CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION • NUCLEAR DIVISION
for the
U. S. ATOMIC ENERGY COMMISSION

LOCKHEED MARTIN ENERGY RESEARCH LIBRARIES
3 4456 0513859 8

ORNL-TM-3516

cy. 79

ØRRIBLE — A COMPUTER PROGRAM FOR FLOW AND TEMPERATURE DISTRIBUTION IN LMFBR FUEL ROD BUNDLES

J. L. Wantland

OAK RIDGE NATIONAL LABORATORY
CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON
If you wish someone else to see this document, send in name with document and the library will arrange a loan.
UCN-7969
(3 3-67)

NOTICE This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report.

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or 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.

ORNL-TM-3516

Contract No. W-7405-eng-26

REACTOR

ØRRIBLE — A COMPUTER PROGRAM FOR FLOW AND TEMPERATURE DISTRIBUTION IN LMFBR FUEL ROD BUNDLES

J. L. Wantland

OCTOBER 1971

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

LOCKHEED MARTIN ENERGY RESEARCH LIBRARIES

3 4456 0513859 8

CONTENTS

	Page
ABSTRACT	1
1. INTRODUCTION	1
2. TRANSVERSE INTERACTIONS	2
2.1 Turbulent Interchange	2
2.2 Pressure Diversion Crossflow	4
2.3 Sweeping Crossflow	5
2.4 Transverse Thermal Conduction	6
3. CONSERVATION EQUATIONS	7
3.1 Conservation of Mass	7
3.2 Conservation of Energy	8
3.3 Conservation of Axial Momentum	10
4. DIVERSION CROSSFLOW EQUATION	12
5. DESCRIPTION OF THE PROGRAM	15
5.1 Referencing Arrays	15
5.2 Input Data	17
5.3 Computational Arrays	18
5.4 Computational Procedure	18
5.5 Input Format	19
5.6 FØRTRAN Listing of ØRRIBLE 081271	19
6. NOMENCLATURE	24
6.1 Non-indexed	24
6.2 Indexed	24
REFERENCES	26

ØRRIBLE — A COMPUTER PROGRAM FOR FLOW AND TEMPERATURE DISTRIBUTION IN LMFBR FUEL ROD BUNDLES

J. L. Wantland

ABSTRACT

A computer program named ØRRIBLE was written to predict the flow and temperature distribution for steady single-phase flow through a bundle of nineteen heated rods spaced by helical wire wraps in a hexagonal duct. Any combination of flow subchannels can be blocked at the inlet. The section can have an unheated entrance length followed by a heated section and an unheated exit length. In the heated section the linear heat rate of each of the rods can be individually specified. Turbulent interaction, sweeping crossflow due to the wire wrap, and transverse thermal conduction are considered. An approximate relationship for pressure diversion crossflow in terms of local axial mass velocities is used to eliminate pressure as a variable. Hence the computational procedure does not require iterative techniques. ØRRIBLE can be extended to larger bundles with different internal configurations.

Keywords: computer program, digital; reactor, LMFBR; temperature; temperature distribution; temperature gradient; flow; flow distribution; flow blockage.

1. INTRODUCTION

The fuel-failure mockup (FFM)[1] at the Oak Ridge National Laboratory is a large high-temperature sodium cooled facility in which simulated liquid metal fast breeder reactor (LMFBR) core segments are subjected to thermal and hydraulic testing at typical operating conditions. The initial test program is to investigate the effects of partial flow blockage by plugging at the inlet of the test section.

It was desired to have a relatively simple computer program to predict the flow and temperature distribution in the FFM test section. The resulting program, named ØRRIBLE, was written specifically for the geometry of the LMFBR-FFM Bundle No. 2[2] but it can easily be extended to larger test sections with different internal configurations.

The LMFBR-FFM Bundle No. 2 consists of nineteen electrically-heated rods in a hexagonal duct with rounded corners. It has an unheated entrance length followed by a heated section and an unheated exit length. For spacing, each rod is wrapped with a right-hand-pitch helical wire. The wire wraps are oriented so that at the start of the heated section the wraps are directly in the gaps separating adjacent rods.

A cross-sectional view of the test section is shown in Fig. 1. The rods are numbered 1 through 19. The flow area is considered to consist of 42 parallel interconnected flow channels numbered as is shown. Interactions between adjacent flow channels take place through the 60 gaps numbered as shown. The different types of flow channels have different cross-sectional areas; for convenience they are all assumed to have the same hydraulic diameters. All of the gaps are of the same size.

The interactions through the gaps are due to turbulent interchange, pressure induced diversion crossflow, directed sweeping crossflow due to the helical wire wrap, and transverse thermal conduction.

Expressions for the transverse interactions are used in the equations of conservation of mass and energy to establish the thermal and hydrodynamic characteristics of the system.

A salient feature of ØRRIBLE is the implicit use of the equation of conservation of axial momentum by obtaining an expression for pressure diversion crossflow in terms of the axial mass velocities in the two adjacent flow channels. By so doing, pressure is eliminated as a variable and the solution is obtained without recourse to iterative techniques.

2. TRANSVERSE INTERACTIONS

In this section the expressions used for transverse interactions are described. Much useful information was obtained from the CØBRA code written by D. S. Rowe.[3]

2.1 Turbulent Interchange

Turbulent transport of mass, heat, and momentum occurs between adjacent channel segments. This transport is handled mathematically by

ORNL-DWG 71-3614

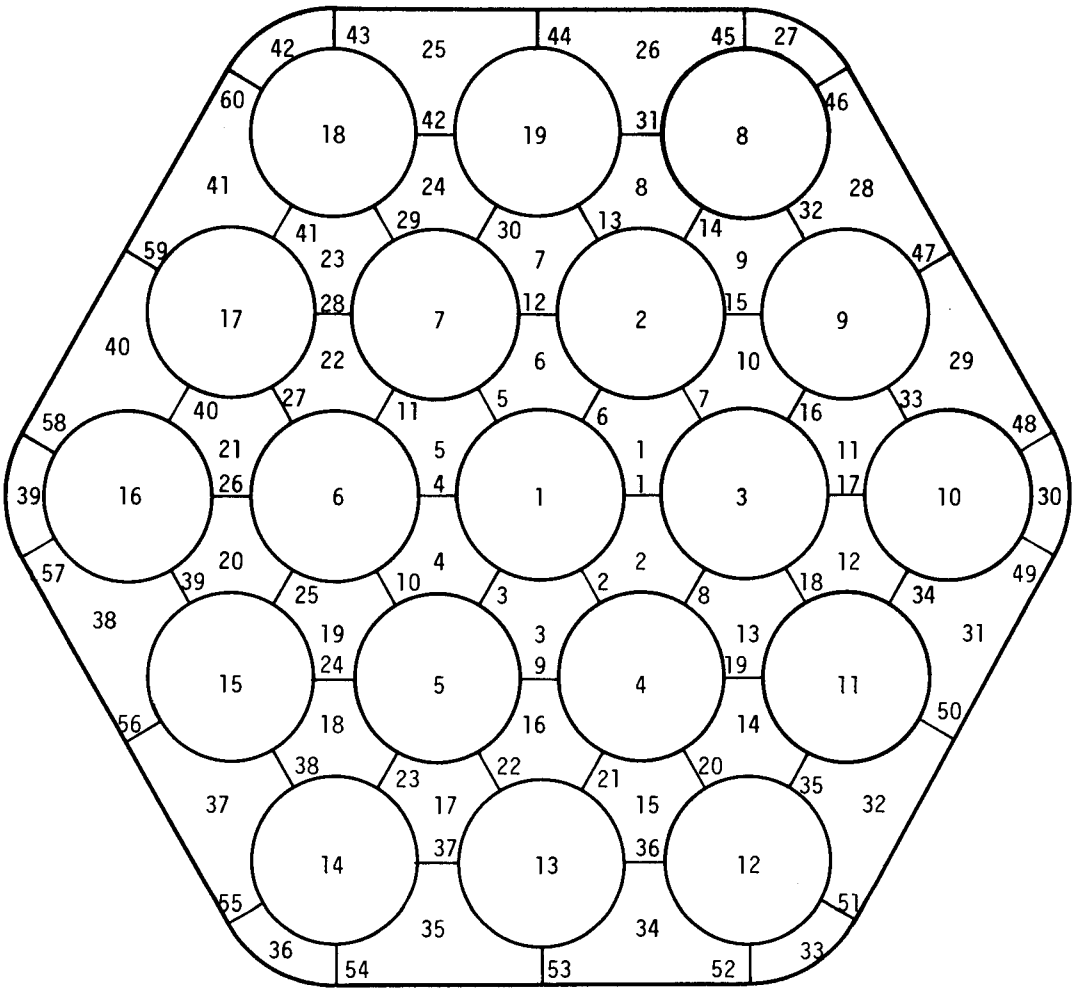

Fig. 1. Rod, Channel, and Gap Numbering System for ØRRIBLE; 19 Rods, 42 Channels, 60 Gaps.

assuming the interchange mechanism to be in the form of a turbulent cross-flow mass velocity

$$w_{T_{\ell m}} = C_T \left(|w_\ell| + |w_m|\right) , \tag{1}$$

where

$w_{T_{\ell m}}$ = the local turbulent cross flow mass velocity between channels ℓ and m, $lb_m/hr \cdot ft^2$,

w_ℓ, w_m = the local values of the axial mass velocities in channels ℓ,m; $lb_m/hr \cdot ft^2$,

C_T = the dimensionless turbulent crossflow coefficient.

For channel ℓ having a local property s_ℓ (per unit mass), this property is turbulently transported into channel m at the rate $s_\ell \, w_{T_{\ell m}} \, \delta A$ where δA is the area joining the two channel segments. Similarly the turbulent transport of s_m from channel m to channel ℓ is at the rate $s_m \, w_{T_{m\ell}} \, \delta A$ and $w_{T_{m\ell}} = w_{T_{\ell m}}$. For $s_m \neq s_\ell$ there is a net transport of the property between the two channels and turbulent interchange must be considered in the equations of conservation of momentum and energy. For an incompressible fluid, $\rho_m = \rho_\ell$ and the turbulent interchange terms cancel in the equation of conservation of mass.

2.2 Pressure Diversion Crossflow

Where a pressure difference exists between adjacent channels, flow will be diverted from the channel with the higher pressure to the channel with the lower pressure. The relationship usually assumed for this pressure induced diversion crossflow is

$$P_m - P_\ell = C_D \frac{w_{P_{m\ell}}^2}{2\rho g_c} , \tag{2}$$

or for $P_\ell \neq P_m$,

$$w_{P_{m\ell}} = \frac{P_m - P_\ell}{|P_m - P_\ell|} \sqrt{(2\rho g_c/C_D) \, |P_m - P_\ell|} , \tag{3}$$

where

P_ℓ, P_m = the local pressures in channels ℓ, m; lb_f/ft^2,

$w_{P_{m\ell}}$ = the pressure diversion crossflow from channel m into channel ℓ, $lb_m/hr \cdot ft^2$,

ρ = the fluid density, lb_m/ft^3,

g_c = the gravitational conversion factor, $4.170 \times 10^8 \frac{lb_m \cdot ft}{lb_f \cdot hr^2}$,

C_D = the dimensionless pressure diversion crossflow coefficient.

Mathematically it is greatly advantageous to be able to express $w_{P_{\ell m}}$ as a function of w_ℓ and w_m. In early versions of ØRRIBLE, several empirical relationships were assumed. The relationship used in the reported version of ØRRIBLE is derived in Section 4.

2.3 Sweeping Crossflow

Due to the directing effect of the helical wire wrap (Fig. 2), flow will be swept along it in the direction of the helix. Thus there will be a sweeping crossflow

$$w_{S_{\ell m}} \sim w_\ell \frac{\pi(D + G)}{\phi}$$

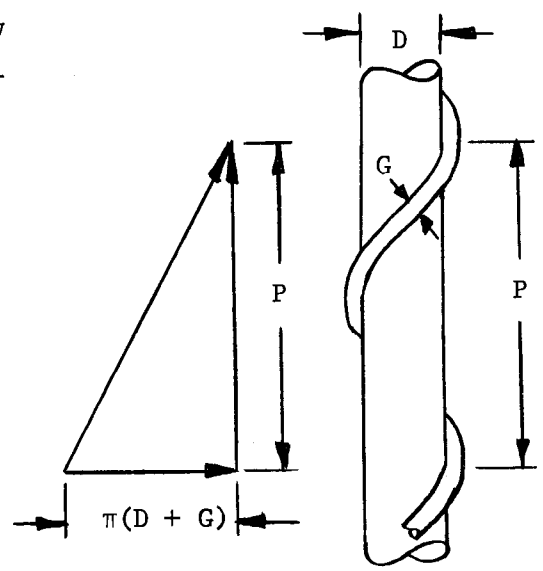

Fig. 2

where

$w_{S_{\ell m}}$ = the sweeping crossflow from channel ℓ into channel m, $lb_m/hr \cdot ft^2$,

w_ℓ = the axial mass velocity in channel ℓ from which the wire is "emerging" at that locality, $lb_m/hr \cdot ft^2$,

D = the rod diameter, ft,

G = the wire wrap diameter (gap thickness), ft,

ϕ = the helical pitch of the wire wrap, ft.

For a given gap between two rods, the wrap on one rod goes through the gap in one direction and further down the bundle the wrap on the other rod goes through the gap in the opposite direction. Hence the sweeping crossflow through a given gap alternately changes direction through the bundle.

The maximum sweeping crossflow is assumed to occur where the wire wrap is immediately in the gap between two adjacent rods, hence for this purpose the wrap is assumed to occupy no flow area but acts as a vane to move the flow between channels. Where the wrap is more than 60° away from the gap (see Fig. 3), its influence on that gap is assumed to be negligible. For $|\theta| \leq 60°$, its influence is assumed to obey the relationship

$$w_{S_{\ell m}} \sim \frac{1}{2} [1 + \cos (3\theta)] .$$

To account for the fact that, on the average, the sweeping crossflow does not follow the wire wrap directly,[4] a dimenionless sweeping crossflow factor $C_S \leq 1.0$ is introduced. Hence for $|\theta| > 60°$, $w_{S_{\ell m}} = 0$ and for $|\theta| \leq 60°$

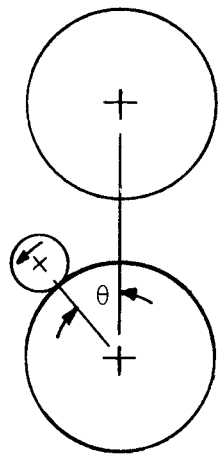

Fig. 3

$$w_{S_{\ell m}} = C_S \, w_\ell \, \frac{\pi(D + G)}{2\theta} [1 + \cos (3\theta)] . \tag{4}$$

2.4 Transverse Thermal Conduction

Heat is transferred by conduction between adjacent channels at the rate

$$q_{c_{m\ell}} = k \, F_S \, \delta x \, (t_m - t_\ell) , \tag{5}$$

where

$q_{c_{m\ell}}$ = the local heat transfer rate from channel m to channel ℓ, Btu/hr,
k = the thermal conductivity of the fluid, Btu/hr·ft·°F,
F_S = the dimensionless shape factor

δx = the length of the axial increment, ft,

t_ℓ, t_m = the local temperatures of channels ℓ, m, °F.

Using electrical resistance paper, the appropriate shape factors for various values of $G/D \leq 0.5$ were determined by Fukuda.[5] The results are correlated by the empirical relationship

$$F_S = 1.38\ (G/D)^{0.674}\ . \tag{6}$$

3. CONSERVATION EQUATIONS

In the derivations to follow,

$$w_D = w_P + w_S\ , \tag{7}$$

the total diversion crossflow in $lb_m/hr \cdot ft^2$ due to pressure diversion and wire wrap sweeping.

3.1 Conservation of Mass

Consider an increment δx ft long of the jth flow channel with a cross-sectional area A_j ft^2 as is shown in Fig. 4. Where w_j is the specific flow

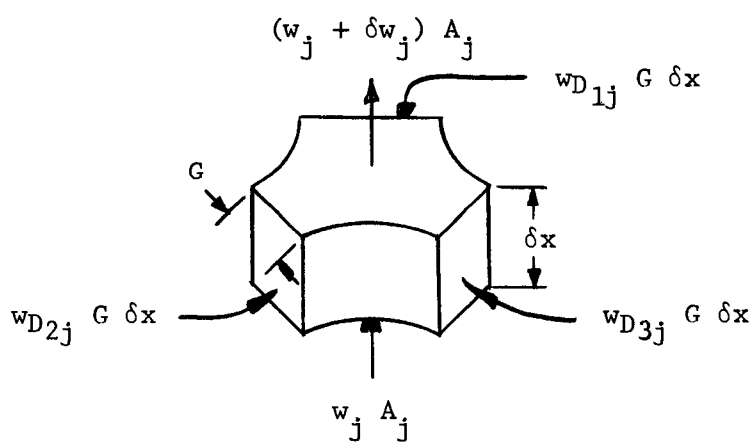

Fig. 4

($lb_m/hr \cdot ft^2$) into the increment, G is the gap between rods (ft) and $w_{D_{aj}}$, a = 1, 2, 3 are the total diversion crossflows into the jth channel from the three adjacent flow channels ($lb_m/hr \cdot ft^2$),

$$w_j A_j + \sum_{a=1}^{3} w_{D_{aj}} G \, \delta x = (w_j + \delta w_j) A_j ,$$

or with

$$y_j = \frac{\delta w_j}{\delta x} , \tag{8}$$

$$y_j = \frac{G}{A_j} \sum_{a=1}^{3} w_{D_{aj}} . \tag{9}$$

3.2 Conservation of Energy

Consider the increment shown in Fig. 4. The energy entering axially at the bottom is $w_j A_j \, c_p \, t_j$ where c_p is the specific heat of the fluid in $Btu/lb_m \cdot °F$. The energy leaving axially at the top is $(w_j + y_j \, \delta x) \, A_j \, c_p \, (t_j + \delta t_j)$. Laterally the channel increment receives energy from the three adjacent rod segments at the rate

$$\sum_{b=1}^{3} q_{bj} \, f_{bj} \, \delta x ,$$

where

q_{bj} = the linear heat rate in Btu/hr·ft of the three rods adjacent to the jth channel,

f_{bj} = the fraction of each of these three rods adjacent to the jth channel.

Due to turbulent interchange the channel increment receives energy from the three adjacent channels at the rate

$$\sum_{a=1}^{3} w_{T_{aj}} \, t_{aj} \, c_p \, G \, \delta x ,$$

where t_{aj}, a = 1, 2, 3 are the temperatures of the three adjacent channels, and imparts energy to them at the rate

$$\sum_{a=1}^{3} w_{T_{aj}} \; t_j \; c_p \; G \; \delta x \; ,$$

hence the net energy received by turbulent interchange is

$$\sum_{a=1}^{3} w_{T_{aj}} \; (t_{aj} - t_j) \; c_p \; G \; \delta x \; .$$

The total diversion cross flow $w_{D_{aj}}$, a = 1, 2, 3 is by definition positive for flow into the jth channel. Hence where $w_{D_{aj}} > 0$, the energy received is $w_{D_{aj}} \; c_p \; t_{aj} \; G \; \delta x$; where $w_{D_{aj}} < 0$ energy is being removed at the rate $- w_{D_{aj}} \; c_p \; t_j \; G \; \delta x$ or energy is received at the rate $w_{D_{aj}} \; c_p \; t_j \; G \; \delta x$. Hence the total energy received due to diversion crossflow is

$$c_p \; G \; \delta x \sum_{a=1}^{3} \begin{cases} w_{D_{aj}} \; t_{ja}, & w_{D_{aj}} > 0 \\ w_{D_{aj}} \; t_j, & w_{D_{aj}} < 0 \end{cases}$$

From Eq. (5) the total energy received by thermal conduction from the three adjacent channels is

$$\sum_{a=1}^{3} k \; F_S \; (t_{aj} - t_j) \; \delta x \; .$$

Letting

$$z_j = \frac{\delta t_j}{\delta x} \; , \tag{10}$$

$$C_f = \frac{k \; F_S}{G \; c_p} \; , \tag{11}$$

and

$$q_j = \frac{1}{c_p A_j} \sum_{b=1}^{3} f_{bj} \; q_{bj} \; , \tag{12}$$

and equating the energy input with the energy output, the following equation is obtained

$$z_j = \frac{1}{w_j + y_j\,\delta x}\left[- y_j t_j + q_j + \frac{G}{A_j}\sum_{a=1}^{3}(w_{T_{aj}} + C_f)\,(t_{aj} - t_j) + \frac{G}{A_j}\sum_{a=1}^{3}\begin{cases} w_{D_{aj}}\,t_{aj}, & w_{D_{aj}} > 0 \\ w_{D_{aj}}\,t_j, & w_{D_{aj}} < 0 \end{cases}\right] \tag{13}$$

3.3 Conservation of Axial Momentum

For steady state conditions, the sum of upward forces on an element plus the increase in upward vertical momentum is equal to zero.

Sum of upward forces

Referring to Fig. 5,

$$\sum F\uparrow = A_j g_c\,P_j - A_j\,g_c(P_j - \delta P_j) - \tau_j \bar{p}_j\,\delta x\,g_c - \rho A_j\,\delta x\,g$$

$$= A_j g_c\,\delta P_j - \tau_j \bar{p}_j\,\delta x\,g_c - \rho A_j\,\delta x\,g$$

where

τ_j = the local wall shear in the jth channel, lb_f/ft^2,
$\bar{p}_j$ = the wetted perimeter of the jth channel, ft,
g = the attraction of gravity, ft/hr^2.

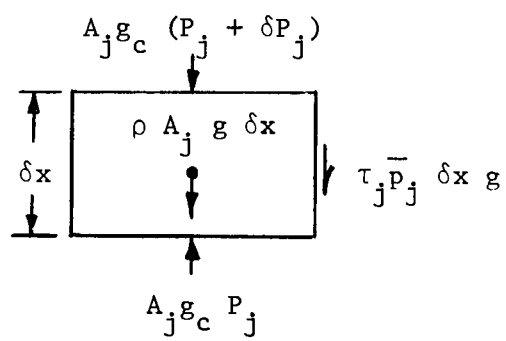

Fig. 5

Increase in upward vertical momentum

Referring to Fig. 6, $\sum$ mom $\uparrow$ = $\uparrow$ mom. in − $\uparrow$ mom. out

$$= w_j A_j u_j + \sum_{a=1}^{3} w_{T_{aj}} G\, \delta x\, u_{ja} + G\, \delta x \sum_{a=1}^{3} \begin{cases} w_{D_{aj}}\, u_{aj}, & w_{D_{aj}} > 0 \\ w_{D_{aj}}\, u_j, & w_{D_{aj}} < 0 \end{cases}$$

$$- \sum_{a=1}^{3} w_{T_{aj}} G\, \delta x\, u_j - [w_j A_j u_j + \delta(w_j A_j u_j)]$$

$$= A_j\, \delta(w_j u_j) + G\, \delta x \sum_{a=1}^{3} w_{T_{aj}} (u_{aj} - u_j) + G\, \delta x \sum_{a=1}^{3} \begin{cases} w_{D_{aj}}\, u_{aj}, & w_{D_{aj}} > 0 \\ w_{D_{aj}}\, u_j, & w_{D_{aj}} < 0 \end{cases}$$

where

$$u_j = \frac{w_j}{\rho}$$

and

$$u_{aj} = \frac{w_{aj}}{\rho}$$

are the upward velocities in the jth and ajth channels respectively. Using

$$\tau_j = \frac{f_F w_j^2}{2\rho g_c} \tag{14}$$

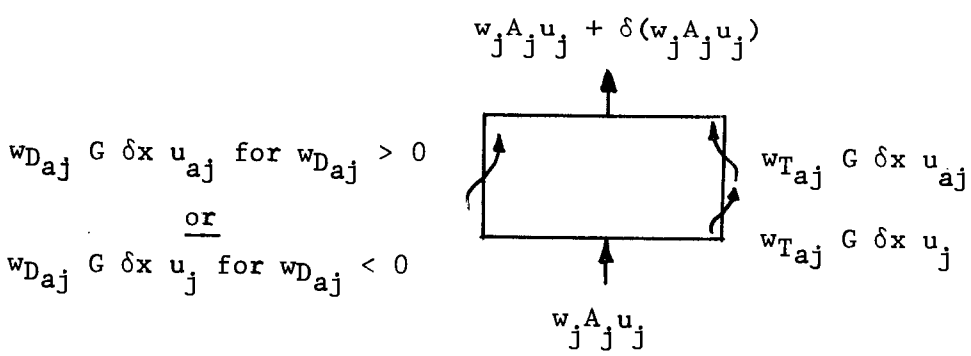

Fig. 6

where f_F is the Fanning friction factor and $\sum F\uparrow + \sum \text{mom}\uparrow = 0$, we obtain

$$\frac{\delta P_j}{\delta x} = \frac{1}{\rho g_c}\left[-\frac{f_F \bar{p}_j}{2A_j} w_j^2 - \rho^2 g - \frac{\delta w_j^2}{\delta x} + \frac{G}{A_j}\sum_{a=1}^{3} w_{Taj}\,(w_{aj} - w_j) + \frac{G}{A_j}\sum_{a=1}^{3}\begin{cases} w_{Daj}\, w_{aj}, & w_{Daj} > 0 \\ w_{Daj}\, w_j, & w_{Daj} < 0 \end{cases}\right]$$

4. DIVERSION CROSSFLOW EQUATION

Consider two parallel interconnected channels 1 and 2 with the same cross-sectional areas and perimeters. Channel 1 has an inlet blockage so that at $x = 0$, $w_1 = 0$. For channel 2 at $x = 0$, $w_2 = 2\,w_\infty$. As $x \to \infty$, $w_1 = w_2 = w_\infty$. Diversion crossflow will be from channel 2 into channel 1. In this derivation the effects of sweeping crossflow will be neglected.

Writing Eq. (15) for each channel we have

$$\frac{dP_1}{dx} = \frac{1}{\rho g_c}\left[\frac{-f_F \bar{p}}{2A} w_1^2 - \rho^2 g - \frac{dw_1^2}{dx} + \frac{G}{A} w_T(w_2 - w_1) + \frac{G}{A} w_P w_2\right] \tag{16}$$

$$\frac{dP_2}{dx} = \frac{1}{\rho g_c}\left[\frac{-f_F \bar{p}}{2A} w_2^2 - \rho^2 g - \frac{dw_2^2}{dx} + \frac{G}{A} w_T(w_1 - w_2) - \frac{G}{A} w_P w_2\right] \tag{17}$$

Writing Eq. (2) for the two channels and differentiating with respect to x yields

$$\frac{dP_2}{dx} - \frac{dP_1}{dx} = \frac{1}{\rho g_c}\, C_D\, w_P \frac{dw_P}{dx} \tag{18}$$

Subtracting Eq. (16) from Eq. (17) and using Eq. (18), pressure terms can be eliminated yielding

$$C_D\, w_P \frac{dw_P}{dx} = \frac{f_F \bar{p}}{2A}(w_1^2 - w_2^2) + \frac{dw_1^2}{dx} - \frac{dw_2^2}{dx} + \frac{G}{A} 2w_T(w_1 - w_2) - \frac{2G}{A} w_P w_2 \tag{19}$$

From conservation of mass

$$w_1 + w_2 = 2\ w_\infty \tag{20}$$

and

$$\frac{dw_1}{dx} = -\frac{dw_2}{dx} = \frac{G}{A}\ w_P \tag{21}$$

The turbulent interchange relationship is

$$w_T = C_T(w_1 + w_2) \tag{22}$$

Substituting these into Eq. (19) and putting into dimensionless form by letting

$$s = \frac{xG}{A} \tag{23}$$

and

$$y = \frac{w_1}{w_\infty} \tag{24}$$

we obtain

$$\frac{C_D}{2}\ \frac{dy}{ds}\ \frac{d^2y}{ds^2} = \left(\frac{f_F\overline{p}}{G} + 4\ C_T\right)(y - 1) + y\ \frac{dy}{ds} \tag{25}$$

with the boundary conditions

$$y = 0 \text{ at } s = 0 \tag{26}$$

$$y = 1 \text{ at } s \to \infty \tag{27}$$

Letting

$$\frac{dy}{ds} = v \text{ so that } \frac{d^2y}{ds^2} = v\ \frac{dv}{dy} \tag{28}$$

Eq. (25) becomes

$$\frac{C_D}{2}\ v^2\ \frac{dv}{dy} = \left(\frac{f_F\overline{p}}{G} + 4\ C_T\right)(y - 1) + yv \tag{28}$$

with the boundary condition that $v = 0$ at $y = 1$.

Letting

$$q = \left(\frac{C_D}{6} v\right)^3 \tag{29}$$

and

$$C = \sqrt{\frac{C_D}{6}}\left(\frac{f_F \bar{p}}{G} + 4\ C_T\right) \tag{30}$$

This becomes

$$\frac{dq}{dy} = C(y - 1) + yq^{1/3} \tag{31}$$

with the boundary condition

$$q = 0 \text{ at } y = 1. \tag{32}$$

Equation (31) was solved numerically for $0 \leq y \leq 1$ and for $0.04 \leq C \leq 0.4$. The resulting family of curves was fit by the empirical expression

$$q^{1/3} = 0.75C^{0.44}\ (1 - y)^{0.80C^{-0.32}} \tag{33}$$

or in terms of the original equations

$$w_{P_{m\ell}} = 0.375 \sqrt{\frac{6}{C_D}}\ \frac{w_m^2 - w_\ell^2}{|w_m - w_\ell|}\ C^{0.44} \left(\frac{|w_m - w_\ell|}{w_m + w_\ell}\right)^{0.80C^{-0.32}} \tag{34}$$

where C is defined by Eq. (30).

Equation (34) is the relationship for pressure diversion crossflow used in the reported version of ØRRIBLE. This is not a completely satisfying procedure and work is continuing on this aspect. The numerical solution of Eq. (31) was not well behaved in the neighborhood of y = 1 but otherwise consistent results were obtained with different numerical techniques. It is tacitly assumed that results for two interconnected channels are applicable to multi-channel systems. Other procedures may be more valid, some of these are being investigated.

5. DESCRIPTION OF THE PROGRAM

If, for a given value of x, values of the channel axial mass velocities and temperatures are known, new values at $x + \delta x$ are computed using the following procedure. From Eqs. (1), (4), and (34) values of the crossflows at x are computed. Using this information and Eqs. (9) and (13), values of the axial mass velocities and temperatures at $x + \delta x$ are computed. A detailed description of this procedure is given in this section.

5.1 Referencing Arrays

In the system herein described there are 19 rods, 42 channels, and 60 gaps numbered as is shown in Fig. 1. The rods are indexed on I: I = 1, 19 indicating the real rods and I = 20 indicating a null rod or duct wall with no heat flux. The channels are indexed on J: J = 1, 42 indicating the real channels and J = 43 indicating a null channel. The gaps are indexed on K: K = 1, 60 indicating the real gaps, K = 61 indicating a null gap through which no interchange takes place.

In general, a channel is surrounded by three rods and three adjacent channels through three adjacent gaps. Use of the null elements allows this generality to be extended to the peripheral channels which are surrounded by one or two rods and the duct wall and two or three adjacent channels.

To identify the three rods surrounding a given channel, three integer arrays I1(J), I2(J), I3(J) are used which give the rod numbers in ascending order of the three rods surrounding the Jth channel. Similarly J1(J), J2(J), J3(J) give the channel numbers in ascending order of the three channels surrounding the Jth channel, and K1(J), K2(J), K3(J) give the gap numbers in ascending order of the three gaps surrounding the Jth channel. JK1(K) and JK2(K) give the channel numbers in ascending order of the two channels separated by the Kth gap.

In computing the total diversion crossflow through a given <u>gap</u> the convention is to consider it positive if flowing from the adjacent channel with the higher channel number to the adjacent channel with the lower channel number. In using the total diversion crossflow into a given <u>channel</u> the convention is to consider it positive if it flows into that channel.

This is accomplished by using arrays SK1(J), SK2(J), SK3(J) which contain only +1.0's and −1.0's as multipliers of the diversion crossflows to give them the correct signs for positive flow into the channel under consideration. Using the numbering system shown in Fig. 1, all values of SK3(J) are +1.0; hence this array was eliminated from ØRRIBLE.

In the LMFBR-FFM Bundle No. 2 the wire wrap at the start of the heated section is at the position designated 1.0 in Fig. 7, that is, referring to Fig. 1 the wire wrap around Rod 1 is directly in the gap between Rod 1 and Rod 7. The reported version of ØRRIBLE allows for different unheated entrance lengths and different wire wrap pitches but the parameters are always adjusted so that at the start of the heated section the wrap has the angular orientation shown in Fig. 7.

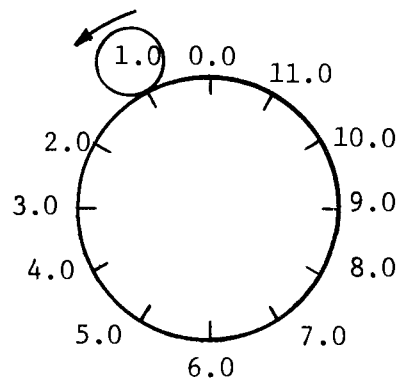

Fig. 7

The wire wrap has a right-hand pitch, i.e., in the direction of flow (increasing x), the wrap "moves" around the rod in a counter-clockwise direction when viewed looking into the source of the flow. The angle of the wrap for a given value of x is denoted by a parameter AW in terms of 30-degree increments. For example for the location shown in Fig. 7, AW = 1.0.

In general, each gap has a characteristic angle for the wire wrap causing the maximum negative sweeping crossflow through the gap, i.e., from the adjacent channel with a low channel number to the adjacent channel with the higher channel number; and a characteristic angle (180° out of phase) for the maximum positive sweeping crossflow through the gap. These characteristic angles are measured in 30-degree increments. By comparing the local value of AW with the two characteristic angles for a given gap it is possible to compute the magnitude and direction of the local sweeping crossflow through that gap. For convenience in ØRRIBLE A1(K) for K = 1, 43 are the characteristic angles for maximum negative sweeping crossflow. A2(K) for K = 1, 42 and A1(K) for K = 44, 60 are the characteristic angles for maximum positive sweeping crossflow. (Negative sweeping crossflow does not occur for K > 43.)

5.2 Input Data

The following input data are necessary to execute ØRRIBLE.

IS	Case number for identification purposes. It is printed at the beginning and end of the printed output of the execution.
NS	Number of axial length increments (δx) in the unheated starting length.
NH	Number of length increments in the heated section.
NT	Number of length increments in the total test section.
NP	Number of length increments between output tables. Tables of channel axial mass velocities and temperatures are printed every NP increments.
DX	δx, value of the axial length increment, ft.
CT	C_T, dimensionless turbulent crossflow coefficient.
CD	C_D, dimensionless pressure diversion crossflow coefficient.
CS	C_S, dimensionless sweeping crossflow coefficient.
FF	f_F, Fanning friction factor.
DIA	D, rod diameter, ft.
G	G, gap width, ft.
P	ϕ, pitch of the wire wrap, ft.
WG	Total flow into the system, lb_m/hr.
TI	Initial fluid temperature, °F.
CP	c_p, fluid specific heat, Btu/lb_m·°F.
CF	k, fluid thermal conductivity, Btu/hr.ft.°F.
QR(I),I = 1, 19	Linear heat rate of each of the rods in the heated section, Btu/hr·ft.
JB(J),J = 1, 42	Channel blockage factors. For JB(J) = 0, that channel is blocked at the inlet; for JB(J) = 1, the channel is open to flow.

5.3 Computational Arrays

The following arrays are used in computation

A(J)	A_j, area of each channel, ft^2.
GA(J)	G/A(J) for each channel, ft^{-1}.
W(J)	w_j, axial mass velocity in each channel, $lb_m/hr \cdot ft^2$.
T(J)	t_j, fluid temperature in each channel, °F.
Y(J)	$y_j = \delta w_j/\delta x$, $lb_m/hr \cdot ft^3$.
Z(J)	$z_j = \delta t_j/\delta x$, °F/ft.
Q(J)	From Eq. (12), proportional to heat added to each channel in the heated zone, $lb_m \cdot °F/hr \cdot ft^3$.
WT(K)	Turbulent transport through each gap, $lb_m/hr \cdot ft^2$.
WD(K)	Total diversion crossflow through each gap $lb_m/hr \cdot ft^2$.

5.4 Computational Procedure

ØRRIBLE consists of three sections: the primary routine MAIN, routine BLØCK DATA, and subroutine XFLØWS.

BLØCK DATA assigns the proper values to all elements of the referencing arrays and assigns zero to all values pertaining to the null rod, null channel and null gap.

XFLØWS computes WT(K) and WD(K). For convenience the transverse thermal conduction term is included in WT(K).

MAIN reads the data cards and computes all constants and array elements peculiar to the case being executed. All channels are assumed to have the same hydraulic diameter and geometric shape factor for transverse thermal conduction. The arrays W(J) and T(J) are set at the appropriate values for x = 0. A title block is printed which contains all input parameters and other useful calculated values.

XFLØWS is called to compute WD(K) and WT(K) at x = 0. Tables of W(J) and T(J) are printed for x = 0.

The remainder of MAIN is a do-loop which recomputes appropriate values for incrementally increasing values of x. In the unheated starting length all channel temperatures remain constant at the specified inlet value and the energy equation is not used. In the heated section the energy equation

is used to compute the channel temperatures. At the end of the heated zone all Q(J) are set at zero and the energy equation is retained in computation. At length intervals specified by the value of the integer NP, tables of W(J) and T(J) are printed.

At the end of computation, an end statement is printed signifying successful completion of the case.

5.5 Input Formats

A case is executed with ØRRIBLE using a set of six input data cards with the following formats

First card

Input: IS, NS, NH, NT, NP, DX, CT, CD, CS, FF

Format: 5I5, 5D11.4

Second card

Input: DIA, G, P, WG, TI, CP, CF

Format: 7D11.4

Third card

Input: QR(I), I = 1, 7

Format: 7D11.4

Fourth card

Input: QR(I), I = 8, 14

Format: 7D11.4

Fifth card

Input: QR(I), I = 15, 19

Format: 5D11.4

Sixth card

Input: JB(J), J = 1, 42

Format: I2, 41I1

A number of unrelated cases may be executed during the same computation session by using the appropriate number of sets of input data cards. Execution terminates when there are no more sets of data cards to be read.

5.6 FØRTRAN Listing of ØRRIBLE 081271

Following is the FØRTRAN listing of ØRRIBLE 081271. This version became operable on August 12, 1971.

```
COMMENT  THIS IS ORRIBLE 081271  19 RODS IN A HEX DUCT
      IMPLICIT REAL*8 (A-H, O-Z)
     0 COMMON/B/ OR(20), A(43), GA(43), W(43), T(43), Y(43), Z(43),
     1 Q(43), WT(61), WD(61), SK1(43), SK2(43), A1(60), A2(42),
     2 CS, CT, CF, CD, AW, PI2, FF
     0 COMMON/L/ I1(43), I2(43), I3(43), J1(43), J2(43), J3(43),
     1 K1(43), K2(43), K3(43), JK1(61), JK2(61), JB(42)
 100 0 READ 101, IS, NS, NH, NT, NP, DX, CT, CD, CS, FF,DIA,G,P,WG,TI,
     1 CP, CF, (QR(I), I = 1, 19), (JB(J), J = 1, 42)
  101 FORMAT (5I5, 5D11.4/ 7D11.4/ 7D11.4/ 7D11.4 /5D11.4/ I2, 41I1)
      D1 = NS *  DX
      D2 = NH *  DX
      D3 = NT *  DX
      D4 = NP *  DX
     0 PRINT 102, IS, D1, NS, D2, NH, D3, NT, D4, NP, DX, DIA, G, P, WG,
     1 TI,CP,CF,CT,CD,CS,FF,   (QR(I), I = 1, 19), (JB(J), J = 1, 42)
 102 0 FORMAT (1H1,'ORRIBLE 081271  19 RODS IN A HEX DUCT  CASE NUMBER',
     1 I6 // ' UNHEATED ENTRANCE LENGTH IS' , 1PE11.4 ,' FT IN', I6, ' I
     2NCREMENTS' / ' TO END OF HEATED SECTION IS' , E11.4 , ' FT IN',
     3 I6, ' INCREMENTS' / ' TOTAL LENGTH IS' , E11.4 , ' FT IN' , I6 ,
     4' INCREMENTS' / ' OUTPUT TABLES EVERY' , F11.4 , ' FT OR' , I6 ,
     5' INCREMENTS' / ' LENGTH PER INCREMENT IS' , E11.4 , ' FT'
     6                / ' ROD DIAMETER IS' , E11.4 , ' FT AND THE GAP BETW
     7EEN RODS IS' , F11.4 , ' FT' / ' WIRE WRAP IS A RIGHT HAND SPIRAL
     8WITH A PITCH OF' ,E11.4,' FT'/ ' TOTAL FLOW IS' , E11.4 , ' LBM/HR
     9 , INLET TEMPERATURE IS' , E11.4 , ' DEG F' / ' COOLANT SPECIFIC H
     AEAT IS' , E11.4 , ' BTU/LBM-DEG F' / ' COOLANT THERMAL CONDUCTIVIT
     BY IS' , E11.4 , ' BTU/HR-FT-DEG F' / ' TURBULENT CROSS FLOW FACTOR
     C IS' , E11.4  /   ' DIVERSION CROSS FLOW FACTOR IS' , E11.4  / ' S
     DWEEPING CROSS FLOW FACTOR IS', E11.4 / ' FANNING FRICTION FACTOR I
     ES', E11.4 / ' HEAT RATES IN BTU/HR/FT/ROD ARE ' , 8E11.4 / 11F11.4
     F /' CHANNEL BLOCKAGE FACTORS ARE',42I2                // ' LENGTH, F
     GT     FIRST ARRAY IS CHANNEL FLOWS IN LBM/HR-FT2
     H   SECOND ARRAY IS FLUID TEMPERATURES IN DEG F')
      CD = DSQRT(CD/6.0)
      FF = CD * (FF * PI2 * DIA/G + 4.0 * CT)
      CD = (0.375 * FF ** 0.44)/CD
      FF = 0.80 * FF ** (-0.32)
      CF = (1.38 * CF * (G/DIA) ** 0.674) / (G * CP)
      AW = 1.0 - 12.0 * D1 / P
  103 IF (AW.GE.0.0) GO TO 104
      AW = AW + 12.0
      GO TO 103
  104 IF (AW.LT.12.) GO TO 105
      AW = AW - 12.0
      GO TO 104
  105 AWI = 12.0 * DX / P
      CS = 2.0 * PI2 * CS * (DIA + G) / P
      D4 = 0.3926990818 * (G ** 2 + DIA ** 2)
      D1 = 0.4330127020 * (G + DIA) ** 2 - D4
      D2 = (G + DIA) * (G + 0.5 * DIA) - D4
      D3 = 0.5235987757 * G * (0.75 * G + DIA)
      D4 = G/D1
      DO 122 J = 1, 24
      A(J) = D1
  122 GA(J) = D4
      D4 = G/D2
      DO 123 J = 25, 41
```

```
      A(J) = D2
  123 GA(J) = D4
      D4 = G/D3
      DO 124 J = 27, 42, 3
      A(J) = D3
  124 GA(J) = D4
      D1 = 0.0
      DO 110 J = 1. 42
  110 D1 = D1 + JB(J) * A(J)
      D1 = WG / D1
      DO 120 J = 1, 42
  120 W(J) = D1 * JB(J)
      D4 = 1.0 / (6.0 * CP)
      DO 125 J = 1, 42
  125 Q(J) = D4 * (QR(I1(J)) + QR(I2(J)) + QR(I3(J)))
      DO 126 J = 25, 40, 3
      Q(J) = 1.5 * Q(J)
  126 Q(J+1) = 1.5 * Q(J+1)
      DO 127 J = 1, 42
      Q(J) = Q(J) / A(J)
  127 T(J) = TI
      CALL XFLOWS
      X = 0.0
      PRINT 128, X, (W(J), J = 1, 42)
  128 0 FORMAT (1H0, 1PE11.4, 10E12.4 / 12X, 10E12.4 / '     FLOW     ',
     1 10E12.4 / (12X, 10E12.4))
      PRINT 129, (T(J), J = 1, 42)
  129 0 FORMAT (1H0, 11X,   1P10E12.4 / 12X, 10E12.4 / '     TEMP     ',
     1 10E12.4 / (12X, 10E12.4))
      NC = 0
      DO 170 N = 1, NT
      X = X + DX
      AW = AW + AWI
      IF (AW.GE.12.) AW = AW - 12.0
      IF (N.GT.NS) GO TO 153
      DO 150 J = 1, 42
  150 0 Y(J) = GA(J) * (WD(K1(J)) * SK1(J) + WD(K2(J)) * SK2(J)
     1 + WD(K3(J)))
      GO TO 156
  153 DO 154 J = 1, 42
      D1 = WD(K1(J)) * SK1(J)
      D2 = WD(K2(J)) * SK2(J)
      D3 = WD(K3(J))
      Y(J) = GA(J) * (D1 + D2 + D3)
      D4 = T(J1(J))
      IF (D1.LT.0.0) D4 = T(J)
      D5 = T(J2(J))
      IF (D2.LT.0.0) D5 = T(J)
      D6 = T(J3(J))
      IF (D3.LT.0.0) D6 = T(J)
  154 0 Z(J) = (Q(J) - Y(J) * T(J) + GA(J) * (D1 * D4 + D2 * D5 + D3 * D6
     1 + WT(K1(J)) * (T(J1(J)) - T(J)) + WT(K2(J)) * (T(J2(J)) - T(J)) +
     2 WT(K3(J)) * (T(J3(J)) - T(J)))) / (W(J) + Y(J) * DX)
      DO 155 J = 1, 42
  155 T(J) = T(J) + Z(J) * DX
  156 DO 157 J = 1, 42
  157 W(J) = W(J) + Y(J) * DX
      CALL XFLOWS
```

```
      NC = NC + 1
      IF (NC.LT.NP) GO TO 151
      NC = 0
      PRINT 128, X, (W(J), J = 1, 42)
      PRINT 129, (T(J), J = 1, 42)
  151 IF (N.NE.NH) GO TO 170
      DO 152 J = 1, 42
  152 Q(J) = 0.0
  170 CONTINUE
      PRINT 180, IS
  180 FORMAT (1H0,'THIS IS THF END OF CASE NUMBER',I6)
      GO TO 100
  190 STOP
      END


      SUBROUTINE XFLOWS
      IMPLICIT REAL*8 (A-H, O-Z)
     0 COMMON/B/ QR(20), A(43), GA(43), W(43), T(43), Y(43), Z(43),
     1 Q(43), WT(61), WD(61), SK1(43), SK2(43), A1(60), A2(42),
     2 CS, CT, CF, CD, AW, PI2, FF
     0 COMMON/L/ I1(43), I2(43), I3(43), J1(43), J2(43), J3(43),
     1 K1(43), K2(43), K3(43), JK1(61), JK2(61), JB(42)
      DO 158 K = 1, 60
      D1 = W(JK1(K))
      D2 = W(JK2(K))
      D3 = DABS(D2 - D1)
      WD(K) = 0.0
      IF (D3.EQ.0.0) GO TO 158
      WD(K) = ((D2 - D1) * (D2 + D1) * CD/D3) * (D3/(D2 + D1)) ** FF
  158 WT(K) =CF + CT * (DABS(D1) + DABS(D2))
      DO 162 K = 1, 42
      D3 = 0.0
      D4 = 0.0
      D1 = DABS(AW - A1(K))
      IF (D1.GT.10.) D1 = 12.0 - D1
      IF (D1.GE.2.0) GO TO 161
      D3 = 0.5 * (1.0 + DCOS(PI2 * D1))
      GO TO 162
  161 D1 = DABS(AW - A2(K))
      IF (D1.GT.10.) D1 = 12.0 - D1
      IF (D1.GE.2.0) GO TO 162
      D4 = 0.5 * (1.0 + DCOS(PI2 * D1))
  162 WD(K) = WD(K) + CS * (D4 * W(JK2(K)) - D3 * W(JK1(K)))
      D1 = DABS(AW - A1(43))
      IF (D1.GT.10.) D1 = 12.0 - D1
      IF (D1.GE.2.0) GO TO 163
      D3 = 0.5 * (1.0 + DCOS(PI2 * D1))
      WD(43) = WD(43) - CS * D3 * W(25)
  163 DO 164 K = 44, 60
      D1 = DABS(AW - A1(K))
      IF (D1.GT.10.) D1 = 12.0 - D1
      IF (D1.GE.2.0) GO TO 164
      D3 = 0.5 * (1.0 + DCOS(PI2 * D1))
      WD(K) = WD(K) + CS * D3 * W(JK2(K))
  164 CONTINUE
      RETURN
      END
```

```
      BLOCK DATA
      IMPLICIT REAL*8 (A-H, O-Z)
     0 COMMON/B/ QR(20), A(43), GA(43), W(43), T(43), Y(43), Z(43),
     1 Q(43), WT(61), WD(61), SK1(43), SK2(43), A1(60), A2(42),
     2 CS, CT, CF, CD, AW, PI2, FF
     0 COMMON/L/ I1(43), I2(43), I3(43), J1(43), J2(43), J3(43),
     1 K1(43), K2(43), K3(43), JK1(61), JK2(61), JB(42)
     0 DATA QR(20) / 0.0 /, A(43) / 0.0 /, GA(43) / 0.0 /, W(43) / 0.0
     1 /, T(43) / 0.0 /, Y(43) / 0.0 /, Z(43) / 0.0 /, Q(43) / 0.0 /,
     2 WT(61) / 0.0 /, WD(61) / 0.0 / , PI2 / 1.570796326794897 /
     0 DATA SK1 / 1., 41*-1., 1. /, SK2 / 5*1.,-1., 1., 1., 1.,-1., 1.,
     1  1.,-1., 1., 1.,-1., 1., 1.,-1., 1., 1.,-1., 1.,-1., 1.,-1., 1.,
     2 -1.,-1., 1.,-1.,-1., 1.,-1.,-1., 1.,-1.,-1., 1.,-1.,-1.,-1., 1./
     0 DATA A1/ 3., 1.,11., 9., 7.,11., 7., 5., 3., 1.,11., 9., 7., 5.,
     1  3., 5., 3., 1., 3., 1.,11., 1.,11., 9.,11., 9., 7., 9., 7.,11.,
     2  9., 7., 7., 5., 5., 3., 3., 1., 1.,11.,11., 9., 0., 0., 0.,10.,
     3 10.,10., 8., 8., 8., 6., 6., 6., 4., 4., 4., 2., 2., 2./,A2/ 9.,
     4  7., 5., 3., 1., 5., 1.,11., 9., 7., 5., 3., 1.,11., 9.,11., 9.,
     5  7., 9., 7., 5., 7., 5., 3., 5., 3., 1., 3., 1., 5., 3., 1., 1.,
     6 11.,11., 9., 9., 7., 7., 5., 5., 3./
     0 DATA I1 / 1, 1, 1, 1, 1, 1, 2, 2, 2, 2, 3, 3, 3, 4, 4, 4, 5, 5,
     1  5, 6, 6, 6, 7, 7,18, 8, 8, 8, 9,10,10,11,12,12,13,14,14,15,16,
     2 16,17,18,20 /,  I2 /  2, 3, 4, 5, 6, 2, 7, 8, 8, 3, 9,10, 4,11,
     3 12, 5,13,14, 6,15,16, 7,17,18,19,19,20, 9,10,20,11,12,20,13,14,
     4 20,15,16,20,17,18,20,20 /,  I3 /  3, 4, 5, 6, 7, 7,19,19, 9, 9,
     5 10,11,11,12,13,13,14,15,15,16,17,17,18,19,19*20/
     0 DATA J1 / 2, 1, 2, 3, 4, 1, 6, 7, 8, 1,10,11, 2,13,14, 3,16,17,
     1  4,19,20, 5,22, 7,24, 8,26, 9,11,29,12,14,32,15,17,35,18,20,38,
     2 21,23,25,43 /,  J2 /  6, 3, 4, 5, 6, 5, 8, 9,10, 9,12,13,12,15,
     3 16,15,18,19,18,21,22,21,24,23,26,25,28,27,28,31,30,31,34,33,34,
     4 37,36,37,40,39,40,41,43 /,  J3 / 10,13,16,19,22, 7,24,26,28,11,
     5 29,31,14,32,34,17,35,37,20,38,40,23,41,25,42,27,43,29,30,43,32,
     6 33,34,35,36,43,38,39,43,41,42,43,43 /
     0 DATA K1 / 1, 1, 2, 3, 4, 5,12,13,14, 7,16,17, 8,19,20, 9,22,23,
     1 10,25,26,11,28,29,42,31,45,32,33,48,34,35,51,36,37,54,38,39,57,
     2 40,41,43,61 /,  K2 /  6, 2, 3, 4, 5, 6,13,14,15,15,17,18,18,20,
     3 21,21,23,24,24,26,27,27,29,30,43,44,46,46,47,49,49,50,52,52,53,
     4 55,55,56,58,58,59,60,61 /,  K3 /  7, 8, 9,10,11,12,30,31,32,16,
     5 33,34,19,35,36,22,37,38,25,39,40,28,41,42,44,45,61,47,48,61,50,
     6 51,61,53,54,61,56,57,61,59,60,61,61 /
     0 DATA JK1/ 1, 2, 3, 4, 5, 1, 1, 2, 3, 4, 5, 6, 7, 8, 9,10,11,12,
     1 13,14,15,16,17,18,19,20,21,22,23, 7, 8, 9,11,12,14,15,17,18,20,
     2 21,23,24,25,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,
     3 43 /, JK2 /  2, 3, 4, 5, 6, 6,10,13,16,19,22, 7, 8, 9,10,11,12,
     4 13,14,15,16,17,18,19,20,21,22,23,24,24,26,28,29,31,32,34,35,37,
     5 38,40,41,25,42,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,
     6 42,43 /
      END
```

6. NØMENCLATURE

6.1 Non-indexed

$$C = \sqrt{\frac{C_D}{6}} \left(\frac{f_F \overline{p}}{G} + 4\ C_T \right)$$

C_D = pressure diversion crossflow coefficient

C_F = $k\ F_S/G\ c_p$, $lb_m/hr \cdot ft^2$

c_p = fluid specific heat, $Btu/lb_m \cdot °F$

C_S = sweeping crossflow coefficient

C_T = turbulent crossflow coefficient

D = rod diameter, ft

f_F = Fanning friction factor

F_S = geometric shape factor, see Eq. (5)

G = gap width, ft

g = attraction of gravity, ft/hr

g_c = gravitational conversion factor, $4.170 \times 10^8\ lb_m \cdot ft/lb_f \cdot hr^2$

k = fluid thermal conductivity, $Btu/hr \cdot ft \cdot °F$

$\overline{p}$ = channel perimeter, ft

x = length in direction of flow, ft

δ = incremental increase, e.g.,

δx = incremental increase in x, ft

θ = local angle of the wire wrap, degrees, see Eq. (4)

ρ = fluid density, lb_m/ft^3

ϕ = wire wrap pitch, ft

6.2 Indexed

A_ℓ = cross-sectional area of the ℓth channel, ft^2

P_ℓ = pressure in the ℓth channel, lb_f/ft^2

$\overline{p}_\ell$ = perimeter of the ℓth channel, ft

t_ℓ = temperature in the ℓth channel, °F

u_ℓ = w_ℓ/ρ, velocity in the ℓth channel, ft/hr

w_ℓ = mass velocity in the ℓth channel, $lb_m/hr \cdot ft^2$

y_ℓ = $\delta w_\ell/\delta x$, $lb_m/hr \cdot ft^3$

z_ℓ = $\delta t_\ell/\delta x$, °F/ft

τ_ℓ = wall shear in the ℓth channel, lb_f/ft^2

$q_{c_{\ell m}}$ = heat transferred by conduction from the ℓth channel to the mth channel, Btu/hr

$w_{T_{\ell m}}$ = turbulent mass velocity between the ℓth channel and the mth channel ($w_{T_{\ell m}} = w_{T_{m\ell}}$) $lb_m/hr \cdot ft^2$

$w_{D_{\ell m}}$ = $w_{P_{\ell m}} + w_{S_{\ell m}}$, $lb_m/hr \cdot ft^2$

$w_{P_{\ell m}}$ = pressure diversion crossflow from the ℓth channel to the mth channel, $lb_m/hr \cdot ft^2$

$w_{S_{\ell m}}$ = sweeping crossflow from the ℓth channel to the mth channel, $lb_m/hr \cdot ft^2$

q_{bj} = heat transferred to the jth channel from each of the three rods surrounding it (b = 1, 2, 3), Btu/hr·ft

f_{bj} = fraction of each of the three surrounding rods exposed to the jth channel (b = 1, 2, 3)

$q_j = \frac{1}{c_p A_j} \sum_{b=1}^{3} f_{bj} q_{bj}$, heat received by the jth channel from the three rods surrounding it, $°F \cdot lb_m/hr \cdot ft^2$

t_{aj} = temperature in each of the three channels surrounding the jth channel (a = 1, 2, 3), °F

u_{aj} = w_{aj}/ρ, velocity in each of the three channels surrounding the jth channel (a = 1, 2, 3), ft/hr

w_{aj} = mass velocity in each of the three channels surrounding the jth channel (a = 1, 2, 3), $lb_m/hr \cdot ft$

w_{Daj} = total diversion crossflow into the jth channel from each of the three channels surrounding it (a = 1, 2, 3) $lb_m/hr \cdot ft^2$

w_{Taj} = turbulent crossflow between the jth channel and each of the three channels surrounding it (a = 1, 2, 3), $lb_m/hr \cdot ft^2$

REFERENCES

1. R. E. MacPherson and M. H. Fontana, Fuel-Failure Mockup Program Plan, USAEC Report ORNL-TM-2529 (June 1969).
2. Wm. B. Cottrell, ORNL Nuclear Safety Research and Development Program Bimonthly Report for July—August 1971, USAEC Report ORNL-TM- (to be issued).
3. D. S. Rowe, Crossflow Mixing Between Parallel Flow Channels During Boiling, Part I, CØBRA — Computer Program for Coolant Boiling in Rod Arrays, BNWL-371, Pt. 1, Pacific Northwest Laboratory, Richland, Washington (March 1967).
4. J. T. Rogers and N. E. Todreas, "Coolant Interchannel Mixing in Reactor Fuel Rod Bundles Single-Phase Coolants," in Heat Transfer in Rod Bundles, American Society of Mechanical Engineers, New York (1968).
5. A. Fukuda, Measurement of Shape Factors for Transverse Conduction Between Rods, USAEC Report ORNL-TM- (to be issued).

Internal Distribution

1. R. K. Adams
2. A. H. Anderson
3. S. E. Beall
4. J. P. Blakely
5. R. H. Bryan
6. J. R. Buchanan
7. R. M. Burnett
8. D. W. Cardwell
9. C. J. Claffey
10. D. L. Clark
11. Wm. B. Cottrell
12. J. S. Crowell
13. F. L. Culler, Jr.
14-18. M. H. Fontana
19. A. P. Fraas
20. D. N. Fry
21. W. R. Gambill
22. P. A. Gnadt
23. A. G. Grindell
24. W. O. Harms
25. F. A. Heddleson
26. D. N. Hess
27. H. W. Hoffman
28. B. L. Houser
29. P. R. Kasten
30. J. O. Kolb
31. E. M. Lees
32. M. I. Lundin
33. R. N. Lyon
34. R. E. MacPherson
35. C. D. Martin
36. H. C. McCurdy
37. A. J. Miller
38. R. L. Moore
39. L. F. Parsly
40. A. M. Perry
41. H. B. Piper
42. M. W. Rosenthal
43. T. H. Row
44. O. W. Russ
45. J. P. Sanders
46. R. L. Scott
47. Myrtleen Sheldon
48. M. J. Skinner
49. I. Spiewak
50. D. A. Sundberg
51. D. B. Trauger
52-76. J. L. Wantland
77. M. L. Winton
78. G. D. Whitman
79-80. Central Research Library
81. Y-12 Document Reference Section
82-84. Laboratory Records Dept.
85. Laboratory Records Dept. (RC)
86-220. Laboratory Records Dept. (Fast Reactor Exchange Program Dist.)
221-540. Laboratory Records Dept. (Nuclear Safety Reports Dist.)

External Distribution

541. R. M. Crawford, Argonne National Laboratory, 9700 S. Cass Ave., Argonne, Ill. 60439
542. R. P. Denise, Division of Reactor Development and Technology, USAEC, Washington, D.C. 20545
543. F. Goldner, Division of Reactor Development and Technology, USAEC, Washington, D.C. 20545
544. Art Graves, Atomics International, P.O. Box 309, Canoga Park, Calif. 91304
545. Pat Magee, General Electric Co., 310 DeGuigne Drive, Sunnyvale Calif. 94086
546. D. R. Riley, Division of Reactor Development and Technology USAEC, Washington, D.C. 20545

547. D. Rowe, Pacific Northwest Laboratories, P.O. Box 999, Richland, Wash. 99352
548. R. M. Scroggins, Division of Reactor Development and Technology, USAEC, Washington, D.C. 20545
549. J. B. Van Erp, Argonne National Laboratory, 9700 S. Cass Ave., Argonne, Ill. 60439
550-551. Division of Technical Information Extension (DTIE)
552. Laboratory and University Division, ORO
553. Patent Office, AEC, ORO