μ_l	Viscosity of liquid, lb/ft-hr.

ρ_F	Fuel density, lbs/ft ³ .
ρ_f	Density of fluid at saturation temperature, lb/ft ³ .
ρ_l	Density of liquid, lb/ft ³ .
ρ_v	Density of vapor at saturation temperature, lbs/ft ³ .
ρ_g	Density of vapor, lbs/ft ³ .
σ	Surface tension, lb/ft,
Φ_L	Martinelli function, Φ_L^2 is equal to the ratio of two-phase frictional pressure drop gradient to corresponding isothermal liquid gradient.
$\Phi_L \text{ at } 10^6$	Same as Φ_L , except evaluated at a mass flow rate of 1.0×10^6 lbs/hr-ft ² .
ϕ	Heat flux, Btu/hr-ft ² .
ϕ_{DNB}	DNB heat flux, Btu/hr-ft ² .
ϕ_{NB}	Heat flux at the point of initial nucleate boiling Btu/hr-ft ² .
ϕ_z	Heat flux at point z, Btu/hr-ft ² .

Subscripts

nom	= Average or nominal design value in the core.
nom ave	= Average or nominal design value in the core, evaluated at the average neutron flux.
ave	= Average value in the fuel element.
max	= Maximum value in the core.
min	= Minimum value in the fuel element.
max local	= Maximum local value in the core.
max ave	= Maximum average value in any one coolant channel.
min local	= Minimum local value in the core.
min ave	= Minimum average value in any one coolant channel.
max local in	
min ave	= Maximum local value in a channel of minimum average dimensions.

B. SYMBOL TABLE

The following symbol table is a list of the variables and sub-program titles used in the program. Subscripted variables and sub-program titles have been identified as such. Fixed point variables under control of Do or input statements have not been included. The numbers in parenthesis refer to sections of the fuel element as numbered in Fig. 5.

ARE2	Area of end plate channel.
ARE3	Area of side plate channel.
ARE10	Area of 1st constriction of upper end box. (No. 10).
ARE11	Area of 2nd constriction and the area of 1st straight section of upper end box. (No. 11 & 12).
ARE13	Area of 3rd constriction and 2nd straight section of upper end box (No. 13 & 14).
AREW1	Area of normal plate channel.
ARG	Dummy variable used in TABLU to indicate the search argument of the table lookup.
ARGT	Dummy subscripted variable used in TABLU to indicate the table to be searched.
ARPHT	Subscripted variable containing the mass flow arguments of table PHIT.
AVGENT	Average enthalpy between two mesh points on the fuel plate.
DA	Heat transfer area of a fuel plate region.
DE1	Equivalent diameter for normal plate channel.
DE2	Equivalent diameter for end plate channel.
DE3	Equivalent diameter for side plate channel.
DE12	Equivalent diameter of 1st straight section of upper end box (No. 12).
DE13	Equivalent diameter for 2nd straight section of upper end box (No. 14).
DELTP	Used to accumulate pressure drop across fuel element. Contains pressure drop across fuel plates during plate section flow-rate determination.

DELTPP	Used to accumulate pressure drop in determining flow rate through plate sections of fuel element.
DENSS	Specific volume of saturated liquid at reactor system pressure.
DENSST	Specific volume of saturated vapor at reactor system pressure.
DENSTI	Specific volume of coolant at inlet temperature and reactor system pressure.
DENSTT	Subscripted variable containing the table of specific volume vs. enthalpy.
DENSTY	Function subprogram to determine specific volume as a function of enthalpy.
DFLO	Mass flow rate increment.
DFLOX	Current value of mass flow rate increment used in determining flow rate through plate sections of fuel element.
DL	Length of fuel plate region. $(L - 1) DL = FL$.
DPFNT	Subscripted variable containing table of $\Delta P_{TPF}/\Delta P$ versus quality.
DPOLD	1) Temporary storage used in finding mass flow rates. 2) Temporary storage during EXPFT table computation.
DPOW	Power increment.
DPRAT	Function subprogram, to determine $\Delta P_{TPF}/\Delta P$ as a function of quality.
DUM	1) Dummy variable used in input statements to space over number field. 2) Temporary storage.
EFLOR	Current value of mass flow rate of hot channel. As input data it is the first mass flow rate tested.
EFLOX	Current value of mass flow rate used in determining flow through plate sections of fuel element.
EMP1	Factor in lower end box pressure drop correlation.
EMP2	Exponent in lower end box pressure drop correlation.
EMP01	Factor in total core flow vs. pressure drop across core correlation.

EMPO2	Exponent in total core flow vs. pressure drop across core correlation.
ENT	Dummy variable in subprogram indicating enthalpy.
ENTH	Subscripted variable used to store the enthalpy of the coolant as a function of position in the water channel of the fuel plate. ENTH(1) is the inlet enthalpy of the coolant.
ENTHFG	Enthalpy required to evaporate coolant at reactor system pressure.
ENTHPY	Dummy variable in subprogram for enthalpy.
ENTHS	Enthalpy of the saturated liquid at the reactor system pressure.
ENTHSS	Enthalpy of saturated vapor at reactor system pressure.
EXPFT	Subscripted variable containing the factor $\exp\left[-\frac{.0012L}{S}\right]$ as a function of channel position.
FHCE	Hot channel factor for enthalpy.
FHCT	Hot channel factor for heat transfer.
FKC1	K_c for normal plate channel entrance.
FKC2	K_c for end plate channel entrance.
FKC3	K_c for side plate channel entrance.
FKC10	K_c for 1st constriction loss of upper end box (No. 10).
FKC11	K_c for 2nd constriction loss of upper end box (No. 11).
FKC13	K_c for 3rd constriction loss of upper end box (No. 13).
FKE1	K_e for normal plate channel exit.
FKE2	K_e for end plate exit.
FKE3	K_e for side plate channel exit.
FKE13	K_e for exit loss of fuel element (No. 15).
FL	Fuel plate length.
FL12	Length of 1st straight section of upper end box (No. 12).
FL14	Length of 2nd straight section of upper end box (No. 14).

FLOM	Maximum core flow in gal/min.
FLOR	Current value of flow rate in lb/hr.
FLORTM	Dummy variable in subprogram for the product of coolant velocity times equivalent diameter.
FLOWO	Total core flow in gal/min.
FLUX	Subscripted variable containing the heat flux per unit power (Btu/ft ² - hr-Mw) as a function of channel position.
L	Number of mesh points in plate section of fuel element (number of regions + 1).
LK	Contains current value of mesh point at which burnout is most probable.
NSW	Switch used to direct program either to printing results or to incrementing flow after finding a safe flow.
PHIR	Function subprogram to determine ϕ_L^2 / ϕ^2 at 10^6 as a function of quality and mass flow rate.
PHIT	Double subscripted variable containing table of ϕ_L^2 / ϕ^2 at 10^6 versus quality and mass flow rate. The table contains the quality argument; the mass flow rate dependence is obtained from an auxiliary table, ARPHT.
PN	Number of normal plate channels.
POW	Current value of reactor power. As input data it is the first power value tested.
PRESS	Reactor system pressure.
Q	1) Contains current value of quality. 2) Used for temporary storage while preparing EXPFT table. 3) Dummy argument of subroutines for quality.
RHNOT	Subscripted variable containing table of viscosity vs. enthalpy.
RMULT	Function subprogram to determine r as a function of quality.
RMULTT	Subscripted variable containing table of r versus quality.
S	Water channel thickness.
SPFFR	Function subprogram to determine f as a function of the product of coolant velocity times equivalent diameter (V De) and coolant enthalpy for the plate section of the fuel element.

SPFFT	Subscripted variable containing table of f versus Reynolds number, to be used in calculating pressure drop in the plate section of the fuel elements.
SPFFU	Function subprogram to determine f as a function of the product of coolant flow times equivalent diameter ($V De$) and coolant enthalpy for the upper end box section of the fuel element.
SPFFUT	Subscripted variable containing table of f versus Reynolds number to be used in calculating pressure drop in the upper end box section of fuel element.
ST01 ST02 ST03	Temporary storage used throughout main program.
SUM1	Used to accumulate total fuel element flow.
SUM2	Used to accumulate sum of products of flow rate and enthalpy. At printout will contain exit enthalpy.
SW	Fuel plate width.
TABLU	Function subprogram containing a search argument and table argument to perform table lookup and interpolation.
TABLUD	Function subprogram containing a search argument, quality, and fixed point argument indicating the mass flow rate dependence to perform table lookup and interpolation in the PHIT table.
TEMP	Temperature of inlet coolant.
XX XXX	Temporary storage, normally to store a common multiplier.

XI. APPENDIX II

FORTRAN STATEMENTS

```

C      704 FORTRAN PROGRAM TO SET OPERATING LIMITS FOR SPERT III IN
C      REGARD TO BURNOUT. INCLUDES TWO PHASE FLOW CALCULATION
C
C      GENERAL SINGLE INTERPOLATION SUBROUTINE
      FUNCTION TABLU(ARG, ARG1)
      DIMENSION DPFNT(42), RMULTT(42), PHIT(10,42), RHNOT(42),
1 SPFFT(42), ARG1(42), ARPHT(10), DENSTT(42)
      COMMON DPFNT, RMULTT, PHIT, RHNOT, SPFFT, ARPHT, DENSTT
      DO 10 I= 3, 41, 2
      IF(ARG1(I)-ARG) 10, 11, 12
11  TABLU =ARG1(I+1)
      GO TO 13
12  TABLU =ARG1(I-1)+(ARG-ARG1(I-2))*(ARG1(I+1)-ARG1(I-1))/(ARG1(I)-
121 ARG1(I-2))
13  RETURN
10  CONTINUE
      STOP 00001
      END (0,1,0,0,0)
C
C      DELTA P RATIO SUBROUTINE
      FUNCTION DPRAT(Q)
      DIMENSION DPFNT(42), RMULTT(42), PHIT(10,42), RHNOT(42),
1 SPFFT(42), ARPHT(10), DENSTT(42)
      COMMON DPFNT, RMULTT, PHIT, RHNOT, SPFFT, ARPHT, DENSTT
      DPRAT= TABLU(Q, DPFNT)
      RETURN
      END (0,1,0,0,0)
C
C      R MULTIPLIER SUBROUTINE
      FUNCTION RMULT(Q)
      DIMENSION DPFNT(42), RMULTT(42), PHIT(10,42), RHNOT(42),
1 SPFFT(42), ARPHT(10), DENSTT(42)
      COMMON DPFNT, RMULTT, PHIT, RHNOT, SPFFT, ARPHT, DENSTT
      RMULT = TABLU(Q, RMULTT)
      RETURN
      END (0,1,0,0,0)
C
C      SINGLE PHASE FRICTION FACTOR SUBROUTINE
      FUNCTION SPFFR(FLOSTM, ENTHPY)
      DIMENSION DPFNT(42), RMULTT(42), PHIT(10,42), RHNOT(42),
1 SPFFT(42), ARPHT(10), DENSTT(42)
      COMMON DPFNT, RMULTT, PHIT, RHNOT, SPFFT, ARPHT, DENSTT
      FLOSTM = FLOSTM/TABLU(ENTHPY, RHNOT)
      IF(FLOSTM - 300.0)10,10,11
10  SPFFR = 64.0/FLOSTM
      GO TO 12
11  SPFFR = TABLU(FLOSTM, SPFFT)
12  RETURN
      END (0,1,0,0,0)

```

```

C
C      FRICTION CORRECTION FACTOR SUBROUTINE
      FUNCTION PHIR(Q,FLORTM)
      DIMENSION DPFNT(42),RMULTT(42), PHIT(10,42), RHNOT(42),
1 SPFFT(42),ARPHT(10), DENSTT(42)
      COMMON DPFNT, RMULTT, PHIT, RHNOT, SPFFT,ARPHT,DENSTT
      DO 10 I = 2,10
      IF(ARPHT(I)-FLORTM) 10,11,12
10  CONTINUE
      STOP 00002
11  PHIR =TABLUD(I,Q)
      GO TO 13
12  PHIR =TABLUD(I-1,Q)+(FLORTM-ARPHT(I-1))*(TABLUD(I,Q)-TABLUD(I-1,Q
121 ))/(ARPHT(I)-ARPHT(I-1))
13  RETURN
      END (0,1,0,0,0)

C
C      DOUBLE SUBSCRIPTED INTERPOLATION
      FUNCTION TABLUD(I,Q)
      DIMENSION DPFNT(42), RMULTT(42), PHIT(10,42), RHNOT(42),
1 SPFFT(42),ARPHT(10), DENSTT(42)
      COMMON DPFNT, RMULTT, PHIT, RHNOT, SPFFT, ARPHT, DENSTT
998 DO 10 J = 3,41,2
999 IF(PHIT(I,J)-Q) 10, 11, 12
11  TABLUD = PHIT(I, J+1)
      GO TO 13
12  TABLUD = PHIT(I,J-1)+(Q-PHIT(I,J-2))*(PHIT(I,J+1)-PHIT(I,J-1))/
121 (PHIT(I,J)-PHIT(I,J-2))
13  RETURN
10  CONTINUE
      STOP 00003
      FREQUENCY 999(7,0,1), 998 (7)
      END (0,1,0,0,0)

C
C      SINGLE PHASE FRICTION FACTOR SUBROUTINE FOR UPPER END BOX.
      FUNCTION SPFFU(FLORTM, ENTHPY)
      DIMENSION DPFNT(42),RMULTT(42),PHIT(10,42),RHNOT(42),
1 SPFFT(42),ARPHT(10),DENSTT(42), SPFFUT(42)
      COMMON DPFNT,RMULTT,PHIT,RHNOT,SPFFT,ARPHT,DENSTT,ENTHS,ENTHFG,
1 ENTHSS,DENSTI,DENSS,DENSST,SPFFUT
      FLORTM = FLORTM/TABLU(ENTHPY,RHNOT)
      IF(FLORTM - 300.0)10,10,11
10  SPFFU = 64.0/FLORTM
      GO TO 12
11  SPFFU = TABLU(FLORTM, SPFFUT)
12  RETURN
      END (0,1,0,0,0)

```

```

C
C   DENSITY VS. ENTHALPY SUBROUTINE
C   FUNCTION DENSITY(ENT)
C   DIMENSION DPFNT(42),RMULTT(42),PHIT(10,42), RHNOT(42),
1 SPFFT(42), ARPHT(10), DENSTT(42)
C   COMMON DPFNT, RMULTT, PHIT, RHNOT, SPFFT, ARPHT, DENSTT, ENTHS,
1 ENTHFG, ENTHSS, DENSTI, DENSS, DEN SST
C   IF (ENT -ENTHS) 10, 11, 12
11 DENSTY = DENSS
C   GO TO 13
12 Q = (ENT-ENTHS)/ENTHFG
C   DENSTY = (1.0-Q)*DENSS + Q*DENSST
C   GO TO 13
10 DENSTY = TABLU(ENT, DENSTT)
13 RETURN
C   END (0,1,0,0,0)

C
C   MAIN ROUTINE
C   DIMENSION DPFNT(42),RMULTT(42),PHIT(10,42),RHNOT(42),SPFFT(42),
1 ARPHT(10), DENSTT(42),ENTH(51),FLUX(51),EXPFT(51),SPFFUT(42)

C   COMMON DPFNT, RMULTT,PHIT,RHNOT,SPFFT,ARPHT,DENSTT,ENTHS,
1 ENTHFG,ENTHSS,DENSTI,DENSS,DENSST,SPFFUT
1 FORMAT (I12, 5E12.0/(6E12.0))
2 FORMAT (6E12.0)
3 FORMAT ( 94H1PROGRAM TO SET OPERATING LIMITS FOR SPERT III IN REG
31ARD TO BURNOUT. INCLUDES TWO PHASE FLOW.)
4 FORMAT(7HOTEMP.=F6.1,17H DEGF. PRESS.=F7.1,23H PSI. INITIAL
41 POWER=F7.2,24H MW. POWER INCREMENT=F6.1, 4H MW.//19H INITIAL M
42ASS FLOW=1PE 9.3,35H LB/HR-SQFT MASS FLOW INCREMENT=E 9.3,25H L
43B/HR-SQFT MAX. FLOW=OPF8.1, 4H GPM)
6 FORMAT(120H0FLOW POWER HOT SPOT PRESS DROP HOT CHAN FL
61OW HOT CHAN ENTH ELMT FLOW EXIT ENTH N.C. ENTH E.C. ENTH
62 / 6H (GPM) 5X, 4H(MW) 4X, 7H MESH PT 4X, 5H(PSI) 8X, 12H(LB/H
63R-SQFT) 4X, 8H(BTU/LB) 8X, 7H(LB/HR) 5X, 8H(BTU/LB) 4X, 8H(BTU/LB
64) 4X, 8H(BTU/LB) //)
7 FORMAT (1H F7.0, F8.1, I11, F13.3, 1PE16.3, OPF16.1, 1PE12.3,
71 OPF12.1, 2F12.1 )
8 FORMAT (80H0MAXIMUM FLOW HAS BEEN EXCEEDED. END OF CALCULATIONS
81FOR ONE SET OF INPUT DATA. )
5 FORMAT(112H0THE FOLLOWING ARE THE OPERATING LIMITS OF THE REACTOR
1. DECREASE IN FLOW BY THE FLOW INCRMT WILL CAUSE BURNOUT.)
C   INPUT OF DATA AND PRELIMINARY CALCULATIONS
100 IF (SENSE SWITCH 5) 800, 801
800 READ INPUT TAPE2,2,TEMP,PRESS,ENTH(1),ENTHS ,ENTHFG,ENTHSS,
8001 DENSTI,DENSS,DENSST
C   READ INPUT TAPE2,1,L, FL, DL, POW, DPOW, EFLOR, DFLO, FLOM, DA, S
C   READ INPUT TAPE2,2, XX, (FLUX(I), I=1,L)
C   READ INPUT TAPE2,2,FHCE,FHCT,FKC1,DE1,FKE1,AREW1, PN,FKC2,
1 DE2,FKE2,ARE2,FKC3,DE3,FKE3,ARE3,EMP1,EMP2,FKC10,ARE10,
2 FKC11,ARE11,DE12,FL12,FKC13,ARE13,DE13,FL14,FKE13,EMP01,EMP02
C   READ INPUT TAPE2,1, N, DUM, (DPFNT(2*I-1), DPFNT(2*I), I=1,N)
C   READ INPUT TAPE2,1,J, (ARPHT(I), I=1,J)

```

```

526 DO 802 I= 1,J
802 READ INPUT TAPE2,1,N,DUM, (PHIT(I,2*K-1),PHIT(I,2*K), K=1,N)
   READ INPUT TAPE2,1,N,DUM,(RMULTT(2*I-1),RMULTT(2*I), I= 1,N)
   READ INPUT TAPE2,1,N,DUM,(RHNOT(2*I-1),RHNOT(2*I),I=1,N)
   READ INPUT TAPE2,1,N,DUM,(SPFFT(2*I-1),SPFFT(2*I),I=1,N)
   READ INPUT TAPE2,1,N,DUM,(SPFFUT(2*I-1),SPFFUT(2*I), I=1,N)
   READ INPUT TAPE2,1,N,DUM,(DENSTT(2*I-1),DENSTT(2*I), I=1,N)
   GO TO 803

801 READ2, TEMP, PRESS, ENTH(1), ENTHS, ENTHFG, ENTHSS, DENSTI,
8011 DENSS, DENSSST
   READ 1, L, FL, DL, POW, DPOW, EFLOR, DFLO, FLOM, DA,S
   READ 2, XX, (FLUX(I), I= 1, L)
   READ 2, FHCE,FHCT,FKC1,DE1,FKE1,AREW1, PN,FKC2,DE2,
1 FKE2,ARE2,FKC3,DE3,FKE3,ARE3,EMP1,EMP2,FKC10,ARE10,
2 FKC11,ARE11,DE12,FL12,FKC13,ARE13,DE13,FL14,FKE13,EMPO1,EMPO2
   READ1, N, DUM, (DPFNT(2*I-1), DPFNT(2*I), I= 1, N)
   READ1, J, (ARPHT(I), I =1, J)
702 DO 10 I = 1, J
10 READ 1, N, DUM, (PHIT(I,2*K-1), PHIT(I,2*K), K= 1, N)
   READ 1, N, DUM, (RMULTT(2*I-1), RMULTT(2*I), I= 1, N)
   READ 1, N, DUM, (RHNOT(2*I-1), RHNOT(2*I), I=1, N)
   READ 1, N, DUM, (SPFFT(2*I-1), SPFFT(2*I), I=1, N)
   READ 1, N, DUM, (SPFFUT(2*I-1), SPFFUT(2*I), I= 1, N)
   READ 1, N, DUM, (DENSTT(2*I-1), DENSTT(2*I), I=1, N)
803 Q= .0012/S
   DPOLD =0.0
701 DO 11 I = 1, L
   FLUX(I)= FLUX(I)*XX
   EXPFT(I) = EXPF (-DPOLD*Q)
11 DPOLD = DPOLD +DL
   IF(SENSE SWITCH 6) 804, 805
804 WRITE OUTPUT TAPE10,3
   WRITE OUTPUT TAPE10,4,TEMP,PRESS,POW,DPOW,EFLOR, DFLO,FLOM
   WRITE OUTPUT TAPE10,5
   WRITE OUTPUT TAPE10,6
   GO TO 24
805 PRINT 3
   PRINT 4, TEMP, PRESS, POW, DPOW, EFLOR, DFLO, FLOM
   PRINT 5
   PRINT 6
C FINDING SAFE FLOW
24 ASSIGN 13 TO NSW
240 ST01 = 1.0E25
   I=1
   FLOR = EFLOR* AREW1
   XX =FHCE*POW*DA/FLOR
   XXX=FHCT*POW*.95
525 IF (EFLOR - 1.6E6) 15, 15, 16

```



```

15  ST02 = 0.325E6
    GO TO 17
16  ST02 = ((1.0 + EFLOR/1.0E7)**2)*.24E6
17  ST03 = ST02*EXPFT(I)*(1.0E3/ENTH(I))**2.5 - FLUX(I)*XXX
703 IF (ST03) 18,18,19
19  IF(ST03-ST01) 20,21,21
20  ST01 = ST03
    LK = I
21  I = I+1
704 IF(I-L) 22, 22, 23
22  ENTH(I)= ENTH(I-1)+(FLUX(I-1)+FLUX(I))*XX
    GO TO 17
18  EFLOR = EFLOR + DFLO
    SENSE LIGHT 2
    GO TO 24
23  GO TO NSW,(13, 27)
13  IF(ENTH(L)-ENTHSS) 31, 18, 18
C   GETTING PRESSURE DROP FOR HOT CHANNEL
31  DELTP = (EFLOR**2)*DENSTI*FKC1/8.34E8
    ST01=ENTH(L)
706 DO 32 I = 2, L
    AVGENT = (ENTH(I-1)+ENTH(I))/2.0
707 IF(AVGENT -ENTHS) 80,80,33
80  DELTP=DELTP+SPFFR(EFLOR*DE1,AVGENT)*EFLOR**2*DENSTY(AVGENT)*DL/
801 8.34E8/DE1
    GO TO 32
33  Q = (AVGENT-ENTHS)/ENTHFG
    DELTP = DELTP + (SPFFR(EFLOR*DE1,ENTHS)*EFLOR**2*DENSS*DL/8.34E8)*
1  DPRAT(Q)*PHIR(Q,EFLOR)/DE1
32  CONTINUE
708 IF(ENTH(L)-ENTHS) 91,91,90
90  Q = (ENTH(L)-ENTHS)/ENTHFG
    DELTP = DELTP + EFLOR**2* RMULT(Q)/4.17E8
91  DELTP = DELTP + EFLOR **2 *DENSTY(ENTH(L))*FKC1/8.34E8
C   GETTING FLOW THRU NORMAL CHANNELS
    SENSE LIGHT 3
    EFLOX = EFLOR
    SENSE LIGHT 1
    DFLOX = 0.1 * EFLOR
39  FLOR = EFLOX*AREW1
    XX = DA*POW/FLOR
709 DO 34 I = 2, L
34  ENTH(I) = ENTH(I-1) +(FLUX(I-1)+FLUX(I))*XX
    DELTPP= (EFLOX**2)*DENSTI*FKC1/8.34E8
711 DO 35 I = 2, L
    AVGENT = (ENTH(I-1)+ ENTH(I))/2.
    IF (AVGENT-ENTHS) 81,81,36
81  DELTPP=DELTPP + SPFFR(EFLOX*DE1,AVGENT)*EFLOX**2*DENSTY(AVGENT)*
811 DL/8.34E8/DE1
    GO TO 35
36  Q = (AVGENT-ENTHS)/ENTHFG
    DELTPP=DELTPP + (SPFFR(EFLOX*DE1,ENTHS)*EFLOX**2*DENSS*DL/8.34E8)*
1  DPRAT(Q)*PHIR(Q,EFLOX)/DE1
35  CONTINUE

```

```

715 IF (ENTH(L)-ENTHS) 92,92,93
93 Q = (ENTH(L)-ENTHS)/ENTHFG
DELTTP = DELTTP + EFLOX**2*RMULT(Q)/4.17E8
92 DELTTP = DELTTP + EFLOX ** 2 *DENSTY(ENTH(L))*FKE1/8.34E8
DUM = DELTP - DELTTP
713 IF (SENSE LIGHT 1) 37,38
38 IF (DUM * DPOLD) 41,40,37
37 EFLOX = EFLOX + SIGNF(DFLOX, DUM)
DPOLD = DUM
GO TO 39
41 EFLOX = EFLOX - DUM* DFLOX/(DUM - DPOLD)
40 SUM1 = EFLOX*AREW1*PN
SUM2 = SUM1 * ENTH(L)
STO2=ENTH(L)
C GETTING FLOW THRU END PLATES
SENSE LIGHT 4
SENSE LIGHT 1
42 FLOR =EFLOX*ARE2
XX = DA*POW/FLOR
714 DO 43 I = 2,L
43 ENTH(I) = ENTH(I-1)+(FLUX(I-1) +FLUX(I))*XX
DELTTP= (EFLOX**2)*DENSTI*FKC2/8.34E8
712 DO 44 I = 2, L
AVGENT = (ENTH(I-1)+ ENTH(I))/2.
716 IF (AVGENT-ENTHS)82,82,45
82 DELTTP=DELTTP + SPFFR(EFLOX*DE2,AVGENT)*EFLOX**2*DENSTY(AVGENT)*
821 DL/8.34E8/DE2
GO TO 44
45 Q = (AVGENT-ENTHS)/ENTHFG
DELTTP=DELTTP + (SPFFR(EFLOX*DE2,ENTHS)*EFLOX**2*DENSS*DL/8.34E8)*
1 DPRAT(Q)*PHIR(Q,EFLOX) /DE2
44 CONTINUE
717 IF (ENTH(L)-ENTHS) 94,94,95
95 Q = (ENTH(L)-ENTHS)/ENTHFG
DELTTP = DELTTP +EFLOX**2*RMULT (Q)/4.17E8
94 DELTTP= DELTTP +EFLOX ** 2 *DENSTY(ENTH(L))*FKE2/8.34E8
DUM = DELTP- DELTTP
718 IF (SENSE LIGHT 1) 46, 47
47 IF (DUM*DPOLD) 49, 48, 46
46 EFLOX =EFLOX + SIGNF(DFLOX, DUM)
DPOLD = DUM
GO TO 42
49 EFLOX =EFLOX -DUM*DFLOX/(DUM-DPOLD)
48 DUM = EFLOX *ARE2*2.0
SUM1 = SUM1 +DUM
SUM2 = SUM2 + DUM*ENTH(L)
STO3=ENTH(L)
C GETTING FLOW THRU SIDE PLATES
SENSE LIGHT 1
54 DELTTP= ((EFLOX**2)*DENSTI*(FKC3+FKE3)+SPFFR(EFLOX*DE3,ENTH(1
541 ))*EFLOX**2*DENSTI*FL/DE3)/8.34E8
DUM = DELTP -DELTTP

```

```

719 IF (SENSE LIGHT 1) 50, 51
51 IF (DUM * DPOLD) 53, 52, 50
50 EFLOX = EFLOX + SIGNF(DFLOX, DUM)
   DPOLD = DUM
   GO TO 54
53 EFLOX = EFLOX - DUM * DFLOX / (DUM - DPOLD)
52 DUM = EFLOX * ARE3 * 2.0
   SUM1 = SUM1 + DUM
   SUM2 = (SUM2 + DUM * ENTH(1)) / SUM1
C   GETTING PRESSURE DROP THRU LOWER AND UPPER END BOXES
   DUM = DENSTY(SUM2)
   DELTP = DELTP + (FKC10 * ((SUM1 / ARE10) ** 2) + FKC11 * ((SUM1 / ARE11)
1 ** 2)) / 8.34E8 * DUM
720 IF (SUM2 - ENTHS) 60, 60, 61
60 DELTP = DELTP + SPFFU((SUM1 / ARE11) * DE12, SUM2) * (SUM1 / ARE11) ** 2 * DUM *
601 FL12 / DE12 / 8.34E8
   GO TO 83
61 Q = (SUM2 - ENTHS) / ENTHFG
   SENSE LIGHT 1
   DELTP = DELTP + (SPFFU((SUM1 / ARE11) * DE12, ENTHS) * (SUM1 / ARE11) ** 2 * DUM *
1 FL12 / DE12 / 8.34E8) * DPRAT(Q) * PHIR(Q, (SUM1 / ARE11))
83 DELTP = DELTP + (FKC13 + FKE13) * (SUM1 / ARE13) ** 2 * DUM / 8.34E8
721 IF (SENSE LIGHT 1) 62, 63
63 DELTP = DELTP + SPFFU((SUM1 / ARE13) * DE13, SUM2) * (SUM1 / ARE13) ** 2 * DUM *
631 FL14 / DE13 / 8.34E8
   GO TO 84
62 DELTP = DELTP + SPFFU((SUM1 / ARE13) * DE13, ENTHS) * (SUM1 / ARE13) ** 2 * DUM *
621 FL14 / DE13 / 8.34E8 * DPRAT(Q) * PHIR(Q, SUM1 / ARE13)
84 DELTP = (DELTP + EMP1 * SUM1 ** EMP2) / 144.0
C   GETTING TOTAL FLOW
   FLOWO = 0.1247 * ((DELTP / EMP01) ** (1.0 / EMP02)) * DENSTI
   SENSE LIGHT 0
C   PRINTING RESULTS AND TEST FOR END OR RETURN TO SAFE FLOW CALC.
   IF (SENSE SWITCH6) 810, 815
810 WRITE OUTPUT TAPE10, 7, FLOWO, POW, LK, DELTP, EFLOR, STO1, SUM1, SUM2
8101 , STO2, STO3
   GO TO 722
815 PRINT 7, FLOWO, POW, LK, DELTP, EFLOR, STO1, SUM1, SUM2, STO2, STO3
722 IF (FLOWO - FLOM) 65, 64, 64
65 ASSIGN 27 TO NSW
27 POW = POW + DPOW
   GO TO 240
64 IF (SENSE SWITCH6) 812, 811
812 WRITE OUTPUT TAPE10, 8
   END FILE 10
   GO TO 100
811 PRINT 8
   GO TO 100
   FREQUENCY 701(20), 702(10), 525(1,0,2), 703(15,0,1), 19(10,0,1), 704(
1 20,1,1), 13(20,0,1), 706(20), 707(2,0,1), 708(2,0,1), 709(20), 710(20),
2 711(2,0,1), 715(2,0,1), 713(1,10), 38(10,0,1), 714(20), 712(20), 716(2,
3 0,1), 717(2,0,1), 718(1,10), 47(10,0,1), 719(1,10), 51(10,0,1), 720(2,
4 0,1), 721(1,10), 722(30,0,1), 526(10)
   END (0,1,0,0,1)

```

XII. APPENDIX III

A. INPUT DATA

550.E0	2500.E0	549.3E0	730.6E0	360.5E0	1091.1E0	INPUT1
0.0218E0	0.0287E0	.13070E0				INPUT1
19	3.0E0	.16666667E0	5.0E0	5.0E0	0.1E5	INPUT2
.015	+5	25000. +0	.01275 +0	.01067		INPUT2
1.82E0	.283E4	.337E4	.441E4	.540E4	.590E4	INPUT 3
.589E4	.555E4	.503E4	.423E4	.347E4	.273E4	INPUT 3
.200E4	.136E4	.873E3	.553E3	.387E3	.293E3	INPUT 3
.247E3	.207E3					INPUT 3
1.50E0	1.44E0	.145E0	.0192E0	.0400E0	1.030E-3	INPUT 4
30. +0	.12 +0	.0138 +0	.0289 +0	.00147 +0	0.0 +0	INPUT4
.00833 +0	0.0 +0	.000894 +0	-1.465 -10	2.010 +0	.14 +0	INPUT4
.03138 +0	.155 +0	.02462 +0	.1777 +0	.0469 +0	.085 +0	INPUT4
.01917 +0	.1563 +0	.2396 +0	.4 +0	2.84 -13	1.97 +0	INPUT4
13		0	1.0E0	.01E0	1.08E0	DPFNT
.05E0	1.21E0	.10E0	1.39E0	.20E0	1.70E0	DPFNT
.30E0	1.90E0	.40E0	2.20E0	.50E0	2.43E0	DPFNT
.60E0	2.62E0	.70E0	2.83E0	.80E0	2.95E0	DPFNT
.90E0	3.10E0	1.00E0	3.22E0			DPFNT
9	0	.6E6	.7E6	.8E6	1.0E6	ARPHT
1.5E6	2.0E6	5.0E6	1.0E9			ARPHT
12		0	1.00E0	.01E0	1.09E0	PHIT 1
.05E0	1.30E0	.10E0	1.45E0	.20E0	1.62E0	PHIT 1
.30E0	1.77E0	.40E0	1.87E0	.50E0	1.96E0	PHIT 1
.60E0	2.04E0	.70E0	2.11E0	.80E0	2.17E0	PHIT 1
1.00E0	2.30E0					PHIT 1
12		0	1.00E0	.01E0	1.09E0	PHIT 2
.05E0	1.30E0	.10E0	1.45E0	.20E0	1.62E0	PHIT 2
.30E0	1.77E0	.40E0	1.87E0	.50E0	1.96E0	PHIT 2
.60E0	2.04E0	.70E0	2.11E0	.80E0	2.17E0	PHIT 2
1.00E0	2.30E0					PHIT 2
12		0	1.00E0	.01E0	1.07E0	PHIT 3

.05E0	1.19E0	.10E0	1.28E0	.20E0	1.39E0PHIT 3
.30E0	1.45E0	.40E0	1.52E0	.50E0	1.57E0PHIT 3
.60E0	1.60E0	.70E0	1.64E0	.80E0	1.68E0PHIT 3
1.00E0	1.75E0				PHIT 3
12		0	1.00E0	.01E0	1.03E0PHIT 4
.05E0	1.08E0	.10E0	1.16E0	.20E0	1.22E0PHIT 4
.30E0	1.27E0	.40E0	1.29E0	.50E0	1.32E0PHIT 4
.60E0	1.33E0	.70E0	1.35E0	.80E0	1.37E0PHIT 4
1.00E0	1.40E0				PHIT 4
2		0	1.00E0	1.00E0	1.00E0PHIT 5
12		0	1.00E0	.01E0	.97E0PHIT 6
.05E0	.86E0	.10E0	.80E0	.20E0	.74E0PHIT 6
.30E0	.70E0	.40E0	.67E0	.50E0	.64E0PHIT 6
.60E0	.62E0	.70E0	.60E0	.80E0	.58E0PHIT 6
1.00E0	.55E0				PHIT 6
12		0	1.00E0	.01E0	.93E0PHIT 7
.05E0	.80E0	.10E0	.72E0	.20E0	.63E0PHIT 7
.30E0	.57E0	.40E0	.53E0	.50E0	.50E0PHIT 7
.60E0	.48E0	.70E0	.46E0	.80E0	.44E0PHIT 7
1.00E0	.41E0				PHIT 7
12		0	1.00E0	.01E0	.91E0PHIT 8
.05E0	.71E0	.10E0	.59E0	.20E0	.47E0PHIT 8
.30E0	.41E0	.40E0	.36E0	.50E0	.33E0PHIT 8
.60E0	.31E0	.70E0	.29E0	.80E0	.27E0PHIT 8
1.00E0	.25E0				PHIT 8
12		0	1.00E0	.01E0	.91E0PHIT 9
.05E0	.71E0	.10E0	.59E0	.20E0	.47E0PHIT 9
.30E0	.41E0	.40E0	.36E0	.50E0	.33E0PHIT 9
.60E0	.31E0	.70E0	.29E0	.80E0	.27E0PHIT 9
1.00E0	.25E0				PHIT 9
13				.01E0	.0021E0RMULTT
.05E0	.0064E0	.10E0	.0100E0	.20E0	.0170E0RMULTT
.30E0	.0250E0	.40E0	.0340E0	.50E0	.0440E0RMULTT
.60E0	.0560E0	.70E0	.0640E0	.80E0	.0780E0RMULTT
.90E0	.0920E0	1.00E0	.1020E0		RMULTT

18		487.8E0	.262E0	499.8E0	.257E0RHNOT
511.9E0	.251E0	524.1E0	.246E0	536.6E0	.241E0RHNOT
549.3E0	.237E0	562.2E0	.233E0	573.4E0	.228E0RHNOT
588.9E0	.224E0	602.8E0	.219E0	617.0E0	.215E0RHNOT
631.6E0	.210E0	646.7E0	.205E0	662.3E0	.199E0RHNOT
678.6E0	.193E0	695.7E0	.185E0	714.2E0	.177E0RHNOT
734.4E0	.171E0				RHNOT
17		3.0E3	.0430E0	5.0E3	.0370E0SPFFT
7.0E3	.0340E0	1.0E4	.0310E0	2.0E4	.0263E0SPFFT
3.0E4	.0241E0	5.0E4	.0220E0	7.0E4	.0207E0SPFFT
1.0E5	.0196E0	2.0E5	.0178E0	3.0E5	.0170E0SPFFT
5.0E5	.0162E0	7.0E5	.0159E0	1.0E6	.0156E0SPFFT
2.0E6	.0152E0	3.0E6	.0150E0	1.0E8	.0150E0SPFFT
20		3.0E3	.0430E0	7.0E3	.0330E0SPFFUT
1.0E4	.0305E0	2.0E4	.0257E0	3.0E4	.0232E0SPFFUT
5.0E4	.0205E0	7.0E4	.0192E0	1.0E5	.0178E0SPFFUT
2.0E5	.0155E0	3.0E5	.0141E0	5.0E5	.0133E0SPFFUT
7.0E5	.0127E0	1.0E6	.0121E0	2.0E6	.0110E0SPFFUT
3.0E6	.0106E0	5.0E6	.0100E0	7.0E6	.0098E0SPFFUT
1.0E7	.0095E0	7.0E7	.0090E0	1.0E8	.0090E0SPFFUT
18		487.8E0	.0204E0	499.8E0	.0207E0DENSTT
511.9E0	.0209E0	524.1E0	.0212E0	536.6E0	.0215E0DENSTT
549.3E0	.0218E0	562.2E0	.0221E0	575.3E0	.0224E0DENSTT
588.9E0	.0228E0	602.8E0	.0232E0	617.0E0	.0236E0DENSTT
631.6E0	.0241E0	646.7E0	.0247E0	662.3E0	.0253E0DENSTT
678.6E0	.0260E0	695.7E0	.0268E0	714.2E0	.0278E0DENSTT
734.4E0	.0290E0				DENSTT

B. OUTPUT DATA

PROGRAM TO SET OPERATING LIMITS FOR SPERT III IN REGARD TO BURNOUT. INCLUDES TWO-PHASE FLOW

Temp. = 550.0°F
 Press. = 2500.0 psi
 Initial Power = 5.00 Mw
 Power Increment = 5.0 Mw

Initial Mass Flow = 1.000 E 04 lb/hr-sq ft
 Mass Flow Increment = 1.500 E 03 lb/hr-sq ft
 Max. Flow = 25000.00 gpm

The following are the operating limits of the reactor. Decrease in flow by the flow increment will cause burnout.

Flow (gpm)	Power (Mw)	Hot Spot Mesh Pt	Press Drop (psi)	Hot Chan. Flow (lb/hr-sq ft)	Hot Chan. Enth. (Btu/lb)	Elmt. Flow (lb/hr)	Exit Enth. (Btu/lb)	N.C. Enth. (Btu/lb)	E.C. Enth. (Btu/lb)
741.	5.0	19	0.014	3.400E 04	1078.2	3.383E 03	662.6	666.8	656.4
2080.	15.0	10	0.111	1.000E 05	1088.8	1.019E 04	664.6	669.2	655.5
3387.	25.0	9	0.289	1.660E 05	1090.9	1.695E 04	664.9	669.7	655.6
4050.	30.0	8	0.412	2.020E 05	1083.4	2.042E 04	663.5	668.0	655.3
4916.	35.0	8	0.603	2.800E 05	998.9	2.513E 04	656.0	660.3	648.5
5804.	40.0	8	0.836	3.745E 05	933.4	2.984E 04	652.0	656.0	647.3
6616.	45.0	8	1.082	4.945E 05	876.6	3.418E 04	649.6	653.2	643.4
7244.	50.0	8	1.294	6.460E 05	827.7	3.753E 04	654.3	658.5	642.5
7544.	55.0	8	1.401	8.365E 05	785.8	3.883E 04	658.1	661.9	653.0
8225.	60.0	7	1.662	1.096E 06	746.2	4.253E 04	655.2	658.7	647.5
9839.	65.0	7	2.365	1.468E 06	708.5	5.142E 04	642.7	645.8	639.3
11934.	70.0	7	3.459	1.813E 06	688.2	6.314E 04	630.8	633.5	628.3
13548.	75.0	7	4.506	2.093E 06	678.1	7.281E 04	624.9	627.4	622.8
15416.	80.0	7	5.728	2.330E 06	670.2	8.273E 04	620.3	622.6	618.3
17198.	85.0	7	7.106	2.659E 06	663.8	9.262E 04	616.5	618.7	614.8
18994.	90.0	7	8.541	2.952E 06	658.6	1.026E 05	613.5	615.5	611.9
20777.	95.0	7	10.312	3.253E 06	654.3	1.126E 05	611.0	613.0	609.5
22564.	100.0	7	12.132	3.542E 06	650.8	1.225E 05	609.0	610.8	607.5
24339.	105.0	7	14.083	3.830E 06	647.9	1.323E 05	607.3	609.0	605.9
26105.	110.0	7	16.167	4.117E 06	645.4	1.420E 05	605.8	607.5	604.5

Maximum Flow has been exceeded. End of Calculations for one set of Input Data.