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SN5001—AN IBM-650 CODE FOR STEADY-STATE THERMAL EVALUATION OF AN INSTRUMENTED MULTI-FUEL-PLATE SUBASSEMBLY

APRIL 1960

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BETTIS ATOMIC POWER LABORATORY, PITTSBURGH, PA.,
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E. Arbtin and R. B. Westphal

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This report describes an IBM-650 computer program, SN5001, for the calculation of steady-state thermal conditions in the fuel plates and coolant of an instrumented multi-fuel-plate subassembly. The program is applicable for subcooled or bulk boiling coolant conditions and surface conditions of heating, local boiling, and film boiling, and can be used for data reduction or design. The report includes the derivation and a list of the heat conduction and coolant enthalpy equations and a description of the code sufficient for its use.

SN5001 — AN IBM-650 CODE FOR STEADY-STATE THERMAL EVALUATION OF AN INSTRUMENTED MULTI-FUEL-PLATE SUBASSEMBLY

E. Arbtin* and R. B. Westphal*

I. INTRODUCTION

An IBM-650 code has been written to perform steady-state thermal analyses of an instrumented multi-fuel-plate subassembly. The code can be used to analyze test data or predict thermal conditions in subassemblies in the design stage.

The code was written for the purpose of obtaining accurate steady-state fuel-plate temperatures, heat fluxes, coolant thermal conditions, and the normalized axial neutron distribution in the subassemblies from in-pile data. The heat split that occurs in the fuel plates, and the unequal heat fluxes on each side of a coolant channel (resulting from unequal fuel-plate loadings and coolant temperatures in the channels adjacent to the fuel plates) preclude an accurate, simple hand analysis and necessitate a digital computer analysis. The steady-state conditions described by the code include subcooled and bulk boiling coolant conditions, and heating, local boiling, and film boiling surface conditions. Subroutines were written to calculate surface temperatures for film boiling and for use in subassembly design using the axial neutron shape as input data instead of center plate measured temperatures.

*Naval Reactors Facility, Idaho Falls, Idaho.

The subassembly analyzed is a three-fuel-plate, four-coolant channel core subdivision, designed for insertion in a water-moderated and water-cooled, pressurized, nuclear power reactor (see Fig. 1). The two end (outside) fuel plates are clad with non-fuel-bearing material. The center fuel plate is composed of two externally-clad heat generating sections, separated by a non-generating section in which thermocouples are imbedded.

Typical operating times have varied from approximately 15 to 20 minutes for non-boiling runs to runs with local boiling, for a 20-slab problem solving for either the axial neutron flux shape or the middle plates center temperature.

II. CALCULATIONAL PROCEDURE

A. Terminology and Assumptions

Definitions and Symbols

A_{F_u} is the average cross-section area of the flow channel (ft^2).

A_s is the heat transfer area (ft^2).

BOLC is the code word that describes the heat transfer conditions on each surface.

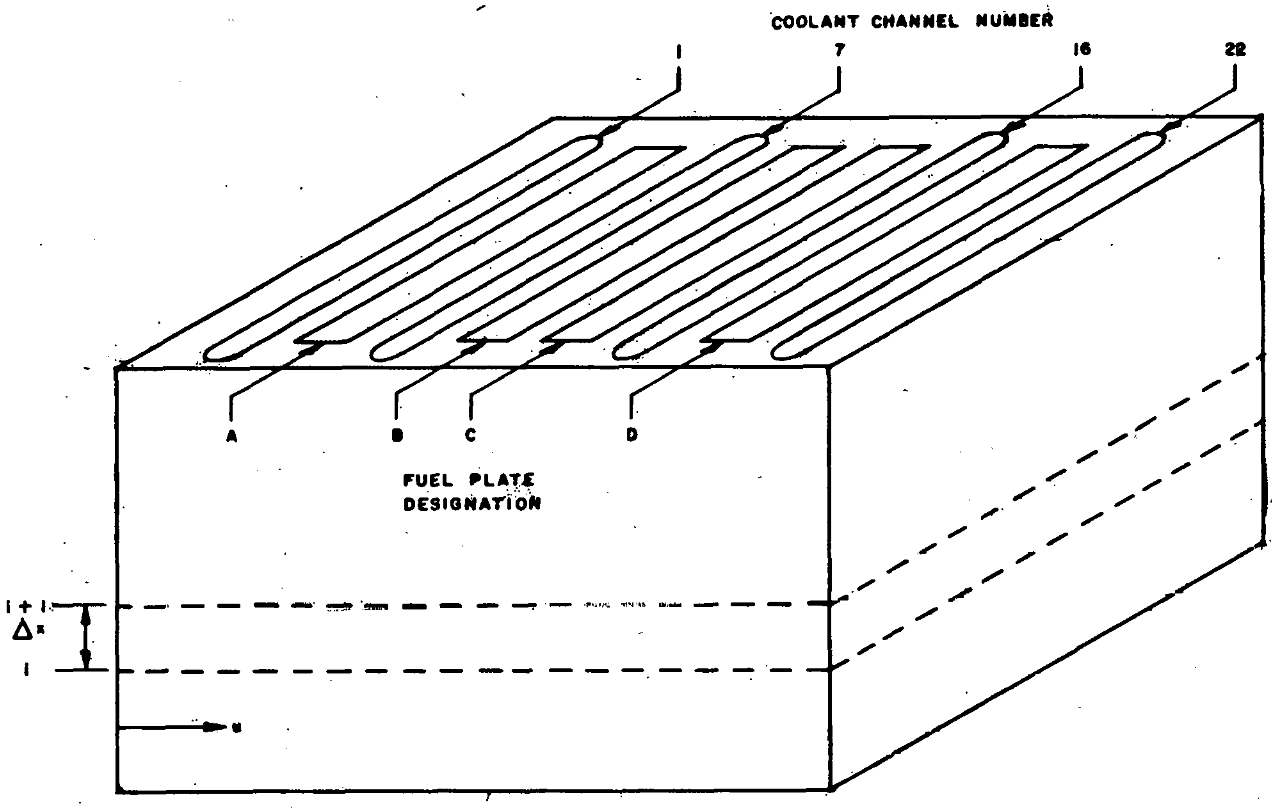

Fig. 1 Axial Section of Typical Instrumented Multifuel Subassembly.

D_e is the coolant channel equivalent diameter (ft).

F_{A_i} is the axial neutron flux factor in a given slab and is defined as the ratio of the average axial neutron flux in a given slab to the average axial neutron flux over the length of the subassembly meat (dimensionless).

F_{L_u} is the loading factor in a given slab and fuel plate, defined as the ratio of the local fuel density divided by the subassembly average fuel density (dimensionless).

F_{R_u} is the radial neutron flux factor and is defined as the ratio of the average radial neutron flux at each of the fuel locations to the average radial neutron flux in the entire subassembly (dimensionless).

G_u is the coolant mass velocity (lb/hr-ft^2).

H is enthalpy of the bulk coolant (Btu/lb).

L is the total fuel length of the subassembly (ft).

N is the number of slabs.

P is the coolant channel power output (Btu/hr).

Q is the total heat rate (Btu/hr) of the subassembly.

T is the temperature (°F).

T* is the local boiling or film boiling surface temperature (°F).

$\overline{T}$ is the average coolant temperature in a slab channel (°F).

T_s is the local boiling surface temperature used in the code test: 0.02°F.

X is the location of the zero temperature gradient in a fuel section measured from the left-hand edge of the fuel (ft).

V_m is the total volume of the fuel (ft^3).

a, b, c, d, e, f, g, j, l, m, n, and r are fuel and clad dimensions (ft). (See Fig. 2.)

a_1 is the constant in the Dittus-Boelter coefficient of heat transfer formula.

c_p is the specific heat of the coolant at constant pressure (Btu/lb-°F).

h is the coefficient of heat transfer (Btu/hr-ft^2-°F).

k is the thermal conductivity of the clad and fuel material (Btu/hr-ft^2-°F-ft).

q is heat flux (Btu/hr-ft^2).

$\bar{q}'''$ is the average heat generation rate in the subassembly (Btu/hr-ft^2).

q'''_{iu} is the uniform heat generation rate in the u'th fuel section in the i'th slab (Btu/hr-ft^3).

t is the thickness dimension (ft).

w is the width dimension (ft).

H_u is the difference in enthalpy of the outlet and inlet coolant of a given channel (Btu/lb).

x is the slab height (ft).

μ is the absolute viscosity of the coolant (lb/hr-ft).

λ is the grouping of water properties used in the Dittus-Boelter equation (Btu/°F)$(1/lb)^{0.8}$ $(1/ft\text{-}hr)^{0.4}$.

ϵ is a tolerance placed on the location of the maximum temperature in fuel section B or C (ft). Used in code as 1×10^{-7} ft.

Subscripts

A, B, C, and D designate the four fuel plates, respectively (see Fig.2).

c designates the coolant channel.

I designates the inlet.

i designates a particular slab.

m designates the fuel.

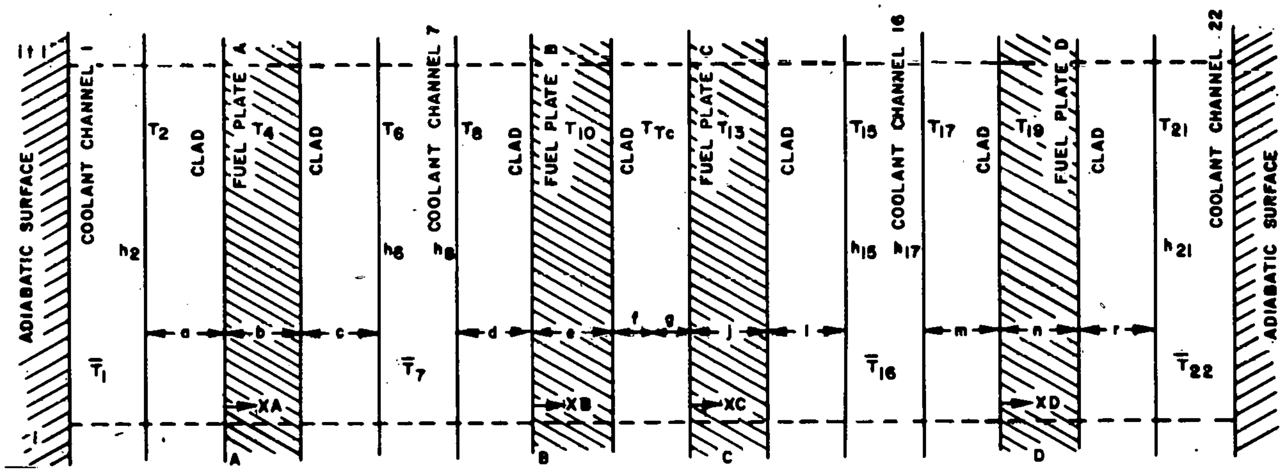

Fig. 2 Side View of Subassembly Showing Nomenclature

O designates the outlet.

tc designates the center fuel-plate thermocouple temperature (see Fig. 2).

u designates a particular coolant channel or fuel section in a slab.

Arabic numerals refer to locations in the subassembly (see Fig. 2).

<u>Assumptions Used</u>

The following assumptions were used in derving the heat conduction and coolant enthalpy equations and the methods of solution:

1) Only one-dimensional heat flow, perpendicular to the heat transfer surface, can occur.

2) Uniform heat generation rate, q'''_{iu} in Btu/hr-ft^3, within each given fuel section of a given slab.

3) All of the heat output of the subassembly is generated in the fuel sections. This assumption specifies that there is no heat generation in clad material or water.

4) The subassembly boundaries are adiabatic.

5) The axial neutron flux factor F_{A_i} is dependent on axial location and independent of radial location in the subassembly.

6) The radial neutron flux factor F_{R_u} is a constant for a given fuel plate.

7) The local boiling surface temperature is a constant and holds until departure from nucleate boiling (DNB) occurs, and is independent of coolant quality and pressure. It is found by the Jens-Lottes formula (Ref 1).

8) The Dittus-Boelter heat transfer film coefficient formula is correct in the subcooled nonboiling region, and is constant over small temperature changes.

Thus,

$$h = a_1 \left(\frac{D_e G}{u}\right)^{0.8} \left(\frac{c_p u}{k}\right)^{0.4} \frac{k}{D_e},$$

and

$$h = a_1 \; G^{0.8} \; D_e^{\;0.2} \lambda,$$

where $\lambda = k^{0.6} \left(\frac{c_p}{u}\right)^{0.4}$.

9) The thermal conductivities of clad and fuel materials are equal and independent of temperature.

10) The specific heat of water is constant over small temperature changes.

11) The split fuel sections of the center fuel plate are the same width at any axial location.

12) The average volumetric heat generation rate is the summation of the product of coolant enthalpy rise in the channels, the coolant mass flowrate, and the channel flow area divided by the total volume of the heat generation material. Thus,

$$\bar{q}''' = \frac{1}{V_m} \text{ channel} \sum_{1}^{4} H_u \, G_u \, A_{F_u}.$$

13) The local volumetric heat generation rate is the product of the average volumetric heat generation rate, the loading factor, and the axial and radial neutron flux factors. Thus,

$$q'''_{iu} = \bar{q}''' \; F_{L_{iu}} \; F_{A_i} \; F_{R_u}.$$

B. <u>General Method</u>

The axial length of the subassembly is divided into not more than 99 slabs of equal or unequal length for calculational purposes. Calculations proceed from the inlet slab consecutively to the exit slab.

A set of equations (Sections III and IV) has been derived that completely describes the heat generation, heat transfer, and average bulk coolant conditions in a slab of the subassembly (i to i + 1 in Figs. 1 and 2). These equations are written as a function of the dimensions, fuel-plate volumetric heat generation rate, coolant channel mass velocities, the thick plate center temperature, and individual plate boundary conditions, i.e., water temperature and film coefficient or surface temperature. The equations were programmed to allow the most flexible use of the code. The calculation is made by solving the set of four simultaneous equations, that describe the thermal conditions in the coolant channels and fuel plates in a given slab, for the proper boundary conditions. Then, the next slab is indexed, using as inlet coolant conditions the exit conditions of the previous slab.

The method of calculation, as coded, permits the evaluation of either the normalized axial neutron flux factor F_A or the center-plate center temperature T_{tc} for each slab, by finding the solution to the set of simultaneous equations.

It is considered necessary and advantageous in analyzing test data to solve for an axial neutron flux shape F_A for each test run, because neutron flux measurements are generally not made for all test runs, and because the flux measuring locations are such that they do not "see" all of the neutron depression in fuel plate sections that contain higher fuel loadings.

C. Calculational Procedure for a Slab when Coolant Is Subcooled or Bulk Boiling and the Heat Transfer Surfaces Are in the Heating or Local Boiling Region

Determination of F_{A_i}

The procedure uses as input data: values of the constant a_1 in the Dittus-Boelter equation, thermocouple temperature T_{tc}, F_R values for each fuel plate, thermal conductivity, mass velocities in each channel, and the average subassembly heat generation rate.

The F_{A_i} in each slab is determined by the following procedure:

1) Assuming nonboiling conditions on all heat transfer surfaces, calculate the location (X_u's) of the maximum temperatures in each fuel plate [Eqs (1a)* and (13a) for the outside fuel plates, A and D, and Eqs (5a) and (7a) for the center fuel plate, assuming the maximum temperature of the center plate is in the B fuel section].

2) Check the location of the maximum temperature in the center plate to see if it agrees with the assumptions.

3) If step 2 does not agree with step 1, then repeat step 1, using Eqs (9a) and (11a) in place of Eqs (5a) and (7a), assuming the maximum temperature of the center plate is in the C fuel section with no local boiling. (See Section III-C.) If surfaces are undergoing local boiling, use the appropriate equations.

4) If step 2 does agree with step 1, go to step 5.

5) Compare all heat transfer surface temperatures with the local boiling surface temperature. (For ease in calculations, an average local boiling surface temperature according to coolant pressure is used for comparison.)

*See Sections III and IV for the listing of equations.

6) If step 5 indicates that all of the heat transfer surface temperatures are below the local boiling surface temperature, calculate and store the items listed in step 15 for that slab and repeat step 1 for the next slab.

7) If step 5 indicates that one or more heat transfer surfaces are local boiling, solve for the X_u's, using the appropriate boundary condition equations of Section III-C.

8) Repeat steps 2 through 5, as applicable.

9) If step 5 indicates that no additional heat transfer surfaces are local boiling, compute and store the items listed in step 15, and repeat step 1 for the next slab.

10) If step 5 indicates that additional heat transfer surfaces are local boiling, solve for the X_u's, using the appropriate boundary condition equations.

11) Repeat step 8.

12) Repeat step 9, if appropriate.

13) Repeat step 10, if appropriate.

14) When the computation for all slabs has been completed, as determined by comparing the slab number to the total number of slabs in the subassembly, compute $F_{A_{ave}}$ for the subassembly.

15) The following information for each slab will be recorded for further use (determination of departure from nucleate boiling heat flux, pressure drop, etc.): the location of the maximum temperature in each fuel plate, average and exit coolant temperature and enthalpy in each channel, fuel plate surface temperatures, and average heat flux on each heat transfer surface.

Determination of T_{tc_i}

The procedure is to solve for the slab conditions listed in steps 14 and 15 above by the method outlined in steps 1 to 13, using F_{A_i} as input to the code instead of T_{tc_i}, in addition to the other inputs listed.

D. Calculational Procedure for a Slab When One Heat Transfer Surface of the Center Plate Is Film Boiling

The film boiling heat transfer surface temperature $T^*_{8_i}$ on the left-hand surface of the center fuel plate (T_8 of Fig. 2) is found by solving the two equations (6a) and (8a), or (10a) and (12a) that describe the center plate simultaneously (see Section III-C). This calculation can be made for any slab in which film boiling is known or suspected. A special routine is required for this calculation. (See Section VI-D.)

F_{A_i} must be known for this calculation, in addition to the other input values listed in Section II-C. The opposite surface (T_{15} of Fig. 2) is assumed to be undergoing local boiling.

The procedure for calculating F_{A_i} (see Section II-C) is used up to the slab in which film boiling is known or suspected; then a separate routine is used to solve for $T^*_{8_i}$ for that slab upon coded signal. Succeeding slabs may or may not use the procedure for film boiling surface temperature calculation.

III. DERIVATION AND LIST OF HEAT CONDUCTION EQUATIONS

Equations were developed for each of the four fuel plates (A, B, C, and D of Figs. 1 and 2) that determined the location of the maximum temperatures in a fuel plate as a function of known or assumed conditions, i.e., water temperature and film coefficient or surface temperature, and the heat generation rate. For the center split-meat plate, an additional boundary condition — the plate center temperature, was used.

The one-dimensional Poisson equation, $\frac{d^2T}{dx^2} = -\frac{q'''}{k}$, was used in calculating the temperature distribution across the heat generating material (meat); and the LaPlace equation, $\frac{d^2T}{dx^2} = 0$, was used in calculating the temperature distribution across the non-heat generating material (clad). (See Ref 3.)

Because of the similarity of the equations, only two sample derivations are presented, one for the two end plates and one for the center split-meat plate. The dimensional symbols and numbering scheme used in the derivations are shown in Fig. 2.

A. Sample Heat Conduction Equations for the End Plates (A or D).

For the boundary conditions T_1 and T_6^* at the local boiling temperature), the equations from the maximum metal temperature T_4 to T_1 and T_6^* are

$$T_4 - \overline{T}_1 = \frac{q_A''' X_A^2}{2k} + \frac{q_A''' X_A a}{k} + \frac{q_A''' X_A}{h_2}$$

and

$$T_4 - T_6^* = \frac{q_A''' (b-X_A)^2}{2k} + \frac{q_A''' (b-X_A)c}{k} .$$

By solving each equation for T_4 and then setting the resultant equations equal to each other, the location of the maximum metal temperature X_A is found to be

$$X_A = \frac{T_6^* - \overline{T}_1}{q_A''' \left(\frac{a+b+c}{k} + \frac{1}{h_2}\right)} + \frac{\frac{(b^2 + 2\,bc)}{2k}}{\left(\frac{a+b+c}{k} + \frac{1}{h_2}\right)} \quad (3a)^\dagger$$

† The equation numbers given are from the Tabulation of Heat Conduction Equations, Section III-C.

Then, temperatures and plate surface heat fluxes can be found as a function of q_A''', the boundary conditions, and X_A as follows:

$$T_2 = \frac{q_A''' X_A}{h_2} + \overline{T}_1 \quad (3b)$$

$$T_4 = \frac{q_A''' X_A^2}{2k} + \frac{q_A''' X_A a}{k} + T_2 \quad (3d)$$

$$q_2 = q_A''' X_A \quad (3e)$$

$$q_6 = q_A''' (b - X_A) \quad (3f)$$

The method of derivation for the A and D fuel plates is similar; only the letter and number designations are different. Equations (1) through (4) in Section III-C of this report completely describe all of the possible boundary conditions for fuel plates A and D.

B. Sample Heat Conduction Equation for the Center Fuel Plate

The equations derived for the center fuel plate utilize the three boundary conditions: coolant temperature and film coefficient — or surface temperature on each side of the plate, and the plate center temperature T_{tc}. Separate sets of equations, Eqs (5) through (8) and Eqs (9) through (12), are derived for the two possible locations of the maximum metal temperatures, plate B or C, respectively. The procedure will be to assume that the maximum metal temperature is in one fuel section (assume B) and then solve for X_B, the location of the maximum temperature. If the solution for X_B is in an impossible location $(0 < X_B < e)$, then the set of equations for the maximum metal temperature location in the other fuel section (C) will be used for that slab calculation.

One example for the boundary conditions of $\overline{T}_7$, h_8, T_{tc}, and T_{15}^* (Fig. 2) and the assumed location of the maximum metal temperature, T_{10}, in plate B is given. The heat transfer equations are

$$T_{10} - \overline{T}_7 = \frac{q_B''' X_B^2}{2k} + \frac{q_B''' X_B^d}{k} + \frac{q_B''' X_B}{h_8}$$

$$T_{10} - T_{tc} = \frac{q_B''' (e-X_B)^2}{2k} + \frac{q_B''' (e-X_B)f}{k} .$$

Solving each equation for T_{10} and setting the resultant equations equal to each other, the location of the maximum metal temperature is found in terms of $\overline{T}_{tc}$, T_7, and q_B'''. Thus,

$$X_B = \frac{T_{tc} - \overline{T}_7}{q_B''' \left(\frac{d+e+f}{k} + \frac{1}{h_8}\right)} + \frac{\left(\frac{e^2}{2k} + \frac{ef}{k}\right)}{\left(\frac{d+e+f}{k} + \frac{1}{h_8}\right)} . \quad (5a)$$

Solving from T_{tc} to T_{15} gives

$$T_{tc} - T_{15}^* = q_B''' \frac{(e-X_B)(g+j+1)}{k} + \frac{q_c''' j^2}{2k} + \frac{q_c''' jl}{k}$$

and

$$X_B = - \frac{T_{tc} - T_{15}^*}{q_B''' \left(\frac{g+j+1}{k}\right)} + \frac{q_c''' j \left(\frac{j+21}{2k}\right)}{q_B''' \left(\frac{g+j+1}{k}\right)} + e. \quad (8a)$$

Then, temperatures and plate surface heat fluxes can be found as a function of the heat generation rates, the boundary conditions, and X_B as follows:

$$T_8 = \frac{q_B''' X_B}{h_8} + \overline{T}_7 \quad (8b)$$

$$T_{10} = \frac{q_B''' X_B^2}{2k} + \frac{q_B''' X_B d}{k} + T_8 \quad (8c)$$

$$q_8 = q_B''' X_B \quad (8e)$$

$$q_{15} = q_B''' (e-X_B) + q_c''' j \quad (8f)$$

Equations (5) to (12) of Section III-C completely describe all possible boundary conditions for the center fuel plate.

C. Tabulation of Heat Conduction Equations

T_2 and T_6 in Forced Convection[†]

$$X_A = \frac{\overline{T}_7 - \overline{T}_1}{q_A''' \left(\frac{a+b+c}{k} + \frac{1}{h_2} + \frac{1}{h_6}\right)} + \frac{1}{\left(\frac{a+b+c}{k} + \frac{1}{h_2} + \frac{1}{h_6}\right)} \left(\frac{b^2 + 2bc}{2k} + \frac{b}{h_6}\right) \quad (1a)$$

$$T_2 = \frac{q_A''' X_A}{h_2} + \overline{T}_1 \quad (1b)$$

$$T_6 = \frac{q_A''' (b-X_A)}{h_6} + \overline{T}_7 \quad (1c)$$

$$T_4 = \left(\frac{q_A'''}{2k}\right) X_A^2 + \left(\frac{q_A'''}{k}\right) X_A a + T_2 \quad (1d)$$

$$q_2 = q_A''' X_A \quad (1e)$$

$$q_6 = q_A''' (b - X_A) \quad (1f)$$

T_2 in Nucleate Boiling and T_6 in Forced Convection

$$X_A = \frac{\overline{T}_7 - T_2^*}{q_A''' \left(\frac{a+b+c}{k} + \frac{1}{h_6}\right)} + \frac{1}{\left(\frac{a+b+c}{k} + \frac{1}{h_6}\right)} \left(\frac{b^2 + 2bc}{2k} + \frac{b}{h_6}\right) \quad (2a)$$

$$T_2 = T_2^* \quad (2b)$$

$$T_6 = \frac{q_A''' (b-X_A)}{h_6} + \overline{T}_7 \quad (2c)$$

$$T_4 = \frac{q_A'''}{2k} X_A^2 + \left(\frac{q_A'''}{k}\right) X_A a + T_2 \quad (2d)$$

† See Fig. 2

$$q_2 = q_A''' X_A \quad (2e)$$

$$q_6 = q_A''' (b - X_A) \quad (2f)$$

T_2 in Forced Convection and T_6 in Nucleate Boiling

$$X_A = \frac{T_6^* - \overline{T}_1}{q_A'''\left(\frac{a+b+c}{k} + \frac{1}{h_2}\right)} + \frac{1}{\left(\frac{a+b+c}{k} + \frac{1}{h_2}\right)}\left(\frac{b^2 + 2bc}{2k}\right) \quad (3a)$$

$$T_2 = \frac{q_A''' X_A}{h_2} + \overline{T}_1 \quad (3b)$$

$$T_6 = T_6^* \quad (3c)$$

$$T_4 = \left(\frac{q_A'''}{2k}\right) X_A^2 + \left(\frac{q_A'''}{k}\right) X_A a + T_2 \quad (3d)$$

$$q_2 = q_A''' X_A \quad (3e)$$

$$q_6 = q_A''' (b - X_A) \quad (3f)$$

T_2 and T_6 in Nucleate Boiling

$$X_A = \frac{T_6^* - T_2^*}{q_A'''\left(\frac{a+b+c}{k}\right)} + \frac{1}{\left(\frac{a+b+c}{k}\right)}\left(\frac{b^2 + 2bc}{2k}\right) \quad (4a)$$

$$T_2 = T_2^* \quad (4b)$$

$$T_6 = T_6^* \quad (4c)$$

$$T_4 = \left(\frac{q_A'''}{2k}\right) X_A^2 + \left(\frac{q_A'''}{k}\right) X_A a + T_2 \quad (4d)$$

$$q_2 = q_A''' X_A \quad (4e)$$

$$q_6 = q_A''' (b - X_A) \quad (4f)$$

T_8 in Forced Convection (Hot Spot in B)

$$X_B = \frac{T_{tc} - \overline{T}_7}{q_B'''\left(\frac{d+e+f}{k} + \frac{1}{h_8}\right)} + \frac{1}{\left(\frac{d+e+f}{k} + \frac{1}{h_8}\right)}\left(\frac{e^2}{2k} + \frac{ef}{k}\right), \quad (5a)$$

where $0 < X_B \leq e$

$$T_8 = \frac{q_B''' X_B}{h_8} + \overline{T}_7 \quad (5b)$$

$$T_{10} = \left(\frac{q_B'''}{2k}\right) X_B^2 + \left(\frac{q_B'''}{k}\right) X_B^d + T_8 \quad (5c)$$

$$q_8 = q_B''' X_B \quad (5e)$$

$$q_{15} = q_B''' (e - X_B) + q_C''' j \quad (5f)$$

T_8 in Nucleate Boiling (Hot Spot in B)

$$X_B = \frac{T_{tc} - T_8^*}{q_B'''\left(\frac{d+e+f}{k}\right)} + \frac{1}{\left(\frac{d+e+f}{k}\right)}\left(\frac{e^2}{2k} + \frac{ef}{k}\right), \quad (6a)$$

where $0 < X_B \leq e$

$$T_8 = T_8^* \quad (6b)$$

$$T_{10} = \left(\frac{q_B'''}{2k}\right) X_B^2 + \left(\frac{q_B'''}{k}\right) X_B^d + T_8 \quad (6c)$$

$$q_8 = q_B''' X_B \quad (6d)$$

$$q_{15} = q_B''' (e - X_B) + q_C''' j \quad (6e)$$

T_{15} in Forced Convection (Hot Spot in B)

$$X_B = \frac{T_{tc} - \overline{T}_{16}}{q_B'''\left(\frac{g+j+\ell}{k} + \frac{1}{h_{15}}\right)} + \frac{1}{q_B'''\left(\frac{g+j+\ell}{k} + \frac{1}{h_{15}}\right)} \cdot \left[q_C''' j\left(\frac{j+2\ell}{2k} + \frac{1}{h_{15}}\right)\right] + e, \quad (7a)$$

where $0 < X_b \leq e$

$$T_{15} = \frac{q_B'''(e - X_B)}{h_{15}} + \frac{q_C''' j}{h_{15}} + \overline{T}_{16} \quad (7b)$$

$$q_8 = q_B''' X_B \quad (7c)$$

$$q_{15} = q_B'''(e - X_B) + q_C''' j \quad (7d)$$

T_{15} in Nucleate Boiling (Hot Spot in B)

$$X_B = \frac{T_{tc} - T_{15}^*}{q_B'''\left(\frac{g+j+\ell}{k}\right)} + \frac{1}{q_B'''\left(\frac{g+j+\ell}{k}\right)}\left[q_C''' j\left(\frac{j+2\ell}{2k}\right)\right] + e, \quad (8a)$$

where $0 < X_B \leq e$

$$T_8 = \frac{q_B''' X_B}{h_8} + \overline{T}_7 \quad (8b)$$

$$T_{10} = \frac{q_B''' X_B^2}{2k} + \frac{q_B''' X_B d}{k} + T_8 \quad (8c)$$

$$T_{15} = T_{15}^* \quad (8d)$$

$$q_8 = q_B''' X_B \quad (8e)$$

$$q_{15} = q_B'''(e - X_B) + q_C''' j \quad (8f)$$

T_{15} in Forced Convection (Hot Spot in C)

$$X_C = \frac{T_{tc} - \overline{T}_{16}}{q_C'''\left(\frac{g+j+\ell}{k} + \frac{1}{h_{15}}\right)} + \frac{\left(\frac{j^2}{2k} + \frac{j\ell}{k} + \frac{j}{h_{15}}\right)}{\left(\frac{g+j+\ell}{k} + \frac{1}{h_{15}}\right)}, \quad (9a)$$

where $0 \leq X_C < j$

$$T_{13} = \frac{q_C'''(j - X_C)^2}{2k} + \frac{q_C'''(j - X_C)\ell}{k} + \frac{q_C'''(j - X_C)}{h_{15}} + \overline{T}_{16} \quad (9b)$$

$$T_{15} = \frac{q_C'''(j - X_C)}{h_{15}} + \overline{T}_{16} \quad (9c)$$

$$q_8 = q_C''' X_C + q_B''' e \quad (9d)$$

$$q_{15} = q_C'''(j - X_C) \quad (9e)$$

T_{15} in Nucleate Boiling (Hot Spot in C)

$$X_C = \frac{T_{tc} - T_{15}^*}{q_C'''\left(\frac{g+j+\ell}{k}\right)} + \frac{\left(\frac{j^2}{2k} + \frac{j\ell}{k}\right)}{\left(\frac{g+j+\ell}{k}\right)}, \quad (10a)$$

where $0 \leq X_C < j$

$$T_{13} = \frac{q_C'''(j - X_C)^2}{2k} + \frac{q_C'''(j - X_C)\ell}{k} + T_{15} \quad (10b)$$

$$T_{15} = T_{15}^* \quad (10c)$$

$$q_8 = q_C''' X_C + q_B''' e \quad (10d)$$

$$q_{15} = q_C'''(j - X_C) \quad (10e)$$

T_8 in Forced Convection (Hot Spot in C)

$$X_C = \frac{\overline{T}_{tc} - \overline{T}_7}{q_C'''\left(\frac{f+e+d}{k} + \frac{1}{h_8}\right)} - \frac{q_B''' e\left(\frac{e+2d}{2k} + \frac{1}{h_8}\right)}{q_C'''\left(\frac{f+e+d}{k} + \frac{1}{h_8}\right)}, \quad (11a)$$

where $0 \leq X_C < j$

$$T_8 = \overline{T}_7 + \frac{q_B''' e}{h_8} + \frac{q_C''' X_C}{h_8} \qquad (11b)$$

$$q_8 = q_C''' X_C + q_B''' e \qquad (11c)$$

$$q_{15} = q_C''' (j - X_C) \qquad (11d)$$

T_8 in Nucleate Boiling (Hot Spot in C)

$$X_C = \frac{T_{tc} - T_8^*}{q_C''' \left(\frac{f+e+d}{k}\right)} - \frac{q_B''' e\left(\frac{e+2d}{2k}\right)}{q_C''' \left(\frac{f+e+d}{k}\right)}, \qquad (12a)$$

where $0 \leq X_C < j$

$$T_8 = T_8^* \qquad (12b)$$

$$q_8 = q_C''' X_C + q_B''' e \qquad (12c)$$

$$q_{15} = q_C''' (j - X_C) \qquad (12d)$$

T_{17} and T_{21} in Forced Convection

$$X_D = \frac{\overline{T}_{22} - \overline{T}_{16}}{q_D'''\left(\frac{m+n+r}{k} + \frac{1}{h_{17}} + \frac{1}{h_{21}}\right)} + \frac{1}{\left(\frac{m+n+r}{k} + \frac{1}{h_{17}} + \frac{1}{h_{21}}\right)}\left(\frac{n^2+2nr}{2k} + \frac{n}{h_{21}}\right) \qquad (13a)$$

$$T_{17} = \frac{q_D''' X_D}{h_{17}} + \overline{T}_{16} \qquad (13b)$$

$$T_{21} = \frac{q_D''' (n-X_D)}{h_{21}} + \overline{T}_{22} \qquad (13c)$$

$$T_{19} = \frac{q_D''' X_D^2}{2k} + \frac{q_D''' X_D m}{k} + T_{17} \qquad (13d)$$

$$q_{17} = q_D''' X_D \qquad (13e)$$

$$q_{21} = q_D''' (n - X_D) \qquad (13f)$$

T_{17} in Nucleate Boiling and T_{21} in Forced convection

$$X_D = \frac{\overline{T}_{22} - T_{17}^*}{q_D'''\left(\frac{m+n+r}{k} + \frac{1}{h_{21}}\right)} + \frac{1}{\left(\frac{m+n+r}{k} + \frac{1}{h_{21}}\right)}\left(\frac{n^2+2nr}{2k} + \frac{n}{h_{21}}\right) \qquad (14a)$$

$$T_{17} = T_{17}^* \qquad (14b)$$

$$T_{21} = \frac{q_D''' (n-X_D)}{h_{21}} + \overline{T}_{22} \qquad (14c)$$

$$T_{19} = \frac{q_D''' X_D^2}{2k} + \frac{q_D''' X_D m}{k} + T_{17} \qquad (14d)$$

$$q_{17} = q_D''' X_D \qquad (14e)$$

$$q_{21} = q_D''' (n - X_D) \qquad (14f)$$

T_{17} in Forced Convection and T_{21} in Nucleate Boiling

$$X_D = \frac{T_{21}^* - \overline{T}_{16}}{q_D'''\left(\frac{m+n+r}{k} + \frac{1}{h_{17}}\right)} \cdot \frac{1}{\left(\frac{m+n+r}{k} + \frac{1}{h_{17}}\right)}\left(\frac{n^2+2nr}{2k}\right) \qquad (15a)$$

$$T_{17} = \frac{q_D''' X_D}{h_{17}} + \overline{T}_{16} \qquad (15b)$$

$$T_{21} = T_{21}^* \qquad (15c)$$

$$T_{19} = \frac{q_D''' X_D^2}{2k} + \frac{q_D''' X_D m}{k} + T_{17} \qquad (15d)$$

$$q_{17} = q_D''' X_D \qquad (15e)$$

$$q_{21} = q_D''' (n - X_D) \qquad (15f)$$

T_{17} and T_{21} in Nucleate Boiling

$$X_D = \frac{T_{21}^* - T_{17}^*}{q_D'''\left(\frac{m+n+r}{k}\right)} + \frac{1}{\left(\frac{m+n+r}{k}\right)}\left(\frac{n^2+2nr}{2k}\right) \qquad (16a)$$

$$T_{17} = T_{17}^* \qquad (16b)$$

$$T_{21} = T_{21}^* \qquad (16c)$$

$$T_{19} = \frac{q_D''' X_D^2}{2k} + \frac{q_D''' X_D m}{k} + T_{17} \qquad (16d)$$

$$q_{17} = q_D''' X_D \qquad (16e)$$

$$q_{21} \quad q_D''' (n - X_D) \qquad (16f)$$

IV. DERIVATION AND LIST OF COOLANT ENTHALPY EQUATIONS

The change in enthalpy of the coolant in a channel and slab is directly proportional to the heat input from the fuel plates and is inversely proportional to the coolant flowrate in the channel. Thus,

$$H_{iu} = \frac{Q_{iu}}{G_u A_{F_{iu}}},$$

where

H_{iu} is the change in enthalpy in a given slab i and channel u.

Q_{iu} is the total heat rate into channel u in slab i and is equal to $\sum q_{iu} A_{S_{iu}}$.

q_{iu} is the heat flux into the channel u in slab i from fuel plate u in slab i.

$A_{S_{iu}}$ is the heat transfer area of fuel plate u in slab i and is equal to $(w_{m_i})\,(x_i)$. (See Fig. 3.)

G_u is the coolant mass velocity in channel u.

$A_{F}iu$ is the coolant flow area in channel u in slab i and is equal to $(w_{c_{iu}})\,(t_{c_{iu}})$. (See Fig. 3.)

Then,
$$H_{iu} = \frac{\sum q_{iu} A_{S_{iu}}}{G_u A_{F_{iu}}}$$

and
$$H_{iu} = \frac{\sum q_{iu}\, w_{m_{iu}}\, \Delta x_i}{G_u\, w_{c_{iu}}\, t_{c_{iu}}}.$$

The enthalpy at the downstream edge of slab i, channel u, is $H_{i+1,u} = \Delta H_{i,u} + H_{i,u}$

or

$$H_{O_{iu}} = \Delta H_{iu} + H_{I_{iu}}.$$

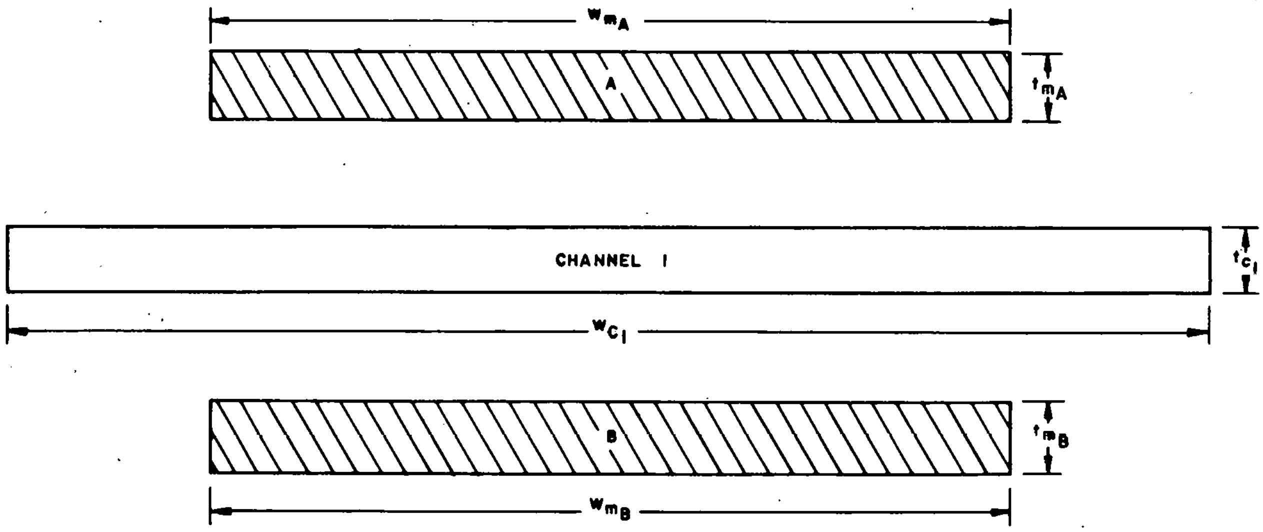

Fig. 3 Partial Top View of Subassembly Showing Channel and Fuel Plate Nomenclature

The average enthalpy in slab i, channel u, is then

$$\bar{H}_{iu} = 0.5\ \Delta H_{iu} + H_{I_{iu}} .$$

It is necessary to have the average enthalpy equations converted to average temperature equations for use with the heat conduction equations in the subcooled region. This is accomplished by dividing the enthalpy rise by the specific heat of water and converting the inlet enthalpy to temperature by formula. Because the specific heat does not vary greatly over small ΔT's, the C_p corresponding to $H_{I_{iu}}$ will be used; therefore,

$$\bar{T}_{iu} = 0.5 \left(\frac{\Delta H_{iu}}{Cp_{iu}} \right) + T_{I_{iu}} .$$

Combining terms,

$$\bar{T}_{iu} = \frac{0.5 \sum q_{iu}\, w_{m_{iu}}\, \Delta x_i}{Cp_{iu}\, G_u\, w_{c_{iu}}\, t_{c_{iu}}} + T_{I_{iu}} .$$

The following equations describe the average water temperature in a given slab i for each channel u as a function of dimensions, water properties, channel mass velocities, and fuel plate heat fluxes.

Channel 1

$$\bar{T}_{i,1} = \frac{0.5\ \Delta x_i\ (q_{i2}\ w_{mi_A})}{C_{pi1}\ G_1\ w_{c_{i1}}\ t_{c_{i1}}} + T_{I_{i,1}} \qquad (17)$$

Channel 7

$$\bar{T}_{i,7} = \frac{0.5\ \Delta x_i\ (q_{i6}\ w_{m_{iA}} + q_{i8}\ w_{m_{iB}})}{C_{p_{i7}}\ G_7\ w_{c_{i7}}\ t_{c_{i7}}} + T_{I_{i,7}} \qquad (18)$$

Channel 16

$$\bar{T}_{i,16} = \frac{0.5\,\Delta x_i\ (q_{i_{15}}\ w_{m_{iC}} + q_{i_{17}}\ w_{m_{iD}})}{C_{p_{i16}}\ G_{16}\ w_{c_{i16}}\ t_{c_{i16}}} + T_{I_{i,16}} \qquad (19)$$

Channel 22

$$\bar{T}_{i,22} = \frac{0.5\,\Delta x_i\ (q_{i21}\ w_{m_{iD}})}{C_{p_{i22}}\ G_{22}\ w_{c_{i22}}\ t_{c_{i22}}} + T_{I_{i,22}} \qquad (20)$$

Note that in Eqs (18) and (19), it is assumed that the widths ($w_{m_{iB}}$ and $w_{m_{iC}}$) are equal.

V. METHOD OF COMBINING THE EQUATIONS

The equations listed in Sections III and IV are reduced to four general equations by substituting the coolant equations of Section IV into the equations of Section III. These substitutions give the following matrix equation for each slab:

$$\begin{vmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S^{41} & S_{42} & S_{43} & S_{44} \end{vmatrix} \times \begin{vmatrix} X_A \\ X_B/C \\ X_D \\ 1/F_A \end{vmatrix} = \begin{vmatrix} S_{15} \\ S_{25} \\ S_{35} \\ S_{45} \end{vmatrix}$$

In this equation, the S constants are functions of dimensions, mass velocities, film coefficients, thermal conductivity, fuel loading factors, radial neutron flux factors, and boundary temperature conditions; and the maximum temperature is located in fuel section B or C in the center fuel plate. The solution is found by the Crout reduction method.

VI. DESCRIPTION OF CODE

The code was developed using IBM-650 Symbolic Optimal Assembly Program (SOAP II) and Soap Interpretive Routine (SIR). The use of the floating point operation was the reason for the use of SIR. Typical operating times have varied from 15 to 20 minutes for nonboiling runs to runs with local boiling for a 20-slab problem, solving for either the F_A's or T_{tc}'s. The machine shows a "9" stop when the final slab is processed and the subassembly computations are completed. A simplified flow chart is presented in Fig. 4.

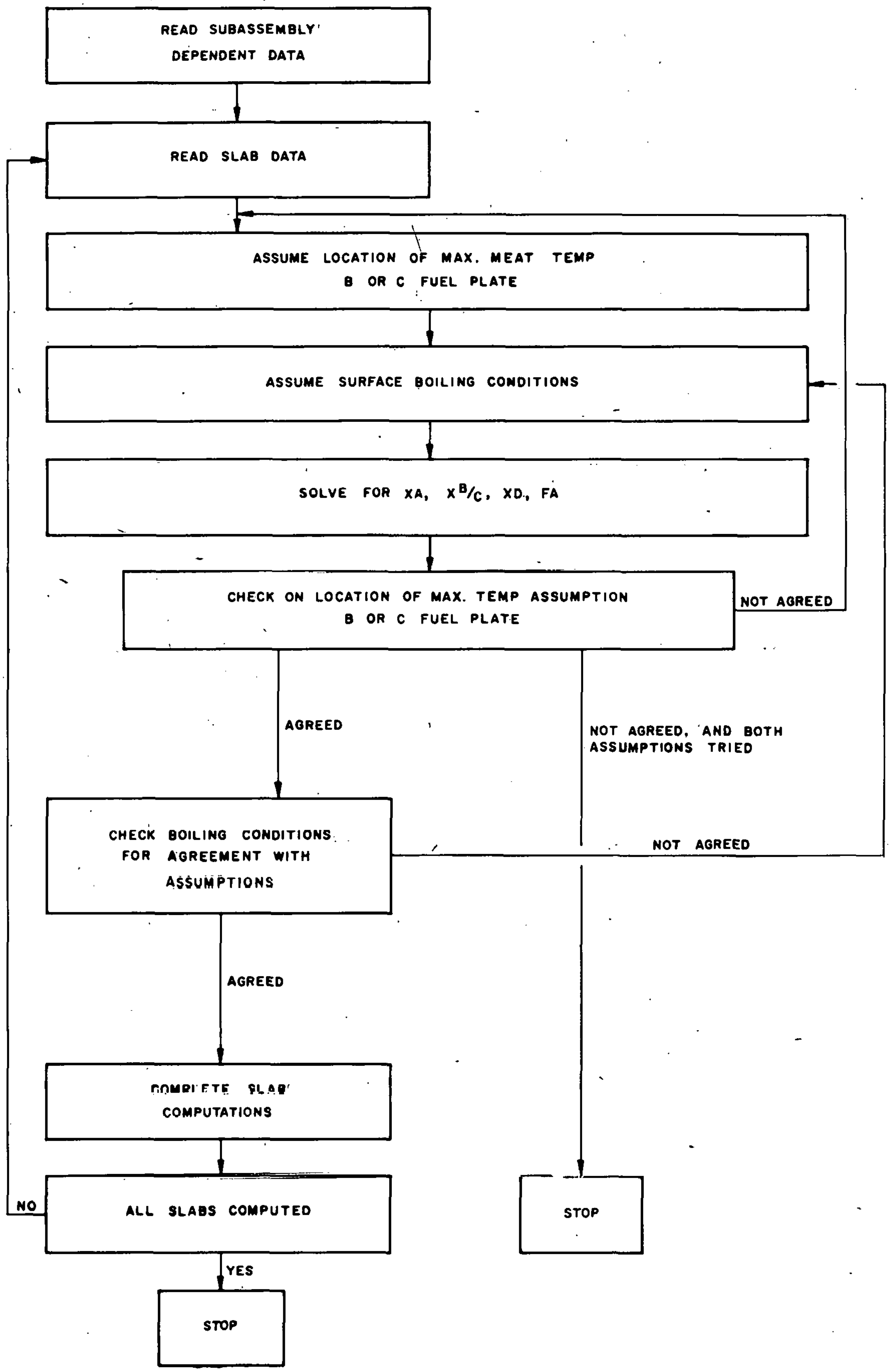

Fig. 4 Simplified Flow Chart

A. Code Input

Table I shows the input format. The subassembly dependent data card group precedes the slab dependent data input. For example, if a 20-slab analysis is being run, there will be 21 subgroups in the entire data deck for that run. Columns 1-5 of the first word on data cards may be used for run number identification of the data cards. All actual operating data entries are in floating point notation. For example, entering k (thermal conductivity) in word 4 of card 1:

k.	Floating point k.
08.1	5081000000
T*	Floating point T*
642.000	5264200000

Entries on card 10: N and Run No., are not in floating point notation. N denotes the number of slabs used in the analysis. For a 20-slab problem, N would be entered as 0000000020, the decimal point being at the right. The Run No. on card 10 is entered as XXXXX00000; XXXXX are the digits used for run number identification to be punched on the output of the code. The last five digits must be punched as 00000. This portion of the Run No. numbers the slab output with the slab number. The code modifies 00000 serially as the analysis proceeds slab-by-slab.

Input data cards must be punched as indicated in Table I, with the load hub punch in column 1 and the appropriate sign for input variables in columns 10, 20, 30, 40, 50, 60, 70, and 80, as necessary. It is not necessary to punch zeros in word spaces where no input is indicated. An example of input listing is shown in Table I.

B. Code Output

Table II displays the output format. Word 1 contains the run identification number and slab number. Word 1 is the output resulting from Word 3 of the data input card of the subassembly dependent data goup. As indicated in Table II, nine cards make up the data output per slab, with a tenth card after the final slab to release the calculated average normalized neutron flux power for each of the four channels, and the average volumetric heat generation rate of the subassembly.

Word 2 of all data output denotes the drum location from which the results are punched out. One exception is the ninth card of slab data where a series of nines is punched. Word 2 in the extra card (10th), at the end of the final slab, is the $\overline{F}_A$.

All data output (computations) are in floating point notation. The eighth word of card 8 on each slab output is labeled BOLC. This is the code word that describes the surface conditions under which the final calculations for that slab were performed. A BOLC appearing as 8888880000 denotes no boiling on heat transfer surfaces 2, 6, 8, 15, 17, and 21, respectively. A BOLC appearing as 8899880000 denotes local boiling on surface Nos. 8 and 15. The first six digits from left to right of BOLC designate the surfaces in question. An eight signifies no boiling and nine signifies local boiling on the surface. In the case of surface 8 film boiling, 9 will be displayed in the 8-surface location.

Data output gives no direct code word for quick location of maximum fuel temperature in the B or C plate, when computing F_A with T_{tc} input. However, when the T_{tc} subroutine is used for F_A input, giving calculations of maximum meat temperature, the T_{tc} calculation will be tagged with a negative sign when the maximum temperature is in the C plate. When T_{tc} is computed, it is produced in the seventh word of the ninth card of each slab output. When T_{tc} is input data for the F_A calculation, it is listed in the eighth word of the ninth card on each slab output. F_A, whether it is input data or output data, will appear only in Word 7 of the eighth card of slab output.

TABLE I

DATA INPUT

Subassembly Data

Card	+ Word 1	±Word 2	±Word 3	±Word 4	±Word 5	±Word 6	±Word 7	±Word 8±
1	Run No., 04016	V_m	L	k	T_s	$\bar{q}'''$	a_1	
2	Run No., 04074	F_{RA}	F_{RB}	F_{RC}	F_{RD}			
3	Run No., 04114	G_1	G_7	G_{16}	G_{22}			
4	Run No., 04154	H_I	H_I	H_I	H_I			
5	Run No., 04194	A	B	C	D		(where $C_p = A + BH + CH^2 + DH^3$)	
6	Run No., 04234	A	B	C	D		(where $T = A + BH + CH^2 + DH^3$)	
7	Run No., 04275	A	B	C	D	H_I	(where $\lambda = A + BT + CT^2 + DT^3$)	
8	Run No., 04324	$G_1^{0.8}$	$G_7^{0.8}$	$G_{16}^{0.8}$	$G_{22}^{0.8}$			
9	Run No., 04366	T*	T*	T*	T*	T*	T*	
10	Run No., 04883	N	Run No.	ϵ				
11				Transfer Card				

Slab Data (10 Cards Per Slab)

Card	+ Word 1	±Word 2	±Word 3	±Word 4	±Word 5	±Word 6	±Word 7	±Word 8±
1	Run No., 04516	Δx	T_{tc}†	w_{M_A}	w_{M_B}	w_{M_C}	w_{M_D}	
2	Run No., 04577	b	c	d	e	f	g	j
3	Run No., 04644	ℓ	m	n	r			
4	Run No., 04684	F_{LA}	F_{LB}	F_{LC}	F_{LD}			
5	Run No., 04724	$D_{e_1}^{-0.2}$	$D_{e_7}^{-0.2}$	$D_{e16}^{-0.2}$	$D_{e22}^{-0.2}$			
6	Run No., 04764	t_{c_1}	t_{c_7}	t_{c16}	t_{c22}			
7	Run No., 04804	w_{c1}	w_{c7}	w_{c16}	w_{c22}			
8	Run No., 04841	F_A						
9	Run No., 07141	a						
10				Transfer Card				

† T_{tc} will be 0000000000 when computing T_{tc}.

The following two pages of this report show actual IBM-704 input and output data sheets for a sample problem. Only the first two slabs are listed with the final slab of a 20-slab problem.

C. Computer Operation

The console settings are as follows:

Storage entry 70 1951 9999

SAMPLE PROBLEM DATA INPUT

0100004016	4810303571	5035504050	5081000000	5264198000	5790000000	4821000000	0000000000	LOAD
0100004074	5010000000	5010000000	5010000000	5010000000	0000000000	0000000000	0000000000	LOAD
0100004114	5614600000	5611810000	5613370000	5614910000	0000000000	0000000000	0000000000	LOAD
0100004154	5241000000	5241000000	5241000000	5241000000	0000000000	0000000000	0000000000	LOAD
0100004194	5077029200-	4856110000	4612056110-	4287499520	0000000000	0000000000	0000000000	LOAD
0100004234	5212325081	4935110253	4715251490	4413560528-	0000000000	0000000000	0000000000	LOAD
0100004275	5020474250	4787490600-	4520694280	4214945200-	5241000000	0000000000	0000000000	LOAD
0100004324	5485410000	5472100000	5479500000	5486850000	0000000000	0000000000	0000000000	LOAD
0100004366	5264200000	5264200000	5264200000	5264200000	5264200000	5264200000	0000000000	LOAD
2090004883	0000000020	2009200000	4310000000	0000000000	0000000000	0000000000	0000000000	LOAD
0100104516	4882542000	0000000000	4914395833	4914645833	4914645833	4914354167	0000000000	LOAD
0100104577	4750000000	4712500000	4712500000	4750000000	4762500000	4762500000	4750000000	LOAD
0100104644	4712500000	4712500000	4750000000	4712500000	0000000000	0000000000	0000000000	LOAD
0100104684	5012279000	4975776000	4975776000	5012369000	0000000000	0000000000	0000000000	LOAD
0100104724	5023700000	5024040000	5024000000	5023880000	0000000000	0000000000	0000000000	LOAD
0100104764	4770041667	4765166667	4765625000	4768333333	0000000000	0000000000	0000000000	LOAD
0100104804	4915337500	4915337500	4915295833	4915400000	0000000000	0000000000	0000000000	LOAD
0100104841	4981995400							LOAD
0100107141	4712500000	0000000000	000000000	0000000000	0000000000	0000000000	0000000000	LOAD
0000109990								
0100204516	4932117000	0000000000	4914395833	4914645833	4914645833	4914354167		LOAD
0100204577	4750000000	4712500000	4712500000	4750000000	4762500000	4762500000	4750000000	LOAD
0100204644	4712500000	4712500000	4750000000	4712500000				LOAD
0100204684	5012279000	4975776000	4975776000	5012369000				LOAD
0100204724	5023700000	5024040000	5024000000	5023880000				LOAD
0100204764	4770041667	4765166667	4765625000	4768333333				LOAD
0100204804	4915337500	4915337500	4915295833	4915400000				LOAD
0100204841	4982400000							LOAD
0100207141	4712500000							LOAD
0000209990								

SAMPLE PROBLEM DATA OUTPUT

2009200001	0000000500	4725835238	4749615349	0000000000-	4724529770	5243093376	5243243531
2009200001	0000000506	5243219160	5243092549	5249056492	5249757275	5251496931	5250833047
2009200001	0000000512	5249269845	5248872421	5256402599	5256115442	5264275813	0000000000
2009200001	0000000518	5523410326	5521896641	5522390307	5523248741	5527744679	5528174870
2009200001	0000000524	5241177359	5241504568	5241451460	5241175558	5339258540	5333616060
2009200001	0000000530	5333616060	5337004578	5337004578	5340223627	5010895723	5010895723
2009200001	0000000536	5010895723	5010895723	5811051100	5768198400	5768198400	5811132100
2009200001	0000000542	5243011987	5243011987	5243011987	5243011987	4981995400	8888880000
2009200001	0099999999	5241088679	5241252284	5241225730	5241087779	5264109331	0000000000
2009200002	0000000500	4726356354	4749561661	0000000000-	4724081300	5243498942	5244367514
2009200002	0000000506	5244227315	5243493195	5249604175	5250747798	5252621051	5251860783
2009200002	0000000512	5250176315	5249396029	5257212643	5256868767	5265439863	0000000000
2009200002	0000000518	5524000376	5521530155	5522089416	5523774835	5527851413	5528344067
2009200002	0000000524	5241884858	5243457736	5243203683	5241874111	5339311154	5333744821
2009200002	0000000530	5333744821	5337131308	5337131308	5340276985	5010911173	5010938668
2009200002	0000000536	5010934290	5010911019	5811051100	5768198400	5768198400	5811132100
2009200002	0000000542	5243174734	5243474733	5243426064	5243173082	4982400000	8888880000
2009200002	0099999999	5241531108	5242481152	5242327571	5241524834	5265249130	0000000000

2009200020	0000000500	4747287491	4749470340	4416763000	4658806841	5252406789	5263021652
2009200020	0000000506	5261374687	5252274814	5256226135	5263273088	5264200000	5263883800
2009200020	0000000512	5261870694	5255781158	5263431539	5262256292	5268820868	0000000000
2009200020	0000000518	5516147684	5392626483	5420228488	5515176245	5510052064	5510232827
2009200020	0000000524	5251629741	5266166410	5263506914	5251470353	5342278663	5336838965
2009200020	0000000530	5336838965	5340782645	5340782645	5343282245	5011842061	5016744255
2009200020	0000000536	5015479693	5011818653	5811051100	5765758500	5765535300	5811132100
2009200020	0000000542	5252368903	5262997063	5261348619	5252239254	4930900000	8898880000
2009200020	0099999999	5251584876	5266125236	5263466561	5251428325	5268737476	0000000000
2009200020	4999999977	5516671957	5529706483	5530205762	5516428287	5790272090	0000000000

Programmed	Run
Half cycle	Run
Control	Run
Display	Distributor
Overflow	Stop
Error	Stop

The program deck is punched to load (self loading) with IBM subroutine 1.2002. On the initial run of a series of runs, the data deck is stacked immediately behind the program deck. (See Fig. 5) The program will load and follow automatically in loading of the subassembly dependent data and first slab input data. Slab computations and slab data read-in follow until completion of the analysis.

For succeeding runs of a series, the program deck need not be reloaded. The next complete data deck (subassembly dependent + slab data) is placed in the card reader. The next steps are to enter 0150 in the address selection, press the computer reset key, and press the program start key.

Control Panel (533 Input-Output Unit)

The control panel for the 533 input-output unit should be wired as follows:

1) Load hub is wired out of column 1.

TABLE II

DATA OUTPUT*

Slab Data

Card	Word 1		+ Word 2	±Word 3	±Word 4	±Word 5	±Word 6	±Word 7	±Word 8±
1	1-8 Run No.	9-10 Slab No.	0000000500	X_A	X_B	X_C	X_D	$\bar{T}_1$	$\bar{\bar{T}}_7$
2			0000000506	$\bar{T}_{16}$	$\bar{T}_{22}$	T_2	T_6	T_8	T_{15}
3			0000000512	T_{17}	T_{21}	T_4	T_{19}	T_{10}	T_{13}
4			0000000518	q_2	q_6	q_{17}	q_{21}	q_8	q_{15}
5			0000000524	H_{O_1}	H_{O_7}	$H_{O_{16}}$	$H_{O_{22}}$	h_2	h_6
6			0000000530	h_8	h_{15}	h_{17}	h_{21}	C_{P_1}	C_{p_7}
7			0000000536	$C_{p_{16}}$	$C_{p_{22}}$				
8			0000000542	T_{I_1}	T_{I_7}	$T_{I_{16}}$	$T_{I_{22}}$	F_A	BOLC
9			0099999999	$\bar{H}_1$	$\bar{H}_7$	$\bar{H}_{16}$	$\bar{H}_{22}$	T_{tc} output	T_{tc} input

Subassembly Data (10th Card)

	Word 1		+ Word 2	±Word 3	±Word 4	±Word 5	±Word 6	±Word 7	±Word 8±
	1-8 Run No.	9-10 No. of last slab	$\bar{F}_A$	$P_{1\ calc}$	$P_{7\ calc}$	$P_{16\ calc}$	$P_{22\ calc}$	$\bar{q}'''$ calc	T_{tc} input

*Slab data output consists of 9 cards per slab.
Additional card (subassembly data) with the last slab.

2) Eight ten-digit words input from READ C.

3) Punch eight ten-digit words from PUNCH C.

4) Read and punch signs over units.

D. Code Subroutines

T_{tc} Computation Subroutine — The code is constructed basically for F_A computation with T_{tc} (thick plate center temperature) input. For T_{tc} computation with F_A input, a subroutine deck insertion is required for the basic program deck. This deck is inserted immediately before the final 13 cards of the main program deck.

Film Boiling Subroutine — This is inserted immediately before the final 13 cards of the main program deck. When a condition of film boiling is known or assumed to exist in a test run, the routine will solve for the actual temperature associated with T_8^*.

The thermocouple T_{tc} input of the run must be tagged for each slab to designate the slab or slabs where film boiling will occur. This is accomplished by punching an "8" in the units position of each T_{tc} input for the slabs where film boiling will occur. All T_{tc} inputs for the other slabs must be punched with a "9" in the units position. For instance, a T_{tc} input of 5287686588 denotes film boiling in the slab, while 5287686589 would denote no film boiling.

This subroutine is used when computing F_A with T_{tc} input only. On slabs where film boiling occurs, F_A must be input in the regular manner (refer to Table I).

APPENDIX A: A NOTE ON THE ASSUMPTION OF SEPARABILITY OF VARIABLES

The assumption was made in the analysis, for calculational purposes, that the axial and radial

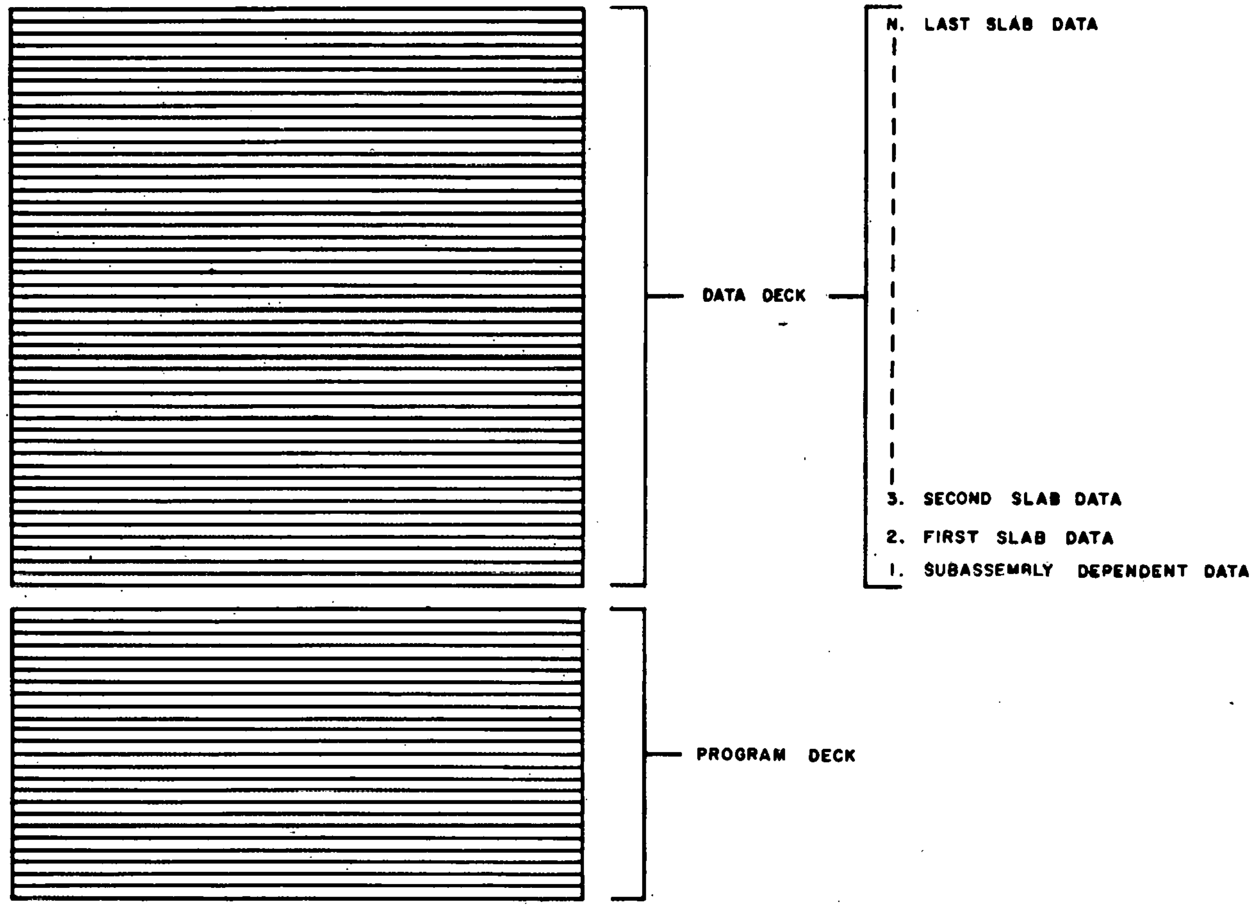

Fig. 5 Card Loading for Initial Run

neutron fluxes were separable, i.e., the axial neutron flux was the same for each fuel plate at any elevation, and the radial neutron factor was a constant in a given fuel plate but could be different for different fuel plates. Also, the assumption was made that the local volumetric heat generation rate could be expressed as

$$q''' = \bar{q}''' F_{L_{iu}} F_{A_i} F_{R_u} .$$

Integrating both sides of this equation with respect to the differential volume gives the total heat output as

$$Q = \int_0^V \bar{q}''' F_{L_{iu}} F_{A_i} F_{R_u} \, dV .$$

Dividing both sides of the equation by the total volume of the meat V_m, and taking the average volumetric heat generation rate outside of the integral sign gives

$$\frac{Q}{V_m} = \bar{q}''' = \left(\frac{\bar{q}'''}{V_m}\right) \int_0^{V_m} F_{L_{iu}} F_{A_i} F_{R_u} \, dV.$$

Reducing the equation gives

$$1 = \left(\frac{1}{V_m}\right) \int_0^{V_m} F_{L_{iu}} F_{A_i} F_{R_u} \, dV.$$

It is apparent that this equation agrees with the assumption of separability of variables if the local product of the factors is equal to one, or if the integration over the volume equals the total volume. Where the variables are assumed separable and each variable has an average of one, as used in this analysis, complete compliance with the given equation would be rare. Therefore, when a problem is calculated and the loading and neutron factors each has an average of one, deviation can be expected between the input and output average volumetric heat generation rate. Inspection of several sets of data indicates that this deviation has a maximum of three-tenths of a percent and is, therefore, quite small when compared to the known accuracy of most data.

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REFERENCES

1. 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).

2. W. H. McAdams, Heat Transmission, 3rd Ed., (New York: McGraw-Hill, 1954).

3. P. J. Schneider, Conduction Heat Transfer, (Cambridge, Mass. Addison-Wesley Publishing Company, Inc., 1955).