NUREG/CR-0994
LA-7965-MS
Informal Report

A Radiative Heat Transfer Model for the TRAC Code

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Informal Report
R-4

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Manuscript submitted: July 1979
Date published: November 1979

Prepared for
Office of Nuclear Regulatory Research
Division of Reactor Safety Research
US Nuclear Regulatory Commission
Washington, DC 20555

NRC FIN No. 7016

UNITED STATES
DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

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by

David A. Mandell

ABSTRACT

This report describes a radiative heat transfer model proposed for the boiling water reactor (BWR) version of the Transient Reactor Analysis Code (TRAC). The model includes radiative heat transfer to the nonequilibrium two-phase fluid, as well as surface-to-surface radiative heat transfer. Radiative properties and geometric view factors are calculated. It is assumed that each surface is a gray surface and that the liquid and vapor are gray fluids. A stand-alone code RADHT is described, and this code was used to examine the effect of the void fraction, liquid droplet diameter, vapor temperature, wall emissivity, and the number of rod groups. The results show that five rod groups (including the channel wall) are sufficient to describe the radiative heat transfer in a BWR bundle. The results also show that radiative heat transfer to the two-phase mixture should be considered in addition to surface-to-surface effects.

I. INTRODUCTION

This report describes the proposed radiative heat transfer models and methods to be incorporated into the Transient Reactor Analysis Code (TRAC).[1] These models are for the boiling water reactor (BWR) version of the code and the coding is written in a very modular form, as is the entire TRAC code, so that model improvements can be made easily. Initially, simplifying assumptions will be made to reduce the complexity and cost of the model. These assumptions will be examined using a small test code called RADHT, which is independent of the TRAC code. If it is necessary for accurate results, the initial assumptions will be relaxed and more detailed models will be implemented into the code. The initial, general model will include surface-to-surface radiative heat transfer and radiative heat transfer to the vapor and liquid droplets.

Radiative heat transfer models for nuclear reactor applications have been presented by a number of authors, and these models involve various simplifying assumptions. In some cases the surface-to-surface radiative heat transfer is

calculated in great detail, and the radiative heat transfer to the fluid is not considered. In other cases, the reverse is used. Brief descriptions of some of the models follow.

Sorensen et al.[2] consider only surface-to-surface radiative heat transfer in a BWR bundle. Each rod, as well as the channel, is considered to be a single surface. A maximum of 64 rods can be used and each rod can have a different diameter. Naitoh, Kawabe, and Chino[3] use a similar model, but they allow circumferential variations in the outside temperatures of the fuel rods and separate each rod into 24 surfaces. Gray surfaces (surfaces with radiative properties independent of wavelength) are assumed in both of these models. Andersen[4] separates the surface-to-surface radiative heat transfer into two components -- isotropic and anisotropic. In addition, Andersen considers radiative heat transfer to the vapor and liquid droplets.

Deruaz and Petitpain[5] consider radiative heat transfer to a two-phase mixture and also scattering by the liquid droplets. They derive the equation of transfer for the two-phase mixture and approximate the nongray nature of the mixture by using the box model in spectral regions where water vapor absorption bands occur and allowing for windows in the remainder of the spectrum. The box model neglects the wings of the spectral lines and underpredicts the spectral absorption in the central portion of the band. Therefore, the absorption by the mixture is underpredicted for large path lengths.[6] The equation of transfer is solved using the Milne-Eddington approximation, which converts the integrodifferential equation into two differential equations. The resulting solutions apply only to a two-phase mixture contained within a cylinder. Surface-to-surface radiative heat transfer is thus not modeled.

Giles[7] allows N surfaces, does not consider scattering by the liquid droplets, and takes the liquid into account only by weighting the transmissivity by the void fraction. The box model is used in the band regions, but the window regions do not appear to be considered.

Sun, Gonzales-Santalo, and Tien[8] consider radiative heat transfer from the wall to the vapor, from the wall to the droplets, and from the vapor to the droplets. Surface-to-surface radiative heat transfer is not considered, nor is scattering. They assume an optically thin two-phase mixture. (A fluid is optically thin if the extinction coefficient times the characteristic dimension is much less than one at all wavelengths.)

Shaffer[9] assumes no liquid is present. He allows N surfaces and assumes that the water vapor absorption bands are step functions as in the box model. Chan and Grolmes[10] consider droplets only and not the surface-to-surface radiative heat transfer or the radiative heat transfer to the vapor. They consider parallel plates and use a two-flux model, resulting in two differential equations that are similar to the equations obtained by using the Milne-Eddington approximation. McCreery and Hendrix[11] consider radiative heat transfer to the vapor and also to the droplets, but details of the model are not given in Ref. 11.

NORCOOL[12] contains a radiative heat transfer model similar to the model in CORECOOL.[4] The model allows for N surfaces and radiative heat transfer to an optically thin two-phase mixture is considered. However, scattering is not modeled. Karyampudi and Chon[13] decouple the surface-to-surface radiative heat transfer from the radiation to the vapor, which is assumed to be a gray gas. Liquid effects are not considered.

II. RADIATIVE HEAT TRANSFER ANALYSIS

The present model considers the radiative heat transfer in one BWR bundle only. The geometry being considered is shown in Fig. 1. The RADHT code allows for a maximum of 96 individual surfaces [(8 x 8 = 64 rods) + (4 x 8 = 32 channel segments)]. These surfaces can be arbitrarily grouped into a maximum of 37 rod groups for the radiative heat transfer calculation.

The general structure of the proposed radiative heat transfer model to be implemented into the BWR version of the TRAC code will be discussed in this section. The radiative properties needed for the analysis, such as the view factors, transmissivity, and absorptivity, will be discussed in the next section. First the basic assumptions will be discussed. Second, the general framework needed for an analysis considering a nongray vapor will be presented.

A. Assumptions

Radiative heat transfer within an absorbing, emitting, and scattering medium is governed by integrodifferential equations. These equations can be solved analytically only for very simple geometries and/or only for limiting conditions, such as an optically thin or optically thick gas.[14-16] Because numerical solutions of these equations are also formidable, the most general model considered in this report will involve a number of assumptions. The following assumptions will be made.

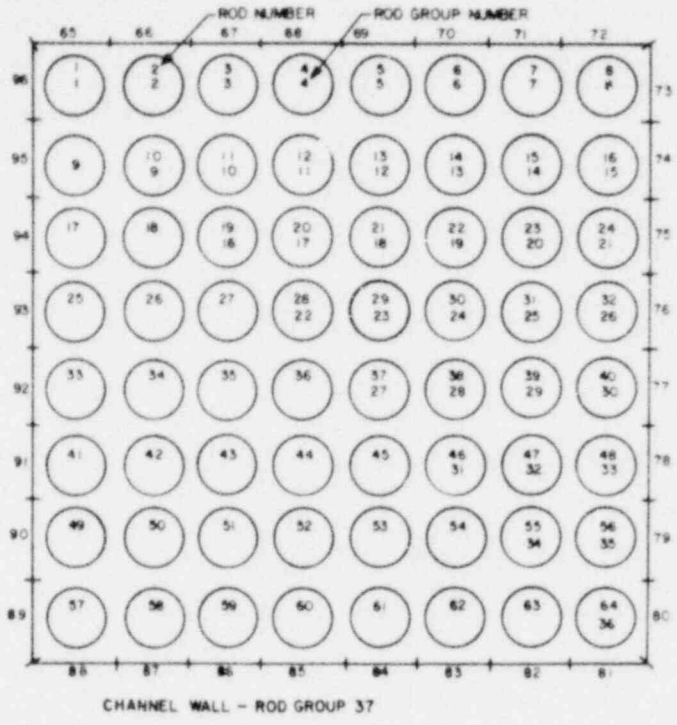

Fig. 1. An 8 x 8 rod group sketch.

(1) The N surfaces are gray and diffuse (emission and reflection).

(2) Each rod is one surface at a constant temperature and the channel wall is one surface.

(3) Axial radiative heat transfer is negligible.

(4) The gas is gray, that is, both the vapor and liquid absorption coefficients are independent of wavelength.

(5) At a given horizontal location, the water vapor is at a constant, known temperature, which may be different from the water droplet temperature. (The temperature from the previous time step will be used.)

(6) At a given horizontal location, the water droplets are at a constant, known temperature, which may be different from the water vapor temperature.

(7) Scattering will be neglected.

B. Basic Equations

The basic equations for the net radiative heat flux from each surface to the other surfaces and to the two-phase mixture can be derived in a manner similar to the single-phase equations derived by Siegel and Howell.[14] For a gray gas, the resulting set of equations is

$$\sum_{j=1}^{N} \left[\frac{\delta_{kj}}{\varepsilon_j} - F_{kj} \frac{\left(1-\varepsilon_j\right)}{\varepsilon_j} \bar{\tau}_{kj} \right] q_j = \sum_{j=1}^{N} \left[\left(\delta_{kj} - F_{kj} \bar{\tau}_{kj} \right) \sigma T_j^4 \right.$$

$$\left. + \varepsilon_{kj}^{V} F_{kj} \sigma T_V^4 + \varepsilon_{kj}^{L} F_{kj} \sigma T_L^4 \right] , \tag{1}$$

where q_j is the net heat flux leaving surface j. The transmissivity $\bar{\tau}_{kj}$, the emissivities ε_{kj}^{V} and ε_{kj}^{L}, and the view factor F_{kj} are discussed below. (Nomenclature is defined in Appendix A.) It should be noted that ε_{kj}^{V} is the vapor emissivity in the presence of droplets, and ε_{kj}^{L} is the droplet emissivity in the presence of the vapor. The methods used in NORCOOL[12] for obtaining ε_{kj}^{V} and ε_{kj}^{L} will be used here.

Once the net heat flux leaving each surface is known, the total energy absorbed by the two-phase mixture can be found.

$$Q_{mix} = \sum_{k=1}^{N} A_k q_k . \tag{2}$$

Because nonequilibrium hydraulics are used in the TRAC code,[1] it is necessary to know the radiative heat flux from the walls to the vapor Q_V and the radiative heat flux from the walls to the liquid droplets Q_L. The sum of these two quantities must equal the total radiative flux to the mixture Q_{mix}.

$$Q_{mix} = Q_V + Q_L . \tag{3}$$

To find Q_V and Q_L, one additional equation is needed. This equation can be derived by considering two surfaces and the emission and absorption of radiant energy within the fluid between these two surfaces. If the radiant energy leaving surface k is $dq_{ok} A_k$ ($dq_{ok} \equiv B_k$ is the radiosity), then a fraction of this energy reaches surface j, $dq_{ok} A_k F_{kj} \bar{\tau}_{kj}$, and a fraction of the energy is absorbed in the vapor before it reaches surface j,

$$dq_{ok} A_k F_{kj} \alpha_{kj}^{V} .$$

The energy emitted from the vapor is[14]

$$A_k F_{kj} \varepsilon^v_{kj} \sigma T_v^4 .$$

The difference between these two quantities is the net energy absorbed by the vapor in the region between surfaces k and j;

$$Q_v = A_k F_{kj} \left(\alpha^v_{kj} B_k - \varepsilon^v_{kj} \sigma T_v^4 \right) . \tag{4}$$

It should be noted that the absorptivity α^v_{kj} in Eq. (4) is the absorptivity of the vapor corrected for the presence of the droplets.

The radiosity is the energy flux leaving the surface.[14]

$$dq_{ok} \equiv B_k = \varepsilon_k e_{bk} + \rho_k dq_{jk} , \tag{5}$$

and the net flux from the surface is

$$q_k = B_k - q_{jk} , \tag{6}$$

where q_{jk} is the energy reaching surface k from surface j, and q_k is obtained from Eq. (1). The radiosity can then be obtained from Eqs. (5) and (6).

By summing Eq. (4) over all surfaces, the total net radiative flux to the vapor is obtained.

$$Q_v = \sum_{j=1}^{N} \sum_{k=1}^{N} A_k F_{kj} \left[\alpha^v_{kj} B_k - \varepsilon^v_{kj} e_b(T_v) \right] . \tag{7}$$

In a similar manner, the net radiative heat transfer to the liquid droplets can be obtained.

$$Q_L = \sum_{j=1}^{N} \sum_{k=1}^{N} A_k F_{kj} \left[\alpha^L_{kj} B_k - \varepsilon^L_{kj} e_b (T_L) \right] . \tag{8}$$

The gray-fluid assumption made above has been shown by Cess, Mighdoll, and Tiwari[6] to overpredict the radiative heat transfer when compared to a nongray analysis. If a nongray analysis is used, there are six bands of water vapor spectral lines and seven window regions between the bands to be considered. Therefore, thirteen matrix equations would have to be solved instead of the one matrix equation required in the gray-fluid approximation for each core node at

each time step. The computer running time in a systems code, such as TRAC, would be excessive for a nongray analysis, and therefore, the gray-fluid model described above is proposed for the initial BWR version of the TRAC code. If data comparisons show that a more detailed radiative heat transfer model is required, one can be implemented.

III. RADIATION PROPERTIES

To solve the equations discussed in the previous section, it is necessary to calculate values for the following quantities.

(1) The fraction of energy leaving surface i that reaches surface j when the intervening medium does not absorb, emit, or scatter radiation F_{ij}.

(2) The transmissivity of the mixture $\bar{\tau}_{ij}$ for the gray mixture.

(3) The absorptivity that can be found from the corresponding transmissivity $\bar{\alpha} = 1 - \bar{\tau}$.

(4) The absorptance of the vapor in the presence of the droplets.

(5) The absorptance of the droplets in the presence of the vapor.

(6) The vapor and liquid two-phase properties.

The emissivity of the gray walls is assumed to be a known constant, which may be different for each surface and which may change when the surfaces are wet. The blackbody emissive power $e_{b\lambda}(T)$ is given by Planck's law[15]

$$e_{b\lambda}(T) = \frac{2\pi h C_o^2}{n^2 \lambda^5 \left[e^{hC_o / n\lambda kT} - 1 \right]} . \tag{9}$$

For the gray-gas assumption and n = 1,

$$e_b(T) = \int_o^\infty e_{b\lambda}(T)\, d\lambda = \sigma T^4 . \tag{10}$$

A. The View Factor F_{ij}

The view factor F_{ij} (also called shape factor, angle factor, or configuration factor) is the fraction of energy leaving surface i that reaches surface j when the fluid between the surfaces does not participate in the radiative heat transfer process. The view factors depend only on the bundle geometry, and they can be calculated by the crossed-string method.[16] The equations for the view factors needed here are discussed in Appendix B. These view factors

include the view factors between every pair of rods, between each rod and each channel segment, and between each pair of channel segments. For a BWR bundle, with N x N rods, the channel wall is divided into 4N segments. This is discussed more fully in Appendix B. The number of calculations can be reduced by using the reciprocity rule[15]

$$A_i F_{ij} = A_j F_{ji} . \tag{11}$$

The calculations can be checked by using conservation of energy[15]

$$\sum_{j=1}^{N} F_{ij} = 1 . \tag{12}$$

The calculation of rod-to-rod view factors is discussed in Ref. 17.

B. The Transmissivity $\bar{\tau}_{ij}$

The transmissivity needed in Eq. (1) is considerably more difficult to evaluate than the view factor because the transmissivity depends on the properties of the two-phase mixture, which change with time, in addition to the geometry. The definition of the spectral transmissivity is given by Siegel and Howell.[14]

$$F_{jk} \bar{\tau}_{\lambda jk} = \frac{1}{A_j} \int_{A_k} \int_{A_j} \frac{\tau_\lambda(S) \cos \beta_k \cos \beta_j}{\pi S^2} \, dA_j \, dA_k , \tag{13}$$

where $\tau_\lambda(S)$ is the mixture value in the present work. The quantity $A_j F_{jk} \bar{\tau}_{\lambda jk}$ is called the geometric transmission factor.[14]

For a gray mixture, τ_λ is independent of λ and equal to $e^{-\kappa S}$ where the mixture absorption coefficient κ is independent of S but is a function of temperature. The κ is the sum of the vapor absorption coefficient κ^V and the liquid absorption coefficient κ^L. By assuming S is approximately constant and equal to the geometric mean beam length, the transmissivity needed in Eq. (1) becomes

$$\tau_{ij} = e^{-\left(\kappa L_{ij}\right)} .$$

C. The Absorptivity $\bar{\alpha}_{ij}$

The absorptivity is found from the equation[14]

$$F_{jk}\,\bar{\alpha}_{\lambda jk} = \frac{1}{A_j}\int_{A_k}\int_{A_j}\frac{\alpha_\lambda(S)\cos\beta_k\cos\beta_j}{\pi S^2}\,dA_j\,dA_k\,, \tag{14}$$

where $A_j\,F_{jk}\,\bar{\alpha}_{\lambda jk}$ is called the geometric absorption factor. The general comments made regarding the evaluation of the transmissivity $\bar{\tau}$ also apply to $\bar{\alpha}$. Here

$$\alpha = 1 - e^{-\kappa S} = 1 - \tau\,.$$

The geometric mean beam length L_{ij} is defined by the equation

$$L_{ij} = \frac{1}{A_i F_{jk}}\int_{A_j}\int_{A_i}\frac{\cos\beta_i\cos\beta_j}{\pi S}\,dA_i\,dA_j\,. \tag{15}$$

The geometric mean beam length is independent of the properties of the mixture and depends only on the geometry. Thus, L_{ij} can be evaluated once for a particular fuel bundle. See Appendix C for detailed calculations of the mean beam lengths.

Because Eq. (15) is difficult to evaluate for a fuel rod bundle, the geometric mean beam length will be taken equal to an equivalent distance between flat surfaces, as was done in NORCOOL.[12]

D. The Absorption Coefficient of Water Vapor

In the general case, to calculate the transmissivity and absorptivity of the two-phase mixture, the absorption and scattering coefficients must be known as a function of wavelength and also as a function of the conditions of the mixture. The water vapor coefficients will be discussed in this section and the coefficients for the droplets will be discussed in the next section.

Radiative properties are discussed in Refs. 18-20. Edwards[20] reviews the models and methods for the calculation of radiative properties of gases. He discusses a number of models for individual spectral lines and for bands of lines, as well as the calculation of the transmissivity and absorptivity. In addition to the engineering literature discussed above,[16,20] a significant amount of water vapor information is available in the atmospheric sciences literature, for example Ref. 21.

The calculation of total radiative heat transfer properties, such as the transmissivity or absorptivity, directly from the spectral absorption

coefficients is a costly calculation because a large part of the spectrum must be considered and a given spectral line can change by several orders of magnitude over a very small part of the spectrum. This requires extremely small integration steps.

For the gray-gas assumption made here, average absorption coefficients over all wavelengths are needed. The two most commonly used mean absorption coefficients are the Planck mean and the Rosseland mean. The Planck mean absorption coefficient is appropriate for optically thin radiative heat transfer and for optically thick conditions the appropriate coefficient is the Rosseland mean. The Planck mean coefficient for water vapor as a function of temperature is given by Abu-Romia and Tien.[22]

The Rosseland mean absorption coefficient involves an integration over wavelength in which one over the spectral absorption coefficient is contained within the integrand. For gases such as water vapor, the spectral absorption coefficient is zero over a portion of the spectrum and thus the Rosseland mean cannot be evaluated. The Rosseland mean has been evaluated by integrating only over the width of each band. This problem has been discussed in Refs. 6 and 20. It should be noted that when the spectral absorption coefficient is nonzero over the entire spectrum (except perhaps at the end points), the Rosseland mean absorption coefficient can be calculated. This occurs for droplets or in ionized gases.[23]

E. The Absorption Coefficient of Liquid Droplets

The radiative heat transfer properties of liquid droplets are discussed in this section. Liquid droplets scatter and absorb energy, and these processes are described in terms of efficiency factors for absorption Q_{abs} and for scattering Q_{sca}. The sum of these efficiencies is the extinction efficiency[24]

$$Q_{ext} = Q_{abs} + Q_{sca}. \tag{16}$$

The spectral absorption and scattering coefficients are related to the efficiency factors through the droplet number density N_d and the actual radius of the droplets R (see Ref. 25).

$$\kappa_\lambda = \pi R^2 N_d Q_{abs} \tag{17}$$

and

$$\sigma_\lambda = \pi R^2 N_d Q_{sca} .$$

The calculation of the extinction and absorption efficiencies is very complicated. A discussion of these calculations along with approximate formulas for limiting conditions are given by Van De Hulst.[24] In the present application, the droplets are very large compared to the wavelength of the incident radiation, that is,

$$x = \frac{2\pi R}{\lambda} >> 1 . \tag{18}$$

If we further assume that for the index of refraction m, $m - 1 << 1$ (actually, $m - 1 = 0.33$), then the approximate formulas for Q_{abs} and Q_{ext} given by Van De Hulst [24] are

$$Q_{abs} = 2K(4xn') \tag{19}$$

where

$$K(w) = \frac{1}{2} + \frac{e^{-w}}{w} + \frac{e^{-w} - 1}{w^2} \tag{20}$$

and n' is the complex part of the index of refraction, and

$$Q_{ext} = 2 - 4e^{-\rho \tan \beta} \frac{\cos \beta}{\rho} \sin (\rho-\beta) - 4e^{-\rho \tan \left(\frac{\cos \beta}{\rho}\right)^2} \cos (\rho-2\beta) + 4 \left(\frac{\cos \beta}{\rho}\right)^2 \cos 2\beta , \tag{21}$$

where

$$\rho = 2x(n-1) \tag{22}$$

and

$$\tan \beta = \frac{n'}{n-1} . \tag{23}$$

For the index of refraction, $m = n - in'$. For small w, K(w) becomes[24]

$$K(w) = \frac{w}{3} - \frac{w^2}{8} + \frac{w^3}{30} - \ldots . \qquad (24)$$

Once Q_{ext} and Q_{abs} have been calculated, the scattering efficiency is found from Eq. (16)

$$Q_{sca} = Q_{ext} - Q_{abs}.$$

Several points can be noted from the above equations. For $\rho >> 1$, Q_{ext} approaches 2.0. If the imaginary part of the index of refraction n' is zero, the spheres are nonabsorbing and $Q_{abs} = 0$. If $4xn' >> 1$, then $Q_{abs} = 1.0$. At small wavelengths, n' is very small; and even though x is large, $w = 4xn'$ may not be large. For example[26], at $\lambda = 1.19$, $n' = 0.00001$. Tables of refractive indicies of water are given by Querry, Curnutte, and Williams[18] and by Stephens.[19]

Plass[27] compares the exact Mie scattering theory with the approximate solution given by Eq. (19) for a range of values of x, n, and n'. Plass shows that for n = 1.33, the exact results are in qualitative agreement with Eq. (19), but Eq. (19) underpredicts the exact result for small values of n'. At $x = 28$ (the largest value for which Plass calculated results) and $n' = 10^{-4}$, Eq. (19) underpredicts Q_{abs} by about 38%, and for $n' = 10^{-2}$, Q_{abs} is underpredicted by approximately 29%.

The results presented in the above references were generally obtained for atmospheric conditions and at low temperatures, typically 20°C. Unfortunately, results at reactor conditions do not appear to have been made. It is of interest to look at typical values of x for reactor conditions. The wavelength of the incident radiation at the maximum value of the emissive power can be obtained from Wien's law. At a given temperature,[15]

$$(n\lambda T)_{max} = 0.2898 \text{ cm·K}.$$

For n = 1.33, Table I shows values of λ for a range of temperatures.

TABLE I

WAVELENGTHS AT MAXIMUM EMISSIVE POWER

T(K)	T(F)	λ (cm)	$\lambda(\mu)$
500	440	4.358×10^{-4}	4.358
1000	1340	2.179×10^{-4}	2.179
1500	2240	1.453×10^{-4}	1.453

For droplet radii[8] of 0.05 to 0.1 cm, x and ρ are shown in Table II.

TABLE II

VALUES OF x AND ρ FOR DIFFERENT WAVELENGTHS AND DROPLET DIAMETERS

Wavelength λ (cm)	Droplet radius (cm)	x	ρ
4.358×10^{-4}	0.05	720	475
	0.1	1440	950
2.179×10^{-4}	0.05	1440	950
	0.1	2880	1800
1.453×10^{-4}	0.05	2160	1426
	0.1	4320	2851

Thus in the present work $x >> 1$ and $\rho >> 1$.

For the optically thin analysis, Q_{ext} will be taken as 2.0. For the wavelengths shown in Table II, approximate values of n' can be obtained from Refs. 18 and 26. These values are shown in Table III.

TABLE III

VALUES OF n' FOR TYPICAL WAVELENGTHS

$\lambda(\mu)$	n'
1.45	0.0003
2.2	0.0003
4.4	0.0127

The smallest value of $w = 4xn'$ occurs for $\lambda = 2.2$ and $x = 1440$. In this case, $w = 0.4965$ and $Q_{abs} = 0.993$. Because Q_{abs} will be closer to 1.0 for other conditions, a value of 1.0 will be used here.

F. Vapor and Liquid Two-Phase Properties

The radiative heat transfer properties, such as the emissivity, for the vapor and liquid are effected by the other phase present in the mixture. Therefore, the emissivities for pure vapor and pure droplets must be modified for use in Eqs. (1), (7), and (8). These modifications have been given by Andersen.[12]

The vapor droplet emissivities in the two-phase mixture are[12]

$$\varepsilon^{V}_{ij} = \frac{k_{gij}}{1 + k_{gij}} \left(\varepsilon^{c}_{gij} + a^{o}_{dij} - \varepsilon^{o}_{gij}\, a^{o}_{dij} \right) \tag{25}$$

and

$$\varepsilon^{L}_{ij} = \frac{k_{dij}}{1 + k_{dij}} \left(\varepsilon^{o}_{dij} + a'^{o}_{gij} - \varepsilon^{o}_{dij}\, a'^{o}_{gij} \right) , \tag{26}$$

where

$$k_{gij} = \frac{\ln \left(1 - \varepsilon^{o}_{gij} \right)}{\ln \left(1 - a^{o}_{dij} \right)} \tag{27}$$

and

$$k_{dij} = \frac{\ln \left(1 - \varepsilon^{o}_{gij} \right)}{\ln \left(1 - a'^{o}_{gij} \right)} . \tag{28}$$

The superscript o indicates the quantity for the pure substance, and a'^{o}_{gij} is the absorptivity of pure vapor for radiation from the droplets. Here a'^{o}_{gij} is assumed equal to a^{o}_{gij}.

The corresponding two-phase absorptivities are

$$a_{gij} = \frac{c_{ij}}{1 + c_{ij}} \left(a^{o}_{gij} + a^{o}_{dij} - a^{o}_{gij}\, a^{o}_{dij} \right) \tag{29}$$

and

$$a_{dij} = \frac{1}{1 + c_{ij}} \left(a^{o}_{gij} + a^{o}_{dij} - a^{o}_{gij}\, a^{o}_{dij} \right) , \tag{30}$$

where

$$c_{ij} = \frac{\ln\left(1 - a^{o}_{gij}\right)}{\ln\left(1 - a^{o}_{dij}\right)} \quad . \tag{31}$$

For a gray fluid, the absorption coefficients of each phase are assumed constant, and therefore,

$$\varepsilon^{V}_{ij} = a_{gij} = a'^{o}_{gij}$$

and

$$\varepsilon^{L}_{ij} = a_{dij} \quad .$$

The absorptivities for the pure substances are calculated from the transmissivities as described previously.

IV. ROD GROUPINGS

A typical reactor core has an extremely large number of rods and it would be impractical to calculate the radiative heat transfer for every surface. For example, a BWR bundle has either a 7 x 7 or 8 x 8 lattice.[28] Therefore, a minimum of 50 surfaces (49 rods plus channel) would have to be considered. To reduce the number of calculations, it is possible to group the rods. For this, it is necessary to combine the view factors of the individual surfaces and also the transmissivities and absorptivities; or in the optically thin case, the individual geometric mean beam lengths have to be combined.

A. View Factor Groups

The view factors between individual surfaces F_{ij} can be grouped by using conservation of energy. This method is commonly called angle-factor algebra.[15] For simplicity, consider four surfaces as shown in Fig. 2.

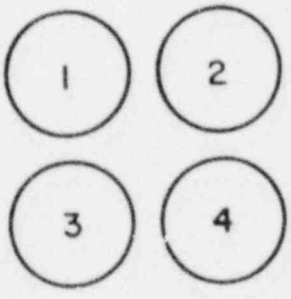

Fig. 2. Geometry for view factor groups.

Let rods 1 and 2 be in group I and rods 3 and 4 in group J.

The energy leaving any surface i in I that reaches surface j in J, with no fluid between the surfaces, is

$$Q_{ij} = A_i F_{ij} B_i ,$$

where B_i is the radiosity leaving surface i. The energy leaving group I that reaches group J is

$$Q_{IJ} = Q_{14} + Q_{13} + Q_{24} + Q_{23} \tag{32}$$

or

$$Q_{IJ} = A_1F_{14}B_1 + A_1F_{13}B_1 + A_2F_{24}B_2 + A_2F_{23}B_2. \tag{33}$$

Assuming that every surface in a group has the same radiosity, $B_1 = B_2 = B$, and Eq. (33) becomes

$$Q_{IJ} = \left[A_1 (F_{14} + F_{13}) + A_2 (F_{24} + F_{23})\right] B = \left(\sum_{i=1}^{2} A_i \sum_{j=3}^{4} F_{ij}\right) B . \tag{34}$$

The view factor for the group is obtained by generalizing Eq. (34).

$$A_I F_{IJ} = \sum_{\substack{\text{over all} \\ \text{group I} \\ \text{rods}}} A_i \sum_{\substack{\text{over all} \\ \text{group J} \\ \text{rods}}} F_{ij} ,$$

where $A_I = \sum_{\substack{\text{over all} \\ \text{group I} \\ \text{rods}}} A_i$.

Therefore, the fraction of energy leaving group I that reaches group J, when no participating fluid exists, is

$$F_{IJ} = \frac{\sum_{\substack{\text{all } i \\ \text{in } I}} A_i \sum_{\substack{\text{all } j \\ \text{in } J}} F_{ij}}{\sum_{\substack{\text{all } i \\ \text{in } I}} A_i} \quad . \tag{35}$$

B. Mean Beam Length Groups

To find an expression for the mean beam length from group I to group J, L_{IJ}, an analysis similar to the one given for the view factors is used. The energy from an individual surface i to an individual surface j is, in the present notation,[14]

$$Q_{ij} = A_i F_{ij} \bar{\tau}_{ij} B_i + A_i F_{ij} \bar{\alpha}_{ij} e_b(T_g) \quad . \tag{36}$$

By using Eqs. (32) and (33) and assuming $B_1 = B_2 = B$, the energy from group I to group J is

$$\begin{aligned} Q_{IJ} = {} & A_1 \left\{ \left[F_{14} \bar{\tau}_{14} + F_{13} \bar{\tau}_{13} \right] + A_2 \left[F_{24} \bar{\tau}_{24} + F_{23} \bar{\tau}_{23} \right] \right\} B \\ & + A_1 \left\{ \left[F_{14} \bar{\tau}_{14} + F_{13} \bar{\tau}_{13} \right] + A_2 \left[F_{24} \bar{\tau}_{24} + F_{23} \bar{\tau}_{23} \right] \right\} \bar{\alpha}_{jk} e_b(T_g) \quad . \end{aligned} \tag{37}$$

Equations similar to Eq. (35) for F_{IJ} can now be obtained for $\bar{\tau}_{IJ}$ and $\bar{\alpha}_{IJ}$.

$$\bar{\tau}_{IJ} = \frac{\sum_{\substack{\text{all } i \\ \text{in } I}} A_i \sum_{\substack{\text{all } j \\ \text{in } J}} F_{ij} \bar{\tau}_{ij}}{A_I F_{IJ}} \tag{38}$$

and

$$\bar{\alpha}_{IJ} = \frac{\sum_{\substack{\text{all } i \\ \text{in } I}} A_i \sum_{\substack{\text{all } j \\ \text{in } J}} F_{ij} \bar{\alpha}_{ij}}{A_I F_{IJ}} \quad . \tag{39}$$

The group mean beam length becomes

$$L_{IJ} = \frac{\sum_{\substack{\text{all } i \\ \text{in } I}} A_i \sum_{\substack{\text{all } j \\ \text{in } J}} F_{ij} \; L_{ij}}{A_I \; F_{IJ}} \quad . \tag{40}$$

Because F_{IJ} and L_{IJ} only depend upon the geometry, they have to be calculated only once unless expansion of the rods is being considered. In that case, these quantities would have to be recalculated periodically during the transient.

V. RADHT CODE

In this section the stand-alone radiative heat transfer code RADHT is discussed. In addition, sample input and output are presented. A listing of the code is given in Appendix D.

The RADHT code calculates the radiative heat transfer (surface-to-surface, as well as the radiative heat transfer to the vapor and droplets) within one BWR bundle. An 8 x 8 bundle is the maximum size that the present code can use. Once the view factors F(I,J) and the mean beam lengths L(I,J) are calculated for the individual surfaces ($I \leq 96$, $J \leq 96$), these quantities are grouped into a maximum of 37 rod groups, including the channel groups. The grouping is arbitrary and determined by the input vector IRØD.

A. Code Structure

The RADHT code is written in a modular form so that model changes can be made easily. A flow chart for the main program is shown in Fig. 3, and a flow chart for subroutine SRADHT, which controls the calculation, is given in Fig. 4. Table IV describes all of the subroutines and functions. It should be noted from Fig. 3 that after an initial case, subsequent cases with the same geometry can be run without recalculating the view factors and mean beam lengths. This is done by setting IØUT > 1.

B. RADHT Input

The RADHT input is defined in Table V and sample input is given in Fig. 5. The input for RADHT must be on a file called RDATA. All input and output are in SI units - watt, meter, and degrees K. The input is through a NAMELIST block called IN. Figure 6 shows a typical RADHT geometry for an 8 x 8 BWR bundle.

TABLE IV

RADHT SUBROUTINES

Subroutine Name	Purpose
SRADHT	Controls calculation by calling other subroutines.
FIJ	Calls subroutines that calculate view factors and mean beam lengths and assigns proper values to F and L matrices.
GRPFIJ	Groups individual surface view factors.
GRPLIJ	Groups individual surface mean beam lengths.
ACØEFF	Calls vapor and liquid absorption coefficient functions and calculates the combined absorption coefficient for the two phases.
EM	Calculates two-phase emissivities and absorptivities.
GLSS	System routine to solve matrix equation.
KV	Function to calculate Planck mean absorption coefficient.
AKNINT	System linear interpolation subroutine.
KL	Function to calculate liquid absorption coefficient.
VIEWPIN	Subroutine to calculate rod-to-rod view factors.
MBL	Calculates rod-to-rod mean beam lengths.
FSBG	Calculates rod-to-channel segment view factors and channel segment-to-channel segment view factors.
MBLS	Calculates rod-to-channel segment and channel segment-to-channel segment mean beam lengths.

TABLE V

RADHT INPUT

Variable	Definition
NMAX	Number of individual surfaces, $\leq$ 96.
NRØD	Number of rods in a row or column (8 for an 8 x 8 bundle), $\leq$ 8.
IRØD(J)	Rod group indicator. IRØD(3) = 5 means surface 3 is in rod group 5.
NGRP	Number of rod groups, $\leq$ 37.
TL	Liquid temperature, K.
TV	Vapor temperature, K.
PITCH	Distance between rod centers, meter.
DRØD	Rod diameter, meter. (All rods are assumed to have the same diameter.)
TW(J)	Surface temperature of group J, K.
EMIS(J)	Surface emissivity of group J.
IØUT	= 0 input not written > 0 input written > 1 F_{ij} and L_{ij} not recalculated from previous case.
ALPHA	Void fraction.
BUNDW	Bundle width, meter.
D	Droplet diameter, meter.
ISURF	= 0, radiation to fluid, as well as surface-to-surface radiation, is calculated. = 1, surface-to-surface radiation only is calculated.
P	Fluid pressure, N/m^2.

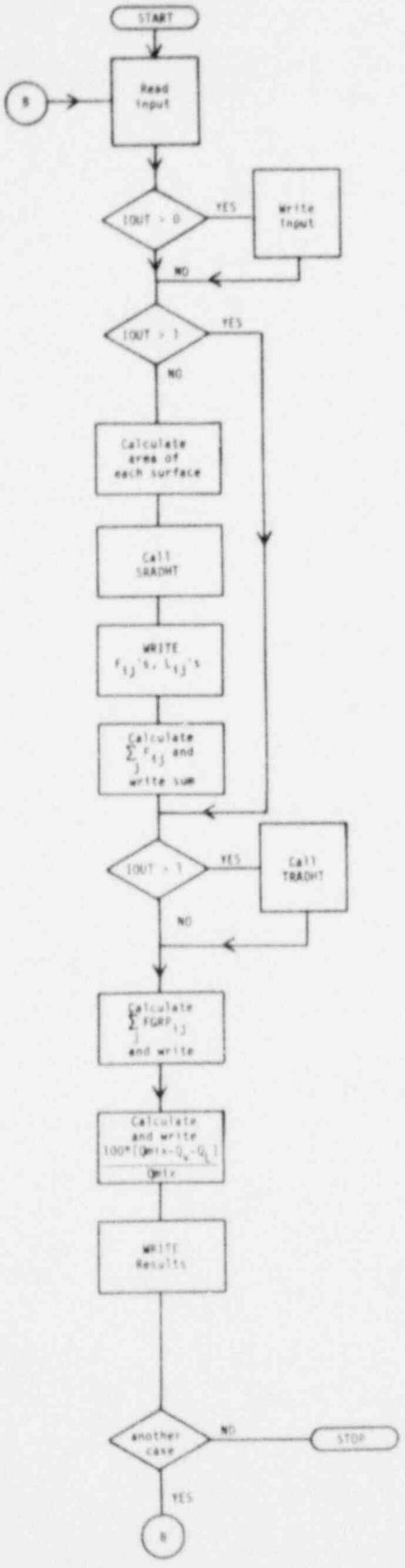

Fig. 3. RADHT main program flow chart.

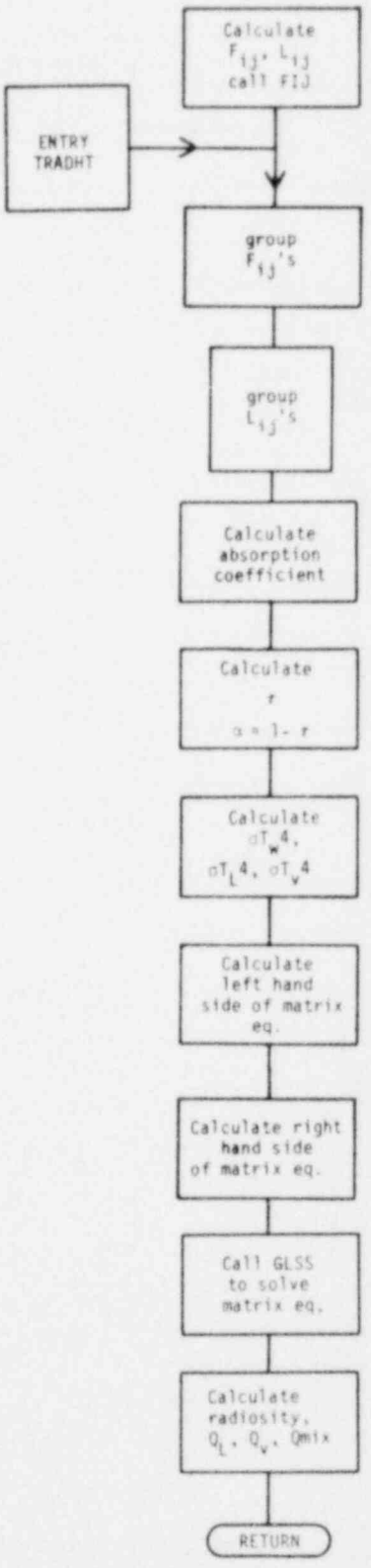

Fig. 4. SRADHT flow chart.

```
$IN
NMAX=96, NROD=8,
PITCH=.016256, DROD=.0125222, BUNDW=.1340612,
EMIS=5*.67, ALPHA=.9, P=4.135E6, D=1.E-4,
TL=525., TV=525., IOUT=1,
NGRP=5, TW=929.7, 908.9, 862.9, 783.6, 310.8,
IROD=9*4, 6*3, 2*4, 3, 4*2, 3, 2*4, 3, 2, 2*1, 2, 3, 2*4,
     3, 2, 2*1, 2,3, 2*4, 3, 4*2, 3, 2*4, 6*3, 9*4, 32*5 $
$IN
 IOUT=2, ALPHA=.8 $
```

Fig. 5. RADHT sample input file.

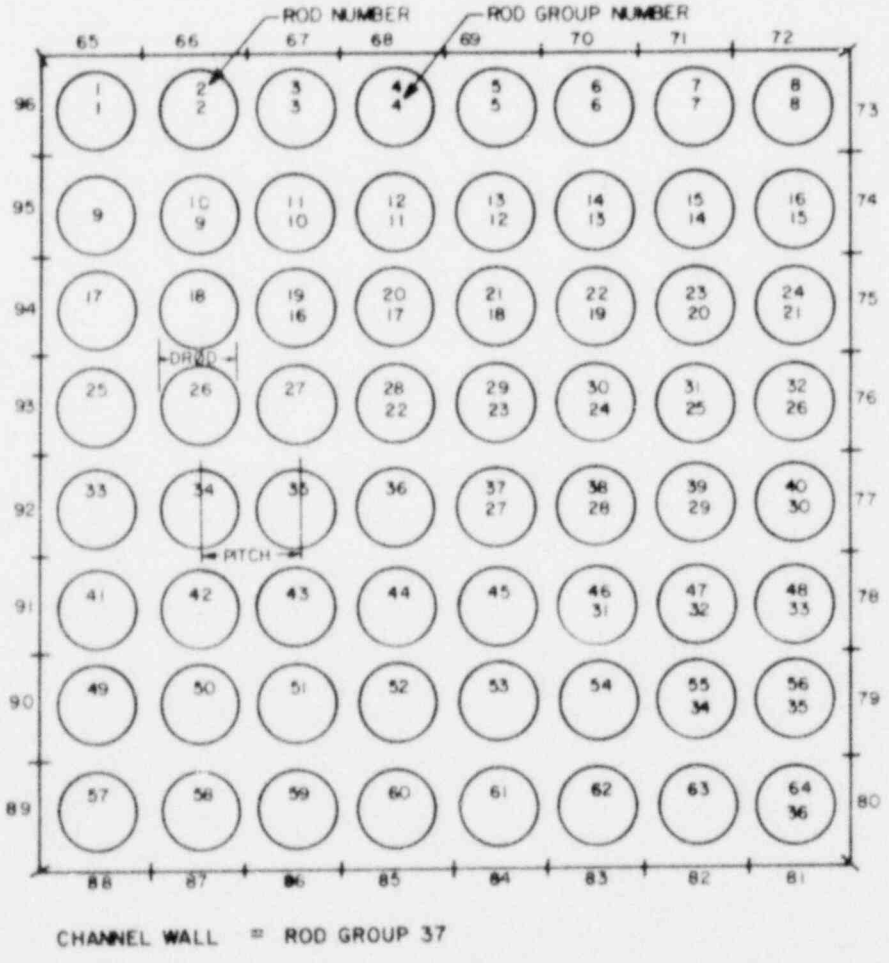

Fig. 6. Typical RADHT 8 x 8 geometry.

C. RADHT Output

Figure 7 shows a sample of the RADHT output, which used the input file RDATA shown in Fig. 5. The RADHT output variables not previously defined are defined in Table VI.

A number of checks for consistency are included in the code. In order for energy to be conserved, the following equations must be satisfied.

$$\sum_{j} F_{ij} = 1.0$$

and

$$\sum_{J} FGRP_{IJ} = 1.0 \ ,$$

where F_{ij} are the individual view factors and $FGRP_{IJ}$ are the grouped view factors. The results of these summations are given in the output.

To check the solution of the matrix equation, the right-hand side of the matrix equation [see Eq. (1)] is recalculated using the solution vector and the original coefficient matrix. The two right-hand side vectors are printed for comparison.

As discussed previously, the sum of the heat transfer to the vapor Q_V and the heat transfer to the droplets Q_L should equal the heat transfer to the mixture Q_{MIX}. The error in this calculation is printed.

If the vapor temperature T_V is below or above the range of the data for the Planck mean absorption coefficient given in Ref. 22, a warning message is printed. This message indicates that the Planck mean used in the calculation was obtained by extrapolating the data.

It should be noted that all of the RADHT output is written to a file called TAPE6.

VI. RESULTS AND DISCUSSION

The results for a sample problem containing an 8 x 8 BWR bundle are presented and discussed in this section. Because this bundle has one-eighth symmetry, the 64 rods can be grouped unto eleven rod groups, which is the maximum number needed if the channel wall is considered as one surface. Fewer than eleven rod groups are also considered to determine the least number of rod groups needed for an accurate solution and to minimize computer costs. Figure 8 shows an 8 x 8 BWR bundle with the eleven rod groups (10 rod groups plus the channel) and the temperatures used for each rod group. (The temperatures were taken from Ref. 2.)

```
$IN     --

NMAX----------------------------------        96
NROD----------------------------------         8
IROD(1)-------------------------------         4
IROD(8)-------------------------------         4
IROD(15)------------------------------         3
IROD(22)------------------------------         2
IROD(29)------------------------------         1
IROD(36)------------------------------         1
IROD(43)------------------------------         2
IROD(50)------------------------------         3
IROD(57)------------------------------         4
IROD(64)------------------------------         5
IROD(71)------------------------------         5
IROD(78)------------------------------         5
IROD(85)------------------------------         5
IROD(92)------------------------------         5
NGRP----------------------------------
TL(1)---------------------------------  5.250000000000E+02
TV(1)---------------------------------  5.250000000000E+02
PITCH---------------------------------  1.625600000000E-02
DROD----------------------------------  1.252220000000E-02
TW(1,1)-------------------------------  9.297000000000E+02  9.089000000000E+02  8.629000000000E+02
TW(4,1)-------------------------------  7.836000000000E+02  3.108000000000E+02  0.
TW(7,1)-------------------------------  0.                  0.                  0.
TW(10,1)------------------------------  0.                  0.                  0.
TW(13,1)------------------------------  0.                  0.                  0.
TW(16,1)------------------------------  0.                  0.                  0.
TW(19,1)------------------------------  0.                  0.                  0.
TW(22,1)------------------------------  0.                  0.                  0.
TW(25,1)------------------------------  0.                  0.                  0.
TW(28,1)------------------------------  0.                  0.                  0.
TW(31,1)------------------------------  0.                  0.                  0.
TW(34,1)------------------------------  0.                  0.                  0.
TW(37,1)------------------------------  0.                  0.                  0.
EMIS(1)-------------------------------  6.699999999999E-01  6.699999999999E-01  6.699999999999E-01
EMIS(4)-------------------------------  6.699999999999E-01  6.699999999999E-01  0.
EMIS(7)-------------------------------  0.                  0.                  0.
EMIS(10)------------------------------  0.                  0.                  0.
EMIS(13)------------------------------  0.                  0.                  0.
EMIS(16)------------------------------  0.                  0.                  0.
EMIS(19)------------------------------  0.                  0.                  0.
EMIS(22)------------------------------  0.                  0.                  0.
EMIS(25)------------------------------  0.                  0.                  0.
EMIS(28)------------------------------  0.                  0.                  0.
EMIS(31)------------------------------  0.                  0.                  0.
EMIS(34)------------------------------  0.                  0.                  0.
EMIS(37)------------------------------  0.                  0.                  0.
IOUT----------------------------------         1
ALPHA(1)------------------------------  9.000000000000E-01
P(1)----------------------------------  4.135000000000E+06
BUMDW---------------------------------  1.340612000000E-01
D(1)----------------------------------  1.000000000000E-04
ISURF---------------------------------         0
$END

I =  1

  PLANCK MEAN ABSORPTION COEFFICIENT
IS OUTSIDE THE RANGE OF THE DATA, I =  1,  TEMPERATURE IS
BELOW THE DATA, I =  2,  TEMPERATURE IS ABOVE THE HIGHEST
DATA POINT. EXTRAPOLATION USED.
```

Fig. 7. RADHT sample output.

```
LHS(I, 1) =
   .14925E+01    -.45545E-12    -.11355E-29    -.16892E-47
  -.19776E-63

LHS(I, 2) =
  -.13663E-11     .14925E+01    -.20356E-12    -.91762E-30
  -.67115E-50

LHS(I, 3) =
  -.56774E-29    -.33926E-12     .14925E+01    -.18258E-12
  -.27589E-29

LHS(I, 4) =
  -.11825E-46    -.21411E-29    -.25561E-12     .14925E+01
  -.12377E-09

LHS(I, 5) =
  -.67394E-63    -.76238E-50    -.18804E-29    -.60256E-10
   .14925E+01
I =  1  RHS(I) =      .38039E+05
I =  2  RHS(I) =      .34375E+05
I =  3  RHS(I) =      .27119E+05
I =  4  RHS(I) =      .17064E+05
I =  5  RHS(I) =     -.37771E+04
CHECK MATRIX SOLUTION BY MATRIX MULT.
I =  1  RE-CALCULATED RHS =      .38039E+05
I =  2  RE-CALCULATED RHS =      .34375E+05
I =  3  RE-CALCULATED RHS =      .27119E+05
I =  4  RE-CALCULATED RHS =      .17064E+05
I =  5  RE-CALCULATED RHS =     -.37771E+04
F(I, 1 )
     0.             .1302E+00      0.             0.
     0.             0.             0.             0.
    .1302E+00       .8664E-01      .1416E-01      .1556E-02
    .4294E-03       .1764E-03      .8919E-04      .5126E-04
     0.             .1416E-01      0.             0.
     0.             0.             0.             0.
     0.             .1556E-02      0.             0.
     0.             0.             0.             0.
     0.             .4294E-03      0.             0.
     0.             0.             0.             0.
     0.             .1764E-03      0.             0.
     0.             0.             0.             0.
     0.             .8919E-04      0.             0.
     0.             0.             0.             0.
     0.             .5126E-04      0.             0.
     0.             0.             0.             0.
    .5010E+00       .1718E+00      .1171E-01      .2048E-02
    .7034E-03       .3231E-03      .1748E-03      .1025E-03
    .3076E-03       .2472E-03      0.             0.
     0.             0.             0.             0.
     0.             0.             0.             0.
     0.             0.             .2472E-03      .3076E-03
    .1025E-03       .1748E-03      .3231E-03      .7034E-03
    .2048E-02       .1171E-01      .1718E+00      .5010E+00
F(I,96 )
    .2326E+00       .6236E-02      .1648E-02      .7507E-03
    .4283E-03       .2767E-03      .1934E-03      .1428E-03
    .7235E-01       .1533E-01      .2115E-02      .7328E-03
    .3649E-03       .2172E-03      .1438E-03      .1021E-03
    .5011E-02       0.             0.             0.
     0.             0.             0.             0.
```

Fig. 7. (cont)

```
    .8978E-03       0.             0.             0.
     0.             0.             0.             0.
    .3126E-03       0.             0.             0.
     0.             0.             0.             0.
    .1448E-03       0.             0.             0.
     0.             0.             0.             0.
    .7879E-04       0.             0.             0.
     0.             0.             0.             0.
    .4760E-04       0.             0.             0.
     0.             0.             0.             0.
    .2418E+00       .1535E-01      .3645E-02      .1597E-02
    .8935E-03       .5704E-03      .3955E-03      .2857E-03
    .4082E-02       .1017E-02      0.             0.
     0.             0.             0.             0.
     0.             0.             0.             .2857E-03
     0.             0.             0.             0.
     0.             0.             0.             0.
L(I, 1 )
     0.             .6421E-02      0.             0.
     0.             0.             0.             0.
    .6421E-02       .1315E-01      .2651E-01      .4157E-01
    .5719E-01       .7305E-01      .8905E-01      .1051E+00
     0.             .2651E-01      0.             0.
     0.             0.             0.             0.
     0.             .4157E-01      0.             0.
     0.             0.             0.             0.
     0.             .5719E-01      0.             0.
     0.             0.             0.             0.
     0.             .7305E-01      0.             0.
     0.             0.             0.             0.
     0.             .8905E-01      0.             0.
     0.             0.             0.             0.
     0.             .1051E+00      0.             0.
     0.             0.             0.             0.
    .5217E-02       .1424E-01      .2914E-01      .4489E-01
    .6089E-01       .7699E-01      .9314E-01      .1093E+00
    .1190E+00       .1201E+00      0.             0.
     0.             0.             0.             0.
     0.             0.             .1201E+00      .1190E+00
    .1093E+00       .9314E-01      .7699E-01      .6089E-01
    .4489E-01       .2914E-01      .1424E-01      .5217E-02
L(I,96 )
    .5217E-02       .2147E-01      .3773E-01      .5399E-01
    .7024E-01       .8650E-01      .1028E+00      .1190E+00
    .1424E-01       .2608E-01      .4072E-01      .5619E-01
    .7198E-01       .8793E-01      .1040E+00      .1201E+00
    .2914E-01       0.             0.             0.
     0.             0.             0.             0.
    .4489E-01       0.             0.             0.
     0.             0.             0.             0.
    .6089E-01       0.             0.             0.
     0.             0.             0.             0.
    .7699E-01       0.             0.             0.
     0.             0.             0.             0.
    .9314E-01       0.             0.             0.
     0.             0.             0.             0.
    .1093E+00       0.             0.             0.
     0.             0.             0.             0.
    .1291E-01       .2888E-01      .4459E-01      .6060E-01
    .7671E-01       .9287E-01      .1091E+00      .1253E+00
    .1341E+00       .1352E+00      0.             0.
     0.             0.             0.             0.
```

Fig. 7. (cont)

```
       0.              0.              0.              0.
       0.              0.              0.             .1253E+00
       0.              0.              0.              0.
       0.              0.              0.              0.
I =  1   SUM OVER J OF F(I,J) =      1.000
I =  2   SUM OVER J OF F(I,J) =      1.000
I =  3   SUM OVER J OF F(I,J) =      1.000
I =  4   SUM OVER J OF F(I,J) =      1.000
I =  5   SUM OVER J OF F(I,J) =      1.000
I =  6   SUM OVER J OF F(I,J) =      1.000
I =  7   SUM OVER J OF F(I,J) =      1.000
I =  8   SUM OVER J OF F(I,J) =      1.000
I =  9   SUM OVER J OF F(I,J) =      1.000
I = 10   SUM OVER J OF F(I,J) =      1.000
I = 11   SUM OVER J OF F(I,J) =      1.000
I = 12   SUM OVER J OF F(I,J) =      1.000
I = 13   SUM OVER J OF F(I,J) =      1.000
I = 14   SUM OVER J OF F(I,J) =      1.000
I = 15   SUM OVER J OF F(I,J) =      1.000
I = 16   SUM OVER J OF F(I,J) =      1.000
I = 17   SUM OVER J OF F(I,J) =      1.000
I = 18   SUM OVER J OF F(I,J) =      1.000
I = 19   SUM OVER J OF F(I,J) =      1.000
I = 20   SUM OVER J OF F(I,J) =      1.000
I = 21   SUM OVER J OF F(I,J) =      1.000
I = 22   SUM OVER J OF F(I,J) =      1.000
I = 23   SUM OVER J OF F(I,J) =      1.000
I = 24   SUM OVER J OF F(I,J) =      1.000
I = 25   SUM OVER J OF F(I,J) =      1.000
I = 26   SUM OVER J OF F(I,J) =      1.000
I = 27   SUM OVER J OF F(I,J) =      1.000
I = 28   SUM OVER J OF F(I,J) =      1.000
I = 29   SUM OVER J OF F(I,J) =      1.000
I = 30   SUM OVER J OF F(I,J) =      1.000
I = 31   SUM OVER J OF F(I,J) =      1.000
I = 32   SUM OVER J OF F(I,J) =      1.000
I = 33   SUM OVER J OF F(I,J) =      1.000
I = 34   SUM OVER J OF F(I,J) =      1.000
I = 35   SUM OVER J OF F(I,J) =      1.000
I = 36   SUM OVER J OF F(I,J) =      1.000
I = 37   SUM OVER J OF F(I,J) =      1.000
I = 38   SUM OVER J OF F(I,J) =      1.000
I = 39   SUM OVER J OF F(I,J) =      1.000
I = 40   SUM OVER J OF F(I,J) =      1.000
I = 41   SUM OVER J OF F(I,J) =      1.000
I = 42   SUM OVER J OF F(I,J) =      1.000
I = 43   SUM OVER J OF F(I,J) =      1.000
I = 44   SUM OVER J OF F(I,J) =      1.000
I = 45   SUM OVER J OF F(I,J) =      1.000
I = 46   SUM OVER J OF F(I,J) =      1.000
I = 47   SUM OVER J OF F(I,J) =      1.000
I = 48   SUM OVER J OF F(I,J) =      1.000
I = 49   SUM OVER J OF F(I,J) =      1.000
I = 50   SUM OVER J OF F(I,J) =      1.000
I = 51   SUM OVER J OF F(I,J) =      1.000
I = 52   SUM OVER J OF F(I,J) =      1.000
I = 53   SUM OVER J OF F(I,J) =      1.000
I = 54   SUM OVER J OF F(I,J) =      1.000
I = 55   SUM OVER J OF F(I,J) =      1.000
I = 56   SUM OVER J OF F(I,J) =      1.000
I = 57   SUM OVER J OF F(I,J) =      1.000
I = 58   SUM OVER J OF F(I,J) =      1.000
I = 59   SUM OVER J OF F(I,J) =      1.000
I = 60   SUM OVER J OF F(I,J) =      1.000
```

Fig. 7. (cont)

```
I = 61   SUM OVER J OF F(I,J) =      1.000
I = 62   SUM OVER J OF F(I,J) =      1.000
I = 63   SUM OVER J OF F(I,J) =      1.000
I = 64   SUM OVER J OF F(I,J) =      1.000
I = 65   SUM OVER J OF F(I,J) =      1.000
I = 66   SUM OVER J OF F(I,J) =      1.000
I = 67   SUM OVER J OF F(I,J) =      1.000
I = 68   SUM OVER J OF F(I,J) =      1.000
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I = 70   SUM OVER J OF F(I,J) =      1.000
I = 71   SUM OVER J OF F(I,J) =      1.000
I = 72   SUM OVER J OF F(I,J) =      1.000
I = 73   SUM OVER J OF F(I,J) =      1.000
I = 74   SUM OVER J OF F(I,J) =      1.000
I = 75   SUM OVER J OF F(I,J) =      1.000
I = 76   SUM OVER J OF F(I,J) =      1.000
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I = 78   SUM OVER J OF F(I,J) =      1.000
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I = 87   SUM OVER J OF F(I,J) =      1.000
I = 88   SUM OVER J OF F(I,J) =      1.000
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I = 94   SUM OVER J OF F(I,J) =      1.000
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FGRP(I, 1 )
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   .1551E-02
FGRP(I, 2 )
   .5769E+00     .3401E+00     .2507E+00     .1752E-01
   .7890E-02
FGRP(I, 3 )
   .6286E-01     .4178E+00     .3083E+00     .2750E+00
   .6378E-01
FGRP(I, 4 )
   .7940E-02     .4088E-01     .3850E+00     .2946E+00
   .8458E+00
FGRP(I, 5 )
   .5285E-02     .8963E-02     .4347E-01     .4117E+00
   .8103E-01
I =  1   SUM OVER J OF GROUPED F(I,J) =     1.000
I =  2   SUM OVER J OF GROUPED F(I,J) =     1.000
I =  3   SUM OVER J OF GROUPED F(I,J) =     1.000
I =  4   SUM OVER J OF GROUPED F(I,J) =     1.000
I =  5   SUM OVER J OF GROUPED F(I,J) =     1.000
LGRP(I, 1 )
   .8102E-02     .1143E-01     .2800E-01     .4495E-01
   .6117E-01
LGRP(I, 2 )
   .1143E-01     .9002E-02     .1190E-01     .2824E-01
   .4822E-01
LGRP(I, 3 )
   .2800E-01     .1190E-01     .8191E-02     .1199E-01
```

Fig. 7. (cont)

```
      .2833E-01
LGRP(I, 4 )
      .4495E-01      .2824E-01      .1199E-01      .7759E-02
      .9619E-02
LGRP(I, 5 )
      .6117E-01      .4822E-01      .2833E-01      .9619E-02
      .2267E-01
ALF(I, 1) =
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      .1000E+01
ALF(I, 2) =
      .1000E+01      .1000E+01      .1000E+01      .1000E+01
      .1000E+01
ALF(I, 3) =
      .1000E+01      .1000E+01      .1000E+01      .1000E+01
      .1000E+01
ALF(I, 4) =
      .1000E+01      .1000E+01      .1000E+01      .1000E+01
      .1000E+01
ALF(I, 5) =
      .1000E+01      .1000E+01      .1000E+01      .1000E+01
      .1000E+01
LV=
      .6421E-02      .1315E-01      .2651E-01      .4157E-01
      .5719E-01      .7305E-01      .8905E-01      .1051E+00
FV=
      .1302E+00      .8664E-01      .1416E-01      .1556E-02
      .4294E-03      .1764E-03      .8919E-04      .5126E-04

ROD GROUP RESULTS

 GROUP      AGRP      RADIOSITY        Q          T WALL
   1     .157E+00     .298E+05     .255E+05     .930E+03
   2     .472E+00     .273E+05     .230E+05     .909E+03
   3     .787E+00     .225E+05     .182E+05     .863E+03
   4     .110E+01     .157E+05     .114E+05     .784E+03
   5     .536E+00     .178E+04    -.253E+04     .311E+03

ROD LEVEL RESULTS

 LEVEL      TV          TL       NDROP            D            P          QV          QL          QMIX
   1     .525E+03    .525E+03    .191E+12     .100E-03     .414E+07    .133E+05    .272E+05    .404E+05

THE PERCENT DIFFERENCE BETWEEN QMIX & QV + QL, BASED ON QMIX, IS       .00


$IN     --

NMAX----------------------------        96
NROD----------------------------         8
IROD(1)-------------------------         4        4        4        4        4        4        4
IROD(8)-------------------------         4        4        3        3        3        3        3
IROD(15)------------------------         3        4        4        4        3        3        3
IROD(22)------------------------         2        3        4        4        4        3        3
IROD(29)------------------------         1        2        3        4        4        4        3
IROD(36)------------------------         1        1        2        3        4        4        4
IROD(43)------------------------         2        2        2        2        3        4        4
IROD(50)------------------------         3        3        3        3        3        3        4
```

Fig. 7. (cont)

```
IROD(57) ------------------------------          4          4          4          4          4          4          4
IROD(64) ------------------------------          5          5          5          5          5          5          5
IROD(71) ------------------------------          5          5          5          5          5          5          5
IROD(78) ------------------------------          5          5          5          5          5          5          5
IROD(85) ------------------------------          5          5          5          5          5          5          5
IROD(92) ------------------------------          5          5          5          5          5          5          5
NGRP ----------------------------------          5
TL(1) ---------------------------------  5.250000000000000E+02
TV(1) ---------------------------------  5.250000000000000E+02
PITCH ---------------------------------  1.625600000000000E-02
DROD ----------------------------------  1.252220000000000E-02
TW(1,1) -------------------------------  9.297000000000000E+02  9.089000000000000E+02  8.629000000000000E+02
TW(6,1) -------------------------------  7.836000000000000E+02  3.108000000000000E+02  0.
TW(7,1) -------------------------------  0.                     0.                     0.
TW(10,1) ------------------------------  0.                     0.                     0.
TW(13,1) ------------------------------  0.                     0.                     0.
TW(16,1) ------------------------------  0.                     0.                     0.
TW(19,1) ------------------------------  0.                     0.                     0.
TW(22,1) ------------------------------  0.                     0.                     0.
TW(25,1) ------------------------------  0.                     0.                     0.
TW(28,1) ------------------------------  0.                     0.                     0.
TW(31,1) ------------------------------  0.                     0.                     0.
TW(34,1) ------------------------------  0.                     0.                     0.
TW(37,1) ------------------------------  0.                     0.                     0.
EMIS(1) -------------------------------  6.699999999999999E-01  6.699999999999999E-01  6.699999999999999E-01
EMIS(4) -------------------------------  6.699999999999999E-01  6.699999999999999E-01  0.
EMIS(7) -------------------------------  0.                     0.                     0.
EMIS(10) ------------------------------  0.                     0.                     0.
EMIS(13) ------------------------------  0.                     0.                     0.
EMIS(16) ------------------------------  0.                     0.                     0.
EMIS(19) ------------------------------  0.                     0.                     0.
EMIS(22) ------------------------------  0.                     0.                     0.
EMIS(25) ------------------------------  0.                     0.                     0.
EMIS(28) ------------------------------  0.                     0.                     0.
EMIS(31) ------------------------------  0.                     0.                     0.
EMIS(34) ------------------------------  0.                     0.                     0.
EMIS(37) ------------------------------  0.                     0.                     0.
IOUT ----------------------------------          2
ALPHA(1) ------------------------------  8.000000000000000E-01
P(1) ----------------------------------  4.135000000000000E+06
BUNDV ---------------------------------  1.340612000000000E-01
D(1) ----------------------------------  1.000000000000000E-04
ISURF ---------------------------------          0
$END

I =  1

  PLANCK MEAN ABSORPTION COEFFICIENT
IS OUTSIDE THE RANGE OF THE DATA, I = 1, TEMPERATURE IS
BELOW THE DATA, I = 2, TEMPERATURE IS ABOVE THE HIGHEST
DATA POINT. EXTRAPOLATION USED.


LHS(I, 1) =
    .14925E+01     -.16372E-19     -.64802E-48     -.88176E-77
   -.27898-103

LHS(I, 2) =
   -.49117E-19      .14925E+01     -.36193E-20     -.36598E-48
   -.25778E-81

LHS(I, 3) =
   -.32401E-47     -.60322E-20      .14925E+01     -.28433E-20
```

Fig. 7. (cont)

```
   -.97023E-48

LHS(I, 4) =
   -.81723E-76    -.85396E-48    -.39806E-20     .14925E+01
   -.67031E-16

LHS(I, 5) =
   -.95071-103    -.29282E-31    -.66127E-48    -.32632E-16
    .14925E+01
I =  1  RHS(I) =     .38039E+05
I =  2  RHS(I) =     .34375E+05
I =  3  RHS(I) =     .27119E+05
I =  4  RHS(I) =     .17064E+05
I =  5  RHS(I) =    -.37771E+04
CHECK MATRIX SOLUTION BY MATRIX MULT.
I =  1  RE-CALCULATED RHS =     .38039E+05
I =  2  RE-CALCULATED RHS =     .34375E+05
I =  3  RE-CALCULATED RHS =     .27119E+05
I =  4  RE-CALCULATED RHS =     .17064E+05
I =  5  RE-CALCULATED RHS =    -.37771E+04
FGRP(I, 1)
     .3470E+00      .1923E+00      .1257E-01      .1134E-02
     .1551E-02
FGRP(I, 2)
     .5769E+00      .3401E+00      .2507E+00      .1752E-01
     .7896E-02
FGRP(I, 3)
     .6286E-01      .4178E+00      .3083E+00      .2750E+00
     .6378E-01
FGRP(I, 4)
     .7940E-02      .4088E-01      .3850E+00      .2916E+00
     .8458E+00
FGRP(I, 5)
     .5285E-02      .8963E-02      .4347E-01      .4117E+00
     .8103E-01
I =  1  SUM OVER J OF GROUPED F(I,J) =     1.000
I =  2  SUM OVER J OF GROUPED F(I,J) =     1.000
I =  3  SUM OVER J OF GROUPED F(I,J) =     1.000
I =  4  SUM OVER J OF GROUPED F(I,J) =     1.000
I =  5  SUM OVER J OF GROUPED F(I,J) =     1.000
LGRP(I, 1)
     .8102E-02      .1143E-01      .2800E-01      .4495E-01
     .6117E-01
LGRP(I, 2)
     .1143E-01      .9002E-02      .1190E-01      .2824E-01
     .4822E-01
LGRP(I, 3)
     .2800E-01      .1190E-01      .8191E-02      .1199E-01
     .2833E-01
LGRP(I, 4)
     .4495E-01      .2824E-01      .1199E-01      .7759E-02
     .9619E-02
LGRP(I, 5)
     .6117E-01      .4822E-01      .2833E-01      .9619E-02
     .2267E-01
ALF(I, 1) =
     .1000E+01      .1000E+01      .1000E+01      .1000E+01
     .1000E+01
ALF(I, 2) =
     .1000E+01      .1000E+01      .1000E+01      .1000E+01
     .1000E+01
ALF(I, 3) =
     .1000E+01      .1000E+01      .1000E+01      .1000E+01
     .1000E+01
```

Fig. 7. (cont)

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ALF(I, 4) =
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     .1000E+01
ALF(I, 5) =
     .1000E+01      .1000E+01      .1000E+01      .1000E+01
     .1000E+01
LV=
     .6421E-02      .1315E-01      .2651E-01      .4157E-01
     .5719E-01      .7305E-01      .8905E-01      .1051E+00
FV=
     .1302E+00      .8664E-01      .1416E-01      .1556E-02
     .4294E-03      .1764E-03      .8919E-04      .5126E-04

ROD GROUP RESULTS

 GROUP      AGRP       RADIOSITY        Q          T WALL

   1     .157E+00     .298E+05     .255E+05     .930E+03
   2     .472E+00     .273E+05     .230E+05     .909E+03
   3     .787E+00     .225E+05     .182E+05     .863E+03
   4     .110E+01     .157E+05     .114E+05     .784E+03
   5     .536E+00     .178E+04    -.253E+04     .311E+03

ROD LEVEL RESULTS

 LEVEL      TV          TL       NDROP            D           P          QV          QL          QMIX

   1     .525E+03    .525E+03    .382E+12    .100E-03    .414E+07    .356E+04    .369E+05    .404E+05

THE PERCENT DIFFERENCE BETWEEN QMIX & QV + QL, BASED ON QMIX, IS       .00
```

Fig. 7. (cont)

TABLE VI

RADHT OUTPUT VARIABLES

Variables[a]	Definition
LHS	Left-hand side of matrix equation, Eq. (1).
RHS	Right-hand side of matrix equation, Eq. (1).
F	Individual surface view factor.
L	Individual surface mean beam length.
FGRP	Grouped view factors.
LGRP	Grouped mean beam length.
ALF	Absorptivity.
LV	Eight types of rod-to-rod mean beam lengths.
FV	Eight types of rod-to-rod view factors.
AGRP(J)	Surface area of group J.
Q(J)	Heat flux leaving surface J.
LEVEL	Axial level. At the present time RADHT is dimensioned for only one level.
NDRØP	Droplet number density, m^{-3}.

[a]In addition to the above variables, the input variables are printed if IØUT > 0.

The results are evaluated relative to the base-case values (eleven rod groups) given in Table VII. Table VIII shows the effect of the number of rod groups on surface-to-surface radiative heat transfer to the channel $-Q_{ch}$ only; that is, the radiative heat transfer to the vapor and to the liquid is arbitrarily set equal to zero. As discussed above, eleven or more rod groups would give identical results. The pattern for five rod groups is shown in Fig. 9. From Table VIII, two groups (one average rod plus the channel) over-predict the heat transfer to the channel by 29.9%, and five rod groups

overpredict the heat transfer by only 2.4%. Two rod groups are clearly inadequate, but five rod groups give sufficiently accurate results considering the model assumptions. For these two cases, the rod group temperatures were calculated by averaging the individual rod temperatures shown in Fig. 8.

Table IX includes the effect of the number of rod groups on the heat transfer to the vapor and the liquid droplets. All other variables have the base-case values. The heat transfer to the channel wall is uneffected by the number of rod groups, and the heat transfer to the vapor increases by 3% between two and eleven rod groups. The heat transfer to the liquid decreases by approximately 6%. Thus, the presence of the two-phase mixture reduces the influence of the number of rod groups.

The influence of the void fraction on the heat transfer is shown in Fig. 10. As would be expected the heat transfer to the vapor increases as the void fraction increases. It should be noted that the model assumes optically thin conditions, and thus does not apply for low void fractions. Typical optical thicknesses for the liquid are shown in Table X.

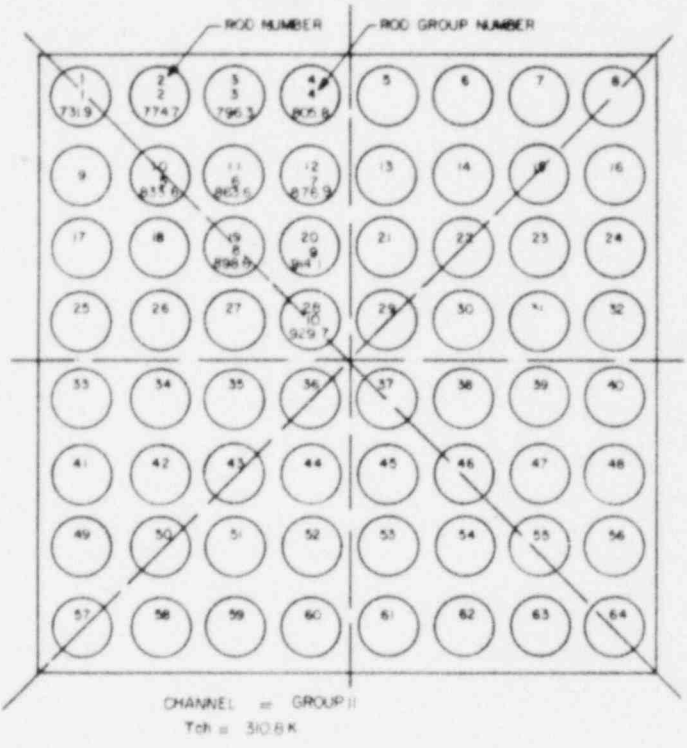

Fig. 8. An 8 x 8 rod group pattern showing rod group temperatures in degrees Kelvin.

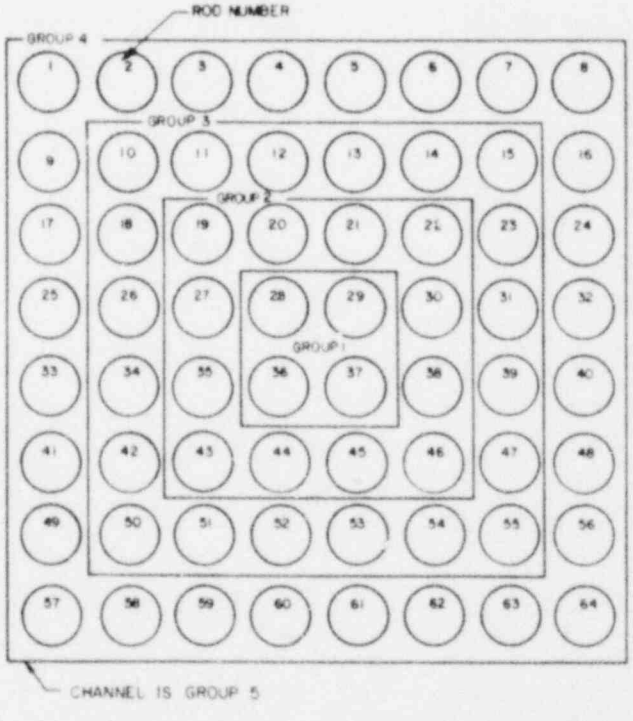

Fig. 9. An 8 x 8 rod group pattern for five rod groups, including one channel.

TABLE VII

RADHT BASE-CASE INPUT DATA

Variable	Symbol	Value
Number of rod groups	NGRP	5
Liquid temperature	TL	525 K
Vapor temperature	TV	525 K
Distance between rod centers	PITCH	0.016256 m
Rod diameter	DRØD	0.0125222 m
Wall emissivity	EMIS	0.67
Pressure	P	4.135×10^{6} N/m^2
Droplet Diameter	D	10^{-4} m
Void Fraction	ALPHA	0.90
Bundle Width	BUNDW	0.1340612 m

TABLE VIII

RESULTS FOR SURFACE-TO-SURFACE RADIATIVE HEAT TRANSFER ONLY

Number of Rod Groups	$-Q_{ch}$ watt
2	0.165×10^{5}
5	0.130×10^{5}
11	0.127×10^{5}

TABLE IX

EFFECT OF NUMBER OF ROD GROUPS

Number of Rod Groups	Heat Transfer Watt		
	$-Q_{ch}$	Q_V	Q_L
2	0.253×10^{4}	0.135×10^{5}	0.258×10^{5}
5	0.253×10^{4}	0.133×10^{5}	0.272×10^{5}
11	0.253×10^{4}	0.131×10^{5}	0.275×10^{5}

Figures 11-13 show the effect of droplet diameter, vapor temperature, and wall emissivity, respectively. Figure 11 shows that the radiative heat transfer increases for the liquid as the droplet diameter decreases.

TABLE X

LIQUID OPTICAL THICKNESSES

(Mean Beam Length = 0.06 m)

Absorptivity α	Optical Thickness (m) for Three Droplet Diameters		
	D = 10^{-2}	10^{-3}	10^{-4}
0.0	9	90	900
0.5	4.5	45	450
0.7	2.7	27	270
0.8	1.8	18	180
0.9	0.9	9	90
1.0	0	0	0

This is due to the increasing liquid optical thickness with decreasing droplet diameter, as seen in Table X. For a given void fraction, the droplet number density is inversely proportional to the droplet diameter. This is the reason for the effect seen in Fig. 11.

As would be expected Fig. 12 shows that the heat transfer to the vapor decreases as the vapor temperature increases. Comparing Figs. 8 and 12 shows that heat transfer to some of the surfaces from the vapor exists for the higher vapor temperatures.

Figure 13 shows that the heat transfer to the channel wall, the vapor, and the liquid increases with increasing wall emissivity. The wall emissivity for BWR Zircaloy bundles is specified for licensing calculations as 0.67 before rod wetting and 0.9 after wetting[29]. The channel wall and vapor heat transfer show a moderate change over the wall emissivity range of interest, but the liquid heat transfer varies substantially. The wall emissivity can vary considerably depending upon the surface finish. Nuclear rods can have an oxide layer on the outside, which will significantly effect the value of wall emissivity. Sutey and Fitzsimmons[30] indicate that Zircaloy under loss-of-coolant conditions can have a wall emissivity between 0.71 and 0.85.

It should also be noted that in Figs. 10, 11, and 12, the heat transfer to the channel wall is a small fraction of the total radiative heat transfer.

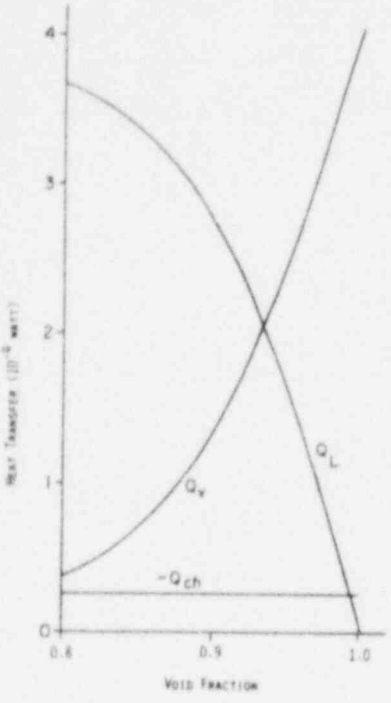

Fig. 10. Effect of void fraction on heat transfer.

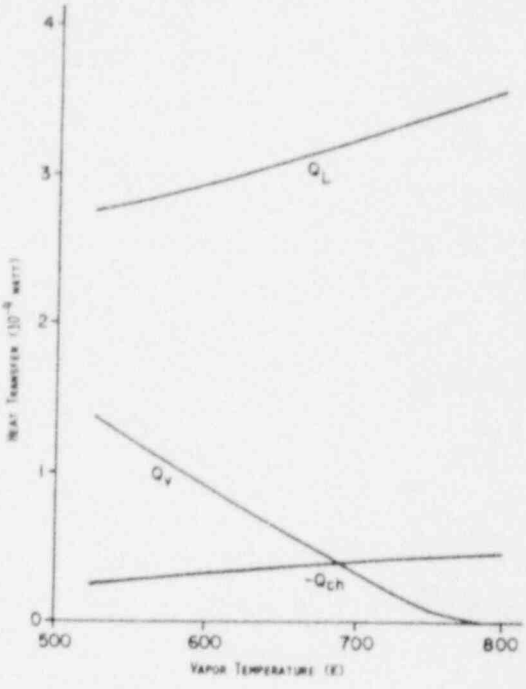

Fig. 12. Effect of vapor temperature on heat transfer.

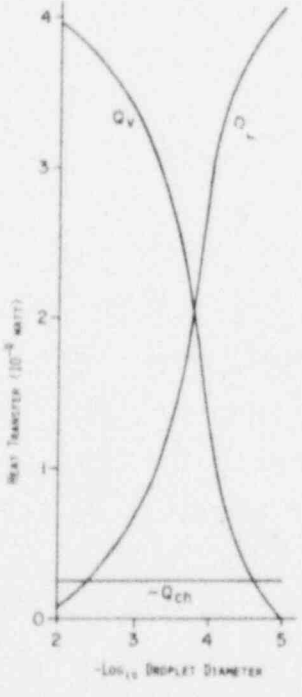

Fig. 11. Effect of droplet diameter on heat transfer.

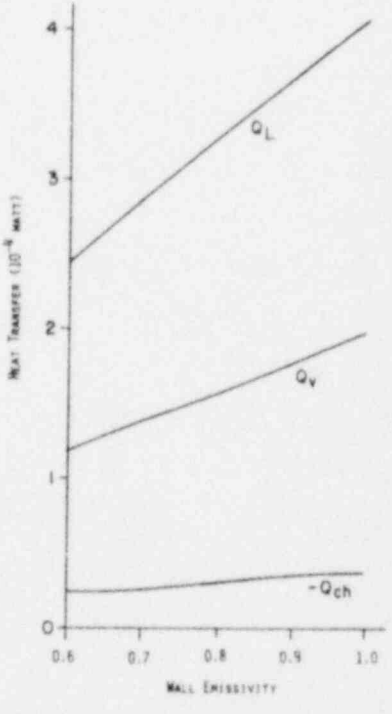

Fig. 13. Effect of wall emissivity on heat transfer.

In summary, this initial radiative heat transfer model proposed for the BWR version of the TRAC code is a compromise between an "exact" solution and the need for minimizing increases in the computer costs. If comparisons between the results obtained with this model, implemented into TRAC, and the data indicate that a more detailed radiative heat transfer model is needed, improvements can be made easily. The radiative heat transfer model has been coded in a very modular fashion to facilitate model improvements.

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APPENDIX A

NOMENCLATURE

A_i , A_j , A_k	surface area , m^2
a^o_{dij}	absorptivity of pure droplets
a^o_{gij}	absorptivity of pure vapor
a'^o_{gij}	absorptivity of pure vapor for radiation from droplets
a_{dij}	droplet absorptivity in two-phase mixture, Eq. (30)
a_{gij}	vapor absorptivity in two-phase mixture, Eq. (29)
B_i, B_k, B	radiosity, energy leaving surface
c_{ij}	Eq. (31)
C_o	speed of light in a vacuum, Eq. (9)
D	rod diameter, m, droplet diameter in RADHT code (Tables V and X)
e_{bj}	Planck's function evaluated at wall temperature of surface j
$e_b(T)$	Planck's function evaluated at T
F_{ij}	view factor, fraction of energy leaving surface i that reaches surface j in a vacuum
h	Planck's constant
i,j,k	surfaces (rods, channel)

k_{dij}	Eq. (28)
k_{gij}	Eq. (27)
k	Boltzmann constant
K(w)	Eq. (20)
L_l	Length of channel segment
L_{ij}	geometric mean beam length between surfaces i and j, m
L_{IJ}	group mean beam length
m	complex index of refraction = n - in'
n	real part of index of refraction
n'	complex part of index of refraction
N_d	droplet number density, m^{-3}
N	number of surfaces
P	pressure, N/m^2
p	pitch, distance between rod centers, m
q_{ij}	heat flux leaving surface i that reaches surface j, watt
q_j	net heat flux leaving surface j, $watt/m^2$
Q_{ext}	extinction cross section for droplets
Q_{abs}	absorption cross section for droplets
Q_{sca}	scattering cross section for droplets
Q_{IJ}	heat transfer leaving group I that reaches group J, watt
Q_V	heat transfer to vapor, watt
Q_L	heat transfer to liquid droplets, watt
Q_{mix}	total heat transfer to two-phase mixture, watt
$-Q_{ch}$	net heat transfer leaving the channel, watt
dq_{ok}	radiosity of surface k, $\equiv B_k$
R	radius of droplets, m
S	distance between surfaces, m

T	temperature, K
T_V	vapor temperature, K
T_L	liquid temperature, K
T_w, T_j	wall temperature, K
w	$4xn'$, Section III
x	$2\pi R/\lambda$, Section III
α	absorptivity
α^v_{kj}	vapor absorptivity = a_{gij}
β_k, β_j	angle between S and normal to surface
λ	wavelength, m
σ	Stefan-Boltzmann constant
σ_λ	scattering coefficient, Eq. (17)
κ	absorption coefficient, 1/m
κ_λ	spectral absorption coefficient, 1/m
ε_j	emissivity of surface j
$\bar{\varepsilon}^v_{kj}$	vapor emissivity between surfaces k and j in presence of droplets
$\bar{\varepsilon}^L_{kj}$	liquid emissivity between surfaces k and j in presence of vapor
ε^o_{dij}	droplet emissivity in two-phase mixture
ε^o_{gij}	vapor emissivity in two-phase mixture
δ_{ij}	$= 0 \quad i \neq j$
	$= 1 \quad i = j$
$\bar{\tau}_{kj}$	transmissivity
ρ	$2x(n-1)$

Superscripts

v	vapor
L	liquid (droplets)
o	indicates a pure substance

Subscripts

v,g	vapor
L,d	liquid (droplets)
w	wall
i,j,k	refers to individual surface i, j, or k
I	refers to group I
J	refers to group J
ch	channel
λ	indicates wavelength-dependent quantity

APPENDIX B
CALCULATION OF VIEW FACTORS

To calculate the surface-to-surface radiative heat transfer and the radiative heat transfer to the vapor and droplets, it is necessary to calculate all of the elements of the view factor array F_{ij} between each pair of surfaces. The view factors can be calculated by the crossed-string method.[B1] An 8 x 8 BWR bundle is shown in Fig. B-1, and this bundle has 96 surfaces. Therefore, the 96 x 96 view factor array must be filled. An examination of Fig. B-1 shows that there is a much smaller number of view factor calculations required because many of the view factors are either zero or identical to other view factors.

I. Rod-to-Rod View Factors

Because all of the rods are assumed to have the same diameter, a given rod can view only rods that are not more than one row or one column away. For example, rod 1 in Fig. B-1 can see rods 2, 9, 10 through 16,and the rods in the column headed by rod 10 (18, 26, etc.). The view factors from rod 1 to the other rods is zero ($F_{1-17} = F_{1-19} = F_{1-3} = 0$ etc.). Rod 1 can also see a number of channel segments, and the calculation of these view factors will be discussed in the next section.

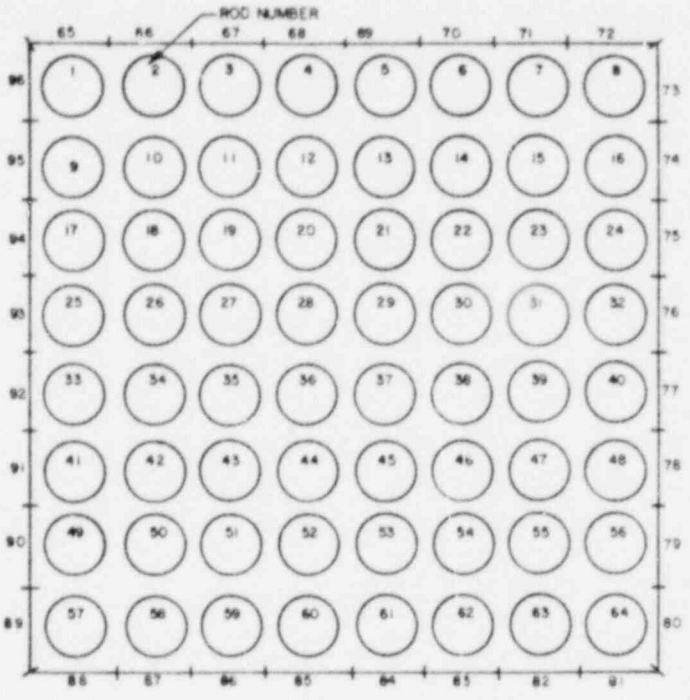


Fig. B-1. View factor geometry.

For adjacent rods of the same diameter, an analytical expression exists for the view factor.[B2] Adjusting the half-circle results of Ref. B2 to a full cylinder gives

$$F_{12} = \frac{1}{\pi}\left[\sqrt{x^2 - 1} - x + \frac{\pi}{2} - \cos^{-1}\frac{1}{x}\right] , \qquad \text{(B-1)}$$

where x = pitch/diameter = p/D.

For rods further away from each other the crossed-string method is used. For example, the crossed strings for second nearest neighbor rods are shown in Fig. B-2. The crossed-string method is

$$F_{12} = \frac{\text{crossed-string length} - \text{uncrossed-string length}}{2(\text{area/length of surface 1})} ,$$

or from Fig. B-2

$$F_{1\text{-}2} = \frac{X_2 - 2X_1 - A_2 + 2A_1}{D} , \qquad \text{(B-2)}$$

where the A's are arcs of the rods and

$$X_1 = \sqrt{p^2 - D^2} \ ,$$

$$X_2 = \sqrt{2p^2 - D^2} \ ,$$

$$A_1 = \frac{D}{2}\left[\tan^{-1}\frac{X_1}{D} + 0.7854 - \tan^{-1}\frac{X_2}{D}\right] \ , \text{ and}$$

$$A_2 = \frac{D}{2}\left[\frac{\pi}{2} - 2\tan^{-1}\frac{X_1}{D}\right] \ .$$

These lengths and arcs are found from basic geometry.

In a similar manner, the view factors for third nearest neighbor rods or rods further away can be found

$$F_{1I} = \frac{X_2 + X_3 - 2\,(X_1 + A_1 - A_2)}{2\pi D} \ ,$$

where

$$X_1 = \left\{\left[(\Delta i - 1)^2 + 1\right] p^2 - D^2\right\}^{1/2} \ ,$$

$$X_2 = \left\{\left[(\Delta i)^2 + 1\right] p^2 - D^2\right\}^{1/2} \ ,$$

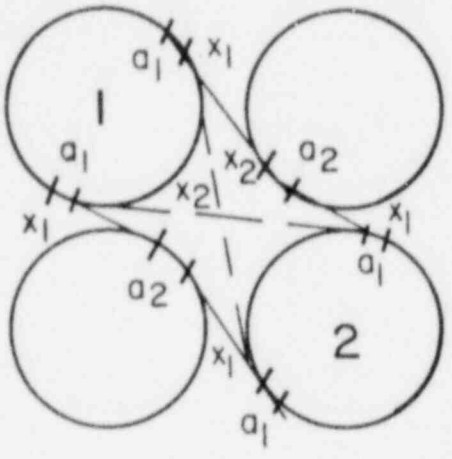
$$X_3 = \left\{\left[(\Delta i - 2)^2 + 1\right] p^2 - D^2\right\}^{1/2} \ ,$$

$$A_1 = \frac{D}{2}\left[\tan^{-1}\frac{X_3}{D} - \tan^{-1}(\Delta i\text{-}2) - \tan^{-1}\frac{X_1}{D} + \tan^{-1}(\Delta i\text{-}1)\right] \ ,$$

and

$$A_2 = \frac{D}{2}\left[\tan^{-1}\frac{X_1}{D} - \tan^{-1}(\Delta i\text{-}1) - \tan^{-1}\frac{X_2}{D} + \tan^{-1}(\Delta i)\right] \ .$$

The $\Delta i = i - 1$ where i is the number of rods away from rod 1 in a given row or column. For example, in Fig. B-1, for $F_{1\text{-}11}$, i=2; for $F_{1\text{-}16}$, I=8; for $F_{1\text{-}58}$, i=8, etc.



—— UNCROSSED STRING
--- CROSSED STRING

Fig. B-2. Crossed string geometry for second nearest neighbor rods.

II. Rod-to-Channel Segment and Channel Segment-to-Channel Segment View Factors

The rod-to-channel segment and channel segment-to-channel segment view factors needed here are shown in Table B-I. The channel segment lengths not at corners are set equal to the pitch, and because the channel sides are not a multiple of the pitch, the corner segment will, in general, not be equal to the pitch. Therefore the expressions for the view factors of Table B-I will be different when the channel segment is a corner segment.

For channel segments not at a corner, the Type 1 view factor has been given by Feingold and Gupta.[B3] For a corner segment the rod is not symmetrically placed with respect to the segment. For this case, and all the other view factor types, the crossed-string method is used to evaluate the view factor.[B1]

The algebraic expressions obtained by the crossed-string method for the view-factor types described in Table B-I are given in Table B-II. These expressions can be verified by assigning the proper view-factor type to each element of the F_{ij} matrix and then summing over j for each i. Each sum should equal 1.0. Even though this does not guarantee that all the view factors are correct, it is highly unlikely that there are errors that would cancel each other, enabling the summations to be satisfied.

TABLE B-I

ROD-TO-CHANNEL SEGMENT AND CHANNEL SEGMENT-TO-CHANNEL SEGMENT VIEW FACTOR GEOMETRIES

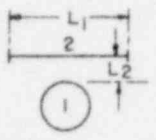
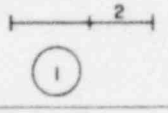
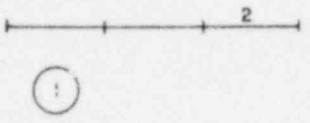
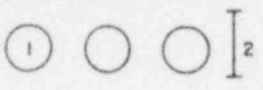
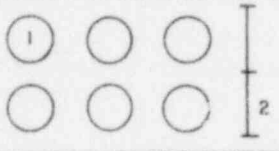
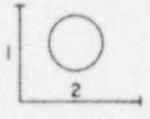
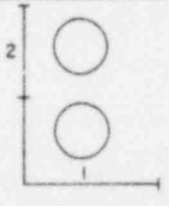
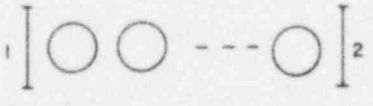
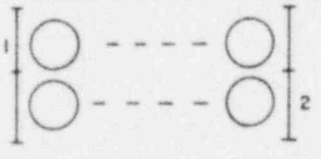
Type	Description
1	
2	
3	
4	
5	
6	
7	
8	
9	

TABLE B-II

ROD-TO-CHANNEL SEGMENT AND CHANNEL
SEGMENT-TO-CHANNEL SEGMENT VIEW FACTORS

TYPE	VIEW FACTOR [a]
1	$F_{12} = \frac{1}{\pi} \tan^{-1} \frac{(L_1)/2}{\frac{D}{2} + L_2}$ not a corner segment
	$= \frac{a_1 + a_2}{2\pi D}$, corner segment
	where $a_1 = \frac{D}{2}\left(0.7854 + \tan^{-1}\frac{2X_1}{D} - \tan^{-1}\frac{2X_2}{D} + \tan^{-1}\frac{0.5P}{C_o}\right)$,
	$a_2 = \frac{D}{2}\left(\tan^{-1}\frac{0.5P}{C_o} + \tan^{-1}\frac{2X_2}{D} - \tan^{-1}\frac{2X_1}{D} + 0.7854\right)$,
	$C_o = \frac{D}{2} + L_2$; $X_1 = \left(2C_o^2 - \frac{D^2}{4}\right)^{1/2}$, and
	$X_2 = \left(C_o^2 + \frac{P^2}{4} - \frac{D^2}{4}\right)^{1/2}$.
2	$F_{12} = \frac{X_2 + X_3 + a_1 - X_5 - X_1 - a_2 - X_4 + a_3}{2\pi D}$,
	where $X_1 = \left\{\left[(\Delta i - 0.5)\, L_1\right]^2 + Y\right\}^{1/2}$,
	$X_2 = \left[\left(\left\lvert \Delta i - 1.5 \right\rvert L_1\right)^2 + Y\right]^{1/2}$,
	$X_3 = \left(L_3^2 + Y\right)^{1/2}$,
	$X_4 = (P^2 - D^2)^{1/2}$, and
	$X_5 = X_1$ not a corner segment
	$= \left\{\left[(\Delta i - 1.5)L_1 + C_o + 0.5p\right]^2 + Y\right\}^{1/2}$ corner segment
	Here, $Y = \left(\frac{D}{2} + L_2\right)^2 - \frac{D^2}{4}$, and
	$L_3 = (\Delta i + 0.5)\, L_1$ not a corner segment
	$= (\Delta i - 0.5)\, L_1 + C_o + 0.5P$. corner segment
	$a_1 = \frac{D}{2}\left[\tan^{-1}\frac{2X_1}{D} - \tan^{-1}\frac{(\Delta i - 0.5)L_1}{C_o} - \tan^{-1}\frac{2X_3}{D} + \tan^{-1}\frac{L_3}{C_o}\right]$,
	$a_2 = \frac{D}{2}\left[\frac{\pi}{2} - \tan^{-1}\frac{X_4}{D} - \tan^{-1}\frac{2X_1}{D} + \tan^{-1}\frac{(\Delta i - 0.5)L_1}{C_o}\right]$ not a corner segment
	$= \frac{D}{2}\left[\frac{\pi}{2} - \tan^{-1}\frac{X_4}{D} - \tan^{-1}\frac{2X_5}{D} + 0.7854\right]$, and corner segment
	$a_3 = \frac{D}{2}\left[\tan^{-1}\frac{X_4}{D} - \tan^{-1}\frac{2X_2}{D} + \frac{\pi}{2} - \tan^{-1}\frac{(\Delta i - 0.5)L_1}{C_o}\right]$.

TABLE B-II (cont)

Type	View Factor

3

F_{12} = Same as Type 2, except

$$a_3 = X_4 = 0 \ ,$$

$$a_2 = \frac{D}{2}\left[\tan^{-1}\frac{2X_2}{D} - \tan^{-1}\frac{|(\Delta i - 1.5)|L_1}{C_o} - \tan^{-1}\frac{2X_1}{D} + \tan^{-1}\frac{(\Delta i - 0.5)L_1}{C_o}\right], \text{ and} \quad \text{not a corner segment}$$

$$= \frac{D}{2}\left[\tan^{-1}\frac{2X_2}{D} - \tan^{-1}\frac{|(\Delta i - 1.5)|L_1}{C_o} - \tan^{-1}\frac{2X_5}{D} + \tan^{-1}\frac{(\Delta i - 1.5)L_1 + C_o + 0.5p}{C_o}\right] \cdot \quad \text{corner segment}$$

4

$$F_{12} = \frac{X_2 + X_2' + 2X_1 - (X_3 + X_3') + a_1 + a_1' - (a_2 + a_2')}{2\pi D} \ ,$$

where $X_1 = p$, $X_2 = \left\{0.25\ L_1^2 + \left[(\Delta i - 1.0)p + \frac{D}{2} + L_2\right]^2 - \frac{D_2}{4}\right\}^{1/2}$,

$$X_3 = \left\{0.25\ L_1^2 + \left[\frac{D}{2} + L_2 + (\Delta i)p\right]^2 - \frac{D_2}{4}\right\}^{1/2} \ ,$$

$$X_2' = \left\{Y + \left[(\Delta i - 1.0)p + \frac{D}{2} + L_2\right]^2 - \frac{D_2}{4}\right\}^{1/2} \ , \text{ and}$$

$$X_3' = \left\{Y + \left[\frac{D}{2} + L_2 + (\Delta i)p\right]^2 - \frac{D_2}{4}\right\}^{1/2} \ .$$

Here, $Y = (0.5L_1)^2$ not a corner segment

$= \left(\frac{D}{2} + L_2\right)^2$. corner segment

$$a_1 = \frac{D}{2}\left[\tan^{-1}\frac{2X_3}{D} + \tan^{-1}\frac{0.5\ L_1}{\frac{D}{2} + L_2 + (\Delta i)p} - \frac{\pi}{2}\right] ,$$

$$a_2 = \frac{D}{2}\left[\tan^{-1}\frac{2X_2}{D} + \tan^{-1}\frac{0.5\ L_1}{(\Delta i - 1.0)p + \frac{D}{2} + L_2} - \frac{\pi}{2}\right] ,$$

$$a_1' = \frac{D}{2}\left[\tan^{-1}\frac{2X_3'}{D} + \tan^{-1}\frac{\sqrt{Y}}{\frac{D}{2} + L_2 + (\Delta i)p} - \frac{\pi}{2}\right] , \text{ and}$$

$$a_2' = \frac{D}{2}\left[\tan^{-1}\frac{2X_2'}{D} + \tan^{-1}\frac{\sqrt{Y}}{(\Delta i - 1)p + \frac{D}{2} + L_2} - \frac{\pi}{2}\right] .$$

5

$$F_{12} = \frac{X_2 + X_3 - X_1 - X_4 - a_1 - a_2 + a_3}{2\pi D} \ ,$$

where $X_1 = \left\{\left[(\Delta i - 1)p + C_o\right]^2 + \frac{L_1^2}{4} - \frac{D^2}{4}\right\}^{1/2}$,

$$X_2 = \left\{\left[(\Delta i)p + C_o\right]^2 + \frac{L_1^2}{4} - \frac{D_2}{4}\right\}^{1/2} \ ,$$

$$X_3 = \left\{\left[(\Delta i - 1)^2 + 1\right]p^2 - D^2\right\}^{1/2} ,$$

$$X_4 = \left\{\left[(\Delta i)^2 + 1\right]p^2 - D^2\right\}^{1/2} ,$$

$$a_1 = \frac{D}{2}\left[\tan^{-1}\frac{X_3}{D} - \tan^{-1}(\Delta i - 1) - \tan^{-1}\frac{X_4}{D} + \tan^{-1}(\Delta i)\right] .$$

TABLE B-II (cont)

TYPE	VIEW FACTOR
5	$a_2 = \frac{D}{2}\left[\tan^{-1}\frac{X_3}{D} - \tan^{-1}(\Delta i - 1) - \tan^{-1}\frac{2X_1}{D} + \tan^{-1}\frac{(\Delta i - 1)p + C_o}{0.5\,L_1}\right]$, and $a_3 = \frac{D}{2}\left[\tan^{-1}\frac{X_4}{D} - \tan^{-1}(\Delta i) - \tan^{-1}\frac{2X_2}{D} + \tan^{-1}\frac{(\Delta i)p + C_o}{0.5\,L_1}\right]$.
6	$F_{12} = \frac{C_o + 0.5p - X - 0.5a}{C_o + 0.5p}$, where $X = \left(0.25\,L_1^2 + C_o^2 - \frac{D_2}{4}\right)^{1/2}$ and $a = D\left[0.25\,\pi - \tan^{-1}\frac{2X}{D} + \tan^{-1}\frac{0.5L_1}{C_o}\right]$.
7	$F_{12} = \frac{0.5(X_1 + X_2 - X_3 - a)}{Y}$, where $Y = p$ surface 1 not a corner segment, $Y = C_o + 0.5p$ surface 1 a corner segment, $X_1 = p$ if surface 1 or surface 2 not a corner segment $= C_o + 0.5p$ if surface 1 and surface 2 are corner segments $X_2 = \left\{\left[(\Delta i - 0.5)p\right]^2 + C_o^2 - \frac{D_2}{4}\right\}^{1/2}$, $X_3 = \left\{\left[(\Delta i - 0.5)p + X_1\right]^2 + C_o^2 - \frac{D_2}{4}\right\}^{1/2}$, and $a = \frac{D}{2}\left[\tan^{-1}\frac{2X_2}{D} - \tan^{-1}\frac{(\Delta i - 0.5)p}{C_o} - \tan^{-1}\frac{2X_3}{D} + \tan^{-1}\frac{(\Delta i - 0.5)p + X_1}{C_o}\right]$.
8	$F_{12} = F_A$ not a corner segment $= \frac{(C_o F_B + 0.5p F_A)}{C_o + 0.5p}$, corner segment where $F_A = 2(X_1 - B + C_o - a_1)/p$, $F_B = \frac{X_2 - B + C_o - a_2}{C_o}$, $X_1 = \left[\left(B - \frac{D}{2} - L_2\right)^2 + 0.25p^2 - \frac{D^2}{4}\right]^{1/2}$, $X_2 = \left[\left(B - C_o\right)^2 + C_o^2 - \frac{D_2}{4}\right]^{1/2}$.

TABLE B-II (cont)

TYPE	VIEW FACTOR
8	$a_1 = \frac{D}{2}\left[\tan^{-1}\frac{2X_1}{D} + \tan^{-1}\frac{0.5p}{B - \frac{D}{2} - L_2} - \frac{\pi}{2}\right]$, and $a_2 = \frac{D}{2}\left[\tan^{-1}\frac{2X_2}{D} + \tan^{-1}\frac{C_o}{B - C_o} - \frac{\pi}{2}\right]$.
9	$F_{12} = (0.5\pi X_2 + B - 2X_1 - 2a)/p$ not a corner segment $= \frac{0.5\pi X_2 + B - 2X_1 - 2a)}{C_o + 0.5p}$ corner segment where $X_1 = \left[\left(B - C_o\right)^2 + \frac{L_1^2}{4} - \frac{D_2}{4}\right]^{1/2}$, $X_2 = \left[p^2 + (B - D - 2L_2)^2 - D^2\right]^{1/2}$, and $a = \frac{D}{2}\left[\tan^{-1}\frac{X_2}{D} - \tan^{-1}\frac{B - D - 2L_2}{p} - \tan^{-1}\frac{2X_1}{D} + \tan^{-1}\frac{2(B - C_o)}{p}\right]$.
	[a] B = bundle width, m. L_1 = channel segment length, p, m. L_2 = shortest distance between channel segment and outer row of rods = $\frac{1}{2}\left[B - (N - 1)p - D\right]$. N = number of rods in one row. p = rod pitch. D = rod diameter. $C_o = \frac{D}{2} + L_2$

REFERENCES

B1. H. C. Hottel and A. F. Sarofim, Radiative Heat Transfer (McGraw-Hill Book Co., New York, 1967).

B2. E. M. Sparrow and R. D. Cess, Radiation Heat Transfer (Brooks/Cole Division, Wadsworth Publishing Co., Inc., Belmont, California, 1966).

B3. A. Feingold and K. Gupta, "New Approach to the Evaluation of Configuration Factors in Radiation from Spheres and Infinitely Long Cylinders," J. Heat Transfer, pp. 69-76 (February 1970).

APPENDIX C

CALCULATION OF MEAN BEAM LENGTHS

As noted previously, the calculation of the geometric mean beam lengths directly from the definition is an extremely complex calculation for the geometry being considered here. Therefore, the method used in the NORCOOL code[C1] is used in RADHT. In this method an equivalent distance between surfaces is used for the mean beam length. This has been shown to give close agreement with exact results.[C2]

The rod-to-rod mean beam length types and results are shown in Table C-I. The curved surface of the rod is replaced by an equivalent flat plate at a distance $D/2 - \pi D/8$ from the center of the rod. The $\pi D/8$ is obtained by considering an average of the distances to the cylinder.

The rod-to-channel segment and the channel segment-to-channel segment geometric mean beam lengths are given in Table C-II. As with the view factors discussed in Appendix B, the results depend upon whether or not the segment is a corner segment. It should also be noted that the geometric mean beam length matrix is symmetric.

REFERENCES

C1. J. G. M. Andersen, et al., "NORCOOL I, A Model for Analysis of a BWR Under LOCA Conditions," Riso National Laboratory report NORHAV-D-47, Denmark (August 1977).

C2. J. G. M. Andersen, General Electric Co., personal communication, January 1979.

TABLE C-I

ROD-TO-ROD MEAN BEAM LENGTHS

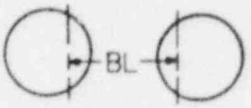
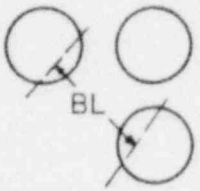
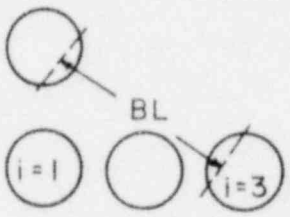
Type	Geometry	Beam Length, BL
Adjacent Rods		$BL = p - \frac{\pi D}{4}$
Second Nearest Neighbors		$BL = p\sqrt{2} - \frac{\pi D}{4}$
Third and Greater Nearest Neighbors		$BL = p\sqrt{(\Delta i)^2 + 1} - \frac{\pi D}{4}$

TABLE C-II

ROD-TO-CHANNEL SEGMENT AND CHANNEL SEGMENT-
TO-CHANNEL SEGMENT MEAN BEAM LENGTHS

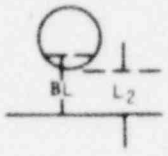
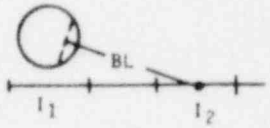
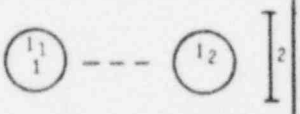
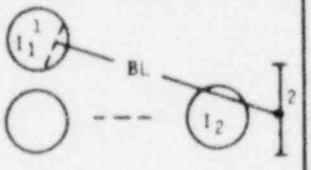
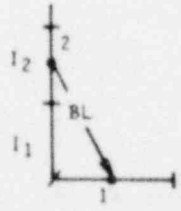
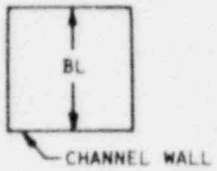
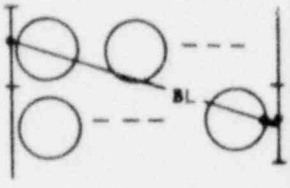
Type	Geometry	Beam Length, BL
1		$BL = C_0 - \frac{\pi D}{8}$. WHERE $C_0 = \frac{D}{2} + L_2$.
2		$BL = \left(\left[(\Delta I)P\right]^2 + C_0 2\right)^{1/2} - \frac{\pi D}{8}$. SEGMENT 2 ≠ CORNER SEGMENT. $BL = \left\{\left[(\Delta I - 0.25)P + 0.5\ C_0\right]^2 + C_0 2\right\}^{1/2} - \frac{\pi D}{8}$. SEGMENT 2 = CORNER SEGMENT.
3		$BL = (\Delta I)P + C_0 - \frac{\pi D}{8}$.
4		$BL = \left\{\left[(\Delta I)P + C_0\right]^2 + P2\right\}^{1/2} - \frac{\pi D}{8}$. SEGMENT 2 ≠ CORNER SEGMENT $BL = \left\{\left[(\Delta I)P + C_0\right]^2 + \left[0.5(0.5P + C_0)\right]^2\right\}^{1/2} - \frac{\pi D}{8}$. SEGMENT 2 = CORNER SEGMENT.
5		$BL = (C_0 + 0.5P)\ \frac{\sqrt{2}}{2}$.
6		$BL = \left\{\frac{(C_0 + 0.5P)^2}{4} + \left[(C_0 + 0.5P + \Delta I - 0.5)P\right]^2\right\}^{1/2}$. SEGMENT 2 ≠ CORNER SEGMENT. $BL = \left\{\frac{(C_0 + 0.5P)^2}{4} + \left[C_0 + 0.5P + (\Delta I - 1)P + \frac{C_0 + 0.5P}{2}\right]^2\right\}^{1/2}$. SEGMENT 2 = CORNER SEGMENT.

TABLE C-II (cont)

Type	Geometry	Beam Length, BL
7		$BL = B$, WHERE B = CHANNEL WIDTH .
8		$BL = \sqrt{B^2 + P^2}$. NEITHER SEGMENT IS A CORNER SEGMENT $BL = \left[B^2 + (0.5C_0 + 0.75P)^2\right]^{1/2}$. IF ONE SEGMENT IS A CORNER SEGMENT.

APPENDIX D

RADHT CODE LISTING

```
      p -gram radchk(input,output,rdata,tape5=rdata,tape6)
c
c     check of the radiative heat transfer package
c
      real l,lgrp,lhs,ndrop,lv,l2
      common/radss/ bundw,pitch,f(96,96),l(96,96),drod
      common/surf/ isurf
      common /radcom/ fgrp(37,37),agrp(37),lgrp(37,37),qv(1),ql(1)
      dimension lhs(37,37),rhs(37),biden(37,37),tv(1),tl(1),
     * tw(37,1),
     1 tau(37,37),stw4(37),alf(37,37),ndrop(1),d(1),p(1),
     2 alpha(1),q(37),qmix(1),fv(8),a(96),
     3 irod(96),emis(37),b(37),lv(8)
c
c     this version of radht is dimensioned for a maximum of 8x8
c     rods and one axial level. maximum number of groups is 37.
c     each rod is one surface. the channel wall is divided into
c     4 times nrod surfaces. these surfaces are then
c     grouped by using the input irod.
c
c     written by d. a. mandell
c                safety code development, q09
c                los alamos sci. lab.
c
      data nd,ndgrp,levmax,pi,bundw/96,37,1,3.141593,.05237812/
      data nfv/8/
c
c*******  n o m e n c l a t u r e  **********************
c
c nmax    total number of surfaces, nrod*nrod+4*nrod
c nrod    number of rods in each row or column
c irod    rod group indicator
c ngrp    number of rod groups
c a       area of individual surfaces
c tl      liquid droplet temperature at a given level
c tv      vapor temperature at a given level
c pitch   rod center-rod center distance
c drod    rod diameter (all rods have the same diameter)
c tw      surface temp. of each rod group
c emis    surface emissivity of each rod group
c iout    output flag, =0, input not written
c                      =1, input written
c alpha   void fraction at each axial level
c p       pressure at each axial level
c d       droplet diameter
c bundw   bundle width
c isurf    =0, radiation to fluid and surface to surface radiation
c          =1, surface to surface radiation only.
c
c*************************************************************
c
      namelist/in/ nmax,nrod,irod,ngrp,tl,tv,pitch,drod,tw,emis,
     1 iout,alpha,p,bundw,d,isurf
c
10    continue
      read(5,in)
      if(eof(5)) 15,18
18    continue
      if(iout.gt.0) write(6,in)
      do 20 level=1,levmax
```

```
      ndrop(level)=6.*(1.-alpha(leve'))/(pi*d(level)**3)
20    continue
c
      if(iout.gt.1) go to 310
c
      l2=.5*(bundw-float(nrod-1)*pitch-drod)
      c0=.5*drod+l2
      nsq=nrod*nrod
      n1=nsq+1
      do 5 i=n1,nmax
      a(i)=pitch
c
c     check for corner segment
c
      if((i.eq.n1).or.(i.eq.n1+nrod-1).or.(i.eq.n1+2*nrod-1)
     *  .or.(i.eq.n1+nrod)
     1 .or.(i.eq.n1+2*nrod).or.(i.eq.n1+3*nrod-1).or.
     2 (i.eq.n1+3*nrod).or.(i.eq.nmax)) a(i)=.5*pitch+c0
c
5     continue
      nmaxm1=nmax-1
      do 11 i=1,nsq
      a(i)=pi*drod
11    continue
c
c     call the steady state radiative heat transfer subroutine
c
      call sradht(nd,ndgrp,levmax,lhs,rhs,biden,tv,tl,tw,tau,
     1 stw4,alf,ndrop,d,p,alpha,q,qmix,fv,a,irod,
     2 emis,b,lv,nfv,nmax,nrod,ngrp)
c
      do 40 j=1,nmax
      write(6,55) j
55    format(5h f(i,,i2,2h ))
      write(6,50) (f(i,j),i=1,nmax)
40    continue
c
c     write the mean beam lengths.
c
      do 140 j=1,nmax
      write(6,150) j
150   format(1x,*l(i,*,i2,* )*)
      write(6,50) (l(i,j),i=1,nmax)
140   continue
c
c     check view factor summmation
c
      do 110 i=1,nmax
      sum=0.
      do 120 j=1,nmax
      sum=sum+f(i,j)
120   continue
      write(6,130) i,sum
110   continue
130   format(1x,*i =*,i3,2x,*sum over j of f(i,j) =*,
     1 f10.3)
c
310   continue
c
      if(iout.gt.1)
```

```
      *call tradht(nd,ndgrp,levmax,lhs,rhs,biden,tv,tl,tw,tau,
     1 stw4,alf,ndrop,d,p,alpha,q,qmix,fv,a,irod,
     2 emis,b,lv,nfv,nmax,nrod,ngrp)
c
      do 70 j=1,ngrp
      write(6,80) j
80    format(8h fgrp(i,,i2,2h ))
      write(6,50) (fgrp(i,j),i=1,ngrp)
70    continue
c
c     check grouped view factor summation
c
      do 315 i=1,ngrp
      sum=0.
      do 320 j=1,ngrp
      sum=sum+fgrp(i,j)
320   continue
      write(6,330) i,sum
315   continue
330   format(1x,*i =*,i3,2x,*sum over j of grouped f(i,j) =*,
     1 f10.3)
      do 160 j=1,ngrp
      write(6,170) j
170   format(1x,*lgrp(i,*,i2,* )*)
      write(6,50) (lgrp(i,j),i=1,ngrp)
160   continue
      do 240 j=1,ngrp
      write(6,250) j
      write(6,50) (alf(i,j),i=1,ngrp)
240   continue
250   format(1x,*alf(i,*,i2,*) =*)
      write(6,190)
190   format(1x,*lv=*/)
      write(6,50) (lv(i),i=1,nfv)
      write(6,200)
200   format(1x,*fv=*/)
      write(6,50) (fv(i),i=1,nfv)
      write(6,260)
260   format(/,*rod group results*/)
      write(6,270)
270   format(2x,*group*,5x,*agrp*,5x,*radiosity*,8x,*q*,
     1 9x,*t wall*/)
      write(6,280) (i,agrp(i),b(i),q(i),tw(i),i=1,ngrp)
280   format(i5,4e12.3)
50    format(4e15.4)
      write(6,210)
210   format(/,*rod level results*/)
      write(6,220)
220   format(1x,*level*,5x,*tv*,9x,*tl*,5x,*ndrop*,13x,*d*,
     1 12x,*p*,9x,*qv*,9x,*ql*,9x,*qmix*/)
      write(6,230) (i,tv(i),tl(i),ndrop(i),d(i),p(i),qv(i),
     1 ql(i),qmix(i),i=1,levmax)
230   format(i3,8e12.3)
      do 300 level=1,levmax
      qdiff=100.*abs(qmix(level)-qv(level)-ql(level))
     1 /qmix(level)
      write(6,290) qdiff
300   continue


290   format(//*the percent difference between qmix qv + ql, *,
     1 *based on qmix, is*, f10.2///)
```

```
      go to 10
15    call exita(1)
      end
      subroutine sradht(nd,ndgrp,levmax,lhs,rhs,biden,tv,tl,
     1 tw,tau,stw4,alf,ndrop,d,p,alpha,q,qmix,fv,a,
     2 irod,emis,b,lv,nfv,nmax,nrod,ngrp)
c
c     the purpose of this subroutine is to initialize the radiative
c     heat transfer calculation. quantities that have to be
c     calculated only once are calculated in this subroutine
c     (individual and grouped view factors and geometrical mean
c     beam lengths).
c
c     optically thin conditions are assumed in he two phase
c     mixture. it is assumed that all of the surface temperatures
c     are known.
c
c     written by
c                 d. a. mandell
c                 thermal reactor safety group, q-6
c                 september, 1978
c
c**********************************************************************
c
c ref., r. siegel and j. howell, thermal radiation heat transfer,
c       mcgraw-hill book co., new york, 1972.
c
c**********************************************************************
c
      real l,lgrp,keq,lv,lhs,ndrop,lhssav(37,37)
      real kv,kl
      common/surf/ isurf
      common/radcom/fgrp(37,37),agrp(37),lgrp(37,37),qv(1),ql(1)
      common/radss/bundw,pitch,f(96,96),l(96,96),drod
      dimension lhs(ndgrp,ndgrp),rhs(ndgrp),biden(ndgrp,ndgrp),
     1 tv(levmax),tl(levmax),tw(ndgrp),tau(ndgrp,ndgrp),
     2 stw4(ndgrp),d(levmax),p(levmax),alpha(levmax),q(ndgrp),
     3 qmix(levmax),fv(nfv),a(nd),
     4 irod(nd),emis(ndgrp),b(ndgrp),lv(nfv),ndrop(levmax),
     5 alf(ndgrp,ndgrp)
      data ia,iy,ib/37,37,37/
      data pi,nl/3.141593,1.0/
c
c     sigma is the stefan-boltzmann constant in
c     watt/meter**2 per deg. k to the 4 th.
c
      data sigma/5.668e-8/
c
c
c     calculate the view factors between each of the individual
c     surfaces. also calculate the mean beam lengths.
c
      call fij(nmax,fv,nfv,a,nrod,nd,lv)
c
c


c     entry point when new f's l's are not needed.
c
      entry tradht
c
c     group the individual view factors
```

```
c
      call grpfij(f,nd,fgrp,ngrp,a,agrp,irod,ndgrp,nmax)
c
c     group the individual mean beam lengths
c
      call grplij(f,nd,fgrp,ngrp,a,agrp,irod,ndgrp,nmax,l,lgrp)
c
c
c     set-up the matrix equation and solve it for the heat flux
c     leaving each surface. then solve for the heat flux from all
c     of the walls to the vapor and from all of the walls to the
c     liquid drops. this is done at each axial level.
c
      do 10 level=1,levmax
c
c-----------------------------------------------------------------
c
c     calculate the equivalent absorption coefficient and the
c     equivalent blackbody emissive power.
c
      call acoeff(tl(level),tv(level),ndrop(level),d(level),
     1 p(level),keq,ebeq,alpha(level),irang)
      if(irang.gt.0) write(6,240) irang
240   format(1x,'i =',i3//2x,'planck mean absorption coefficient '/
     1 'is outside the range of the data. i = 1, temperature is '/
     2 'below the data. i = 2, temperature is above the highest '/
     3 'data point. extrapolation used.'//)
c
c-----------------------------------------------------------------
c
c     calculate the transmissivity, tau
c
      do 20 i=1,ngrp
      do 30 j=1,ngrp
      tau(i,j)=exp(-keq*lgrp(i,j))
      if(isurf.gt.0) tau(i,j)=1.0
30    continue
20    continue
c
c-----------------------------------------------------------------
c
c     calculate the absorptivity, alf
c
      do 40 i=1,ngrp
      do 50 j=1,ngrp
      alf(i,j)=1.0-tau(i,j)
50    continue
40    continue
c
c-----------------------------------------------------------------
c
c     calculate sigma t to the fourth for the walls, vapor and
c     for the drops.
c
      do 60 i=1,ngrp
      stw4(i)=sigma*tw(i)**4
60    continue
      stv4=sigma*tv(level)**4
      stl4=sigma*tl(level)**4
c
```

```
c-----------------------------------------------------------------
c
c     calculate the lhs and the rhs of the matrix equation.
c     (siegel and howell, chap. 17)
c
      do 70 k=1,ngrp
      sum=0.
      do 80 j=1,ngrp
      if(k.ne.j) lhs(k,j)=-fgrp(k,j)*(1.-emis(j))*tau(k,j)
     1 /emis(j)
      if(k.eq.j) lhs(k,j)=1./emis(j)-fgrp(k,j)*(1.-emis(j))
     * *tau(k,j)/emis(j)
      lhssav(k,j)=lhs(k,j)
c
      call em(eg,ed,ag,ad,lgrp(k,j),tv(level),tv(level),tv(level),
     1 ndrop(level),d(level),alpha(level),p(level))
      terma=eg*fgrp(k,j)*stv4
      termb=ed*fgrp(k,j)*st14
      term=terma+termb
      if(alpha(level).le.0.) term=termb
      if(alpha(level).ge.1.0) term=terma
      if(isurf.gt.0) term=0.
      if(k.ne.j) sum=sum-fgrp(k,j)*tau(k,j)*stw4(j)-
     1 term
      if(k.eq.j) sum=sum+(1.0-fgrp(k,j)*tau(k,j))*stw4(j)-
     1 term
80    continue
      rhs(k)=sum
70    continue
c
c-----------------------------------------------------------------
c
c     solve the matrix equation for the net heat flux leaving
c     surface k, q(k).
c
c
c     set-up identity matrix
c
      do 75 i=1,ngrp
      do 75 j=1,ngrp
      biden(i,j)=0.
      if(i.ne.j) go to 75
      biden(i,j)=1.
75    continue
c
      do 150 jj=1,ngrp
      write(6,160) jj
      write(6,170) (lhs(ii,jj),ii=1,ngrp)
150   continue
160   format(/,1x,*lhs(i,*,i2,*) =*)
170   format(4e15.5)
      write(6,180) (ii,rhs(ii),ii=1,ngrp)
180   format(1x,*i =*,i3,2x,*rhs(i) =*,e15.5)
      call glss(ngrp,ngrp,1,ngrp,nr,lhs,ia,rhs,iy,
     1 biden,ib,q,ngrp)
c
      write(6,190)
190   format(1x,*check matrix solution by matrix mult.*)
      do 200 ii=1,ngrp
      sum=0.
```

```
      do 210 jj=1,ngrp
      sum=sum+lhssav(ii,jj)*q(jj)
210   continue
      write(6,220) ii,sum
200   continue
220   format(1x,*i =*,i3,2x,*re-calculated rhs =*,e15.5)
c**********************************************************************
c
c     calculate the radiative heat transfer from all of the groups
c     to the liquid and also to the vapor
c
c----------------------------------------------------------------------
c
c     calculate the radiosity, b(k)
c
      do 90 k=1,ngrp
      b(k)=stw4(k)-q(k)*(1.-emis(k))/emis(k)
90    continue
c
c----------------------------------------------------------------------
c
c     calculate the radiative heat transfer to the vapor
c
      qv(level)=0.
      ql(level)=0.
      if(isurf.gt.0) go to 230
      if(alpha(level).le.0.) go to 235
      sumj=0.
      do 100 j=1,ngrp
      sumk=0.
      do 110 k=1,ngrp
      call em(eg,ed,ag,ad,lgrp(k,j),tv(level),tv(level),tv(level),
     1 ndrop(level),d(level),alpha(level),p(level))
      e=eg
      ah2ov=e
      sumk=sumk+agrp(k)*fgrp(k,j)*(ah2ov*b(k)-e*stv4)
110   continue
      sumj=sumj+sumk
100   continue
      qv(level)=sumj
235   continue
c
c----------------------------------------------------------------------
c
c     calculate the radiative heat transfer to the liquid
c
      sumj=0.
      do 120 j=1,ngrp
      sumk=0.
      do 130 k=1,ngrp
      call em(eg,ed,ag,ad,lgrp(k,j),tv(level),tv(level),tv(level),
     1 ndrop(level),d(level),alpha(level),p(level))
      e=ed
      ah2ol=e
      sumk=sumk+agrp(k)*fgrp(k,j)*(ah2ol*b(k)-e*stl4)
130   continue
      sumj=sumj+sumk
120   continue
      ql(level)=sumj
230   continue
```

```
c
c-----------------------------------------------------------------
c
c     calculate the total radiative heat transfer to the mixture
c
      sum=0.
      do 140 k=1,ngrp
      sum=sum+agrp(k)*q(k)
140   continue
      qmix(level)=sum
c
c*****************************************************************
c
10    continue
c
      return
      end
      subroutine acoeff(tl,tv,ndrop,d,p,keq,ebeq,alpha,i)
c
c     the purpose of this subroutine is to calculate the
c     equivalent absorption coefficient of the two phase mixture
c
c     written by
c                d. a. mandell
c                thermal reactor safety group, q-6
c                august, 1978
c
c************  n o m e n c l a t u r e  ******************
c
c tl      liquid temperature, deg. k
c tv      vapor temperature, deg. k
c ndrop   droplet number density, 1./m**3
c d       droplet diameter, m
c p       pressure, nt/m**2
c keq     equivalent absorption coefficient
c alpha   void fraction
c i       out-of-range flag for planck mean table look-up.
c
c*****************************************************************
c
      real nl2,nv2,ndrop,keq,kl,kv
      data sigma,pi/5.668e-8,3.141593/
      keq=kl(ndrop,d)+kv(tv,p,i)
      if(alpha.le.0.) keq=kl(ndrop,d)
      if(alpha.ge.1.) keq=kv(tv,p,i)
      return
      end
      real function kv(t,p,i)
c
c     the purpose of this function is to calculate the water
c     vapor absorption coefficient. under the optically thin
c     assumption, this is the planck mean absorption coeff.
c
c     ref., m. m. abu-romia and c. l. tien, appropriate mean
c     absorption coefficients for infrared radiation of gases,
c     j. heat transfer, nov., 1967, pp. 321-327.
c
c***************************  nomenclature  ********************
c
c     p     pressure of gas, nt/m**2
```

```
c     t     temperature at which planck mean evaluated, deg. k
c     i     flag to indicate if t outside range of data,
c                 i=0, kv in range of data
c                 i=1, kv below data
c                 i=2, kv above data
c     kp    planck mean absorption coeff. of water vapor,
c                 1./(atm-ft)
c     kv    planck mean, 1./m
c
c*****************************************************************
c
      real kp
      dimension tplank(9),pm(9),aux(40)
      data tplank/1000.,1500.,2000.,2500.,3000.,
     1 3500.,4000.,4500.,5000./
      data pm/5.38,2.69,1.44,.88,.63,.44,.25,.19,.18/
c
c     1./(.3048m/ft) times 1./(1.01325e5 nt/mt**2/atm)
c     = 3.2379372e-5 = conv
c
      data conv/3.2379372e-5/
c
      i=0
      tt=1.8*t
      if(t.lt.555.) i=1
      if(t.gt.2778.) i=2
      kp=aknint(tt,9,9,tplank,pm,aux)
      kv=p*kp*conv
      return
      end
      real function kl(ndrop,d)
c
c     the purpose of this function is to calculate the liquid
c     water droplet absorption coefficient.
c
c*********************  n o m e n c l a t u r e  ************
c
c
c     ndrop liquid droplet number density, 1./m**3
c     d     liquid droplet diameter, m
c     kl    liquid droplet absorption coeff., 1./m
c
c*****************************************************************
c
      real ndrop
      data pi/3.141593/
      kl=.25*ndrop*pi*d*d
      return
      end
      subroutine fij(nmax,fv,nfv,a,nrod,nd,lv)
c
c     the purpose of the subroutine is to calculate the view
c     factors, f(i,j), for the nmax individual surfaces.
c     this subroutine also calculates the geometrical
c     mean beam lengths, l(i,j), for the nmax
c     individual surfaces.
c
      real l,lgrp,lv
      common/radss/ b,p,f(96,96),l(96,96),d
      dimension fv(nfv),a(nd),lv(8)
```

```
      dimension n(8)
      nmaxm1=nmax-1
c
c     initialize all view factors and beam lengths to zero.
c
      do 10 i=1,nmax
      do 10 j=1,nmax
      f(i,j)=0.
      l(i,j)=0.
10    continue
c
c     call viewpin to obtain the needed view factors, fv(k), to
c     be assigned to the elements of the f array.
c
      call viewpin(fv,nfv,d,p)
c
c     call mbl to obtain the needed beam lengths, lv(k),
c     to be assigned to the l array.
c
      call mbl(lv,nfv,d,p)
c
      do 20 i=1,nrod
      do 30 j=1,nrod
      l1=nrod*(j-1)+i
      do 40 ii=1,nrod
      do 50 jj=1,nrod
      l2=nrod*(jj-1)+ii
      if(iabs(i-ii).ne.0) go to 45
c
c     consider rods in the same row.
c
      if(iabs(j-jj).eq.1) l(l1,l2)=lv(1)
      if(iabs(j-jj).eq.1) f(l1,l2)=fv(1)
      go to 60
45    continue
c
      if(iabs(i-ii).ne.1) go to 70
c
c     rods in adjacent rows.
c
      do 80 k=1,nfv
      kk=k-1
      if(iabs(j-jj).ne.kk) go to 80
      f(l1,l2)=fv(k)
      l(l1,l2)=lv(k)
      go to 60
80    continue
c
70    continue
c
c     consider rods two or more rows away from each other.
c
      if(iabs(j-jj).ne.0) go to 75
      f(l1,l2)=0.
      l(l1,l2)=0.
      go to 60
75    continue
      if(iabs(j-jj).gt.1) go to 60
      do 90 k=1,nfv
      kk=k-1
```

```
      if(iabs(i-ii).ne.kk) go to 90
      f(11,12)=fv(k)
      l(11,12)=lv(k)
      go to 60
90    continue
c
60    continue
50    continue
40    continue
30    continue
20    continue
c
c     calculate channel-rod view factors and beam lengths
c
      nsq=nrod*nrod
      n(1)=nsq+1
c
c     calculate the first and last surface numbers for
c     each side of the channel.
c
      do 110 i=2,8,2
      n(i)=n(i-1)+nrod-1
      if(i.eq.8) go to 110
      n(i+1)=n(i)+1
110   continue
c
c     calculate the view factors from the rods to the channel
c     segments. also calculate the mean beam lengths.
c
      do 120 iside=1,4
      n1=n(2*iside-1)
      n2=n(2*iside)
c
      jcrnr=0
      do 130 k=n1,n2
      icrnr=0
      if(k.eq.n1.or.k.eq.n2) icrnr=1
c
c     renumber the side from 1 to nrod
c
      m=k-nsq-(iside-1)*nrod
c
c     go through every rod and calculate the rod-channel
c     segment view factor and the beam lengths.
c
      do 140 i=1,nrod
      do 150 j=1,nrod
      l1=nrod*(i-1)+j
      if(iside.eq.2) go to 1000
      if(iside.eq.3) go to 1010
      if(iside.eq.4) go to 1020
c
c     side 1 (north side)
c
      if(i.eq.1) go to 1030
c
c     interior rods
c
      if(j.ne.m) go to 1040
c
```

```
c     rod and segment in-line
c
      itype=3
      i1=1
      i2=i
      go to 1050
c
1040  continue
c
c     rod and segment not in-line
c
      if(iabs(j-m).gt.1) go to 1160
      itype=4
      i1=1
      i2=i
      go to 1050
1030  continue
c
c     rod next to channel
c
      if(j.ne.m) go to 1060
c
c     rod directly opposite channel segment
c
      itype=1
      go to 1050
1060  continue
c
c     rod adjacent channel-not directly opposite
c     channel segment
c
      itype=2
      i1=m
      i2=j
      go to 1050
c
c*************************************************
c
1000  continue
c
c     side 2 (east side)
c
      if(j.eq.nrod) go to 1070
c
c     interior rods
c
      if(i.ne.m) go to 1080
c
c     rod-segment in-line
c
      itype=3
      i1=1
      i2=nrod-j+1
      go to 1050
1080  continue
c
c     rod-segment not in-line
c
      if(iabs(i-m).gt.1) go to 1160
      itype=4
```

```
      i1=1
      i2=nrod-j+1
      go to 1050
1070  continue
c
c     rod next to channel
c
      if(i.ne.m) go to 1090
c
c     rod directly opposite channel segment
c
      itype=1
      go to 1050
1090  continue
c
c     rod adjacent channel-not directly opposite
c     channel segment
c
      itype=2
      i1=m
      i2=i
      go to 1050
c
c*****************************************************
c
1010  continue
c
c     side 3 (south side)
c
      if(i.eq.nrod) go to 1100
c
c     interior rods
c
      minv=nrod-m+1
      if(j.ne.minv) go to 1110
c
c     rod and segment in-line
c
      itype=3
      i1=1
      i2=nrod-i+1
      go to 1050
1110  continue
c
c     rod and segment not in-line
c
      if(iabs(j-minv).gt.1) go to 1160
      itype=4
      i1=1
      i2=nrod-i+1
      go to 1050
1100  continue
c
c     rod directly next to channel
c
      if(j.ne.minv) go to 1120
c
c     rod directly opposite channel segment
c
      itype=1
```

```
      go to 1050
1120  continue
c
c     rod next to channel, but not directly opposite
c
      itype=2
      i1=minv
      i2=j
      go to 1050
c
c*****************************************************
c
1020  continue
c
c     side 4 (west side)
c
      minv=nrod-m+1
      if(j.eq.1) go to 1130
c
c     interior rods
c
      if(i.ne.minv) go to 1140
c
c     rod and segment in-line
c
      itype=3
      i1=1
      i2=j
      go to 1050
1140  continue
c
c     rod and segment not in-line
c
      if(iabs(i-minv).gt.1) go to 1160
      itype=4
      i1=1
      i2=j
      go to 1050
1130  continue
c
c     rod adjacent to channel
c
      if(i.ne.minv) go to 1150
c
c     rod directly opposite channel segment
c
      itype=1
      go to 1050
1150  continue
c
c     rod adjacent channel-not directly opposite
c     channel segment
c
      itype=2
      i1=minv
      i2=i
c
c*****************************************************
c
1050  continue
```

```
c
      call fseg(b,nrod,p,d,i1,i2,itype,f(l1,k),icrnr,jcrnr)
      call mbls(b,nrod,p,d,i1,i2,itype,l(l1,k),icrnr,jcrnr)
c
1160  continue
150   continue
140   continue
130   continue
120   continue
c
c     calculate the view factors from the channel
c     segments to the rods.
c     also the mean beam lengths.
c
      n1=n(1)
      do 180 i=n1,nmax
      do 190 j=1,nsq
      f(i,j)=a(j)*f(j,i)/a(i)
      l(i,j)=l(j,i)
190   continue
180   continue
c
c     calculate the view factors from one  channel segment
c     to another channel segment. also the mean beam lengths.
c
      do 200 iside=1,3
      n1=n(2*iside-1)
      n2=n(2*iside)
      iz=nsq+(iside-1)*nrod
      do 210 jside=iside,4
      n3=n(2*jside-1)
      n4=n(2*jside)
      jz=nsq+(jside-1)*nrod
      do 230 i=n1,n2
      icrnr=0
      if(i.eq.n1.or.i.eq.n2) icrnr=1
      mi=i-iz
      do 240 j=n3,n4
       if(iside.eq.jside) go to 220
      jcrnr=0
      if(j.eq.n3.or.j.eq.n4) jcrnr=1
      mj=j-jz
      minv=nrod-mj+1
c
      if(iabs(iside-jside).ne.2) go to 250
c
c     channel sides are directly opposite each other
c
      if(iabs(mi-minv).gt.1) go to 220
      itype=8
      if(mi-minv.eq.0) itype=7
      go to 260
250   continue
c
c     channel sides are adjacent
c
      if(iside.eq.1.and.jside.eq.4) go to 255
      if(mi.ne.nrod.and.mj.gt.1) go to 220
      if(mj.ne.1.and.mi.lt.nrod) go to 220
      if(iabs(i-j).ne.1) go to 270
```

```
c
c     segments next to each other at ninty degrees
c
       itype=5
      go to 260
270   continue
c
c     segments on adjacent channel sides but not
c     touching
c
      if(mi.ne.nrod.and.mj.eq.1) go to 280
      if(mi.eq.nrod.and.mj.gt.1) go to 290
      if(iside.eq.1.and.jside.eq.4.and.mi.eq.nrod
     1 .and. mj.eq.1) go to 220
255   continue
c
c     sides 1 and 4
c
      if(i.eq.n(1).and.j.eq.nmax) go to 340
      if(mi.gt.1.and.mj.lt.nrod) go to 220
      if(mi.gt.1.and.mj.eq.nrod) go to 350
c
c     side 1, first segment to side 4, segments < nrod
c
      itype=6
      i1=1
      i2=nrod-mj+1
      go to 260
350   continue
c
c     sides 1 and 4, last segment of side 4 to
c     segments > first of side 1
c
      itype=6
      i1=1
      i2=mi
      go to 260
340   continue
c
c     adjacent touching sides
c
      itype=5
      go to 260
280   continue
      itype=6
      i1=mj
      i2=nrod-mi+1
      go to 260
290   continue
      itype=6
      i1=1
      i2=mj
260   continue
c
      call fseg(b,nrod,p,d,i1,i2,itype,f(i,j),icrnr,jcrnr)
c
      call mbls(b,nrod,p,d,i1,i2,itype,l(i,j),icrnr,jcrnr)
c
220   continue
240   continue
```

```
230   continue
210   continue
200   continue
c
c
c*************************************************
c
c     fill in the rest of the segment-segment view
c     factors.
c                also fill in the rest of the
c     segment-segment mean beam lengths.
c
      do 300 iside=1,3
      n1=n(2*iside-1)
      n2=n(2*iside)
      do 310 jside=iside,4
      n3=n(2*jside-1)
      n4=n(2*jside)
      do 320 i=n1,n2
      do 330 j=n3,n4
      f(j,i)=f(i,j)*a(i)/a(j)
      l(j,i)=l(i,j)
330   continue
320   continue
310   continue
300   continue
c
c*************************************************
c
c
      return
      end
      subroutine viewpin(fv,nfv,d,p)
c
      dimension fv(8)
      data pi/3.141593/
      radius=.5*d
      do 5 i=1,8
      fv(i)=0.
5     continue
      x=p/d
c
c     calculatethe view factor for two rods adjacent
c
      fv(1)=(sqrt(x*x-1.)-x+.5*pi-acos(1./x))/pi
c
c     calculate view factor for second nearest neighbor rods
c
      p2=p*p
      d2=d*d
      x1=sqrt(p2-d2)
      xs1=x1
      x2=sqrt(2.*p2-d2)
      xs2=x2
      c1=atan(x1/d)
      c2=atan(x2/d)
      c3=atan(1.0)
      a1=radius*(c1-c2+c3)
      a2=radius*(.5*pi-2.*c1)
      fv(2)=(x2-2.*x1-a2+2.*a1)/(pi*d)
```

```
c
c     calculate view factors for third and greater nearest
c     neighbors.
c
      twoa=2.*pi*d
      do 10 i=3,8
      di=float(i-1)
      x1=sqrt(((di-1.)**2+1.)*p2-d2)
      x2=sqrt((di*di+1.)*p2-d2)
      x3=sqrt(((di-2.)**2+1)*p2-d2)
      c1=atan(x3/d)
      c2=atan(di-2.)
      c3=atan(x1/d)
      c4=atan(di-1.)
      a1=radius*(c1-c2-c3+c4)
      c5=atan(x2/d)
      c6=atan(di)
      a2=radius*(c3-c4-c5+c6)
      fv(i)=(x2+x3-2.*(x1+a1-a2))/twoa
10    continue
      return
      end
      subroutine grpfij(f,nd,fgrp,ngrp,a,agrp,irod,ndgrp,nmax)
c
c     the purpose of this subroutine is to group the individual
c     view factors, f(i,j), into grouped values.
c
      dimension f(nd,nd),a(nd), agrp(ndgrp),irod(nd)
      dimension fgrp(ndgrp,ndgrp)
c
c     initialize all grouped view factors to zero.
c
      do 5 i=1,ngrp
      do 5 j=1,ngrp
      fgrp(i,j)=0.
5     continue
c
c
c     calculate the group areas.
c
      do 10 k=1,ngrp
      sum=0.
      do 20 i=1,nmax
      if(irod(i).eq.k) sum=sum+a(i)
20    continue
      agrp(k)=sum
10    continue
c
c     group the view factors.
c
      do 30 k=1,ngrp
      do 40 l=1,ngrp
      sumb=0.
      do 50 i=1,nmax
      suma=0.
      do 60 j=1,nmax
c
c     see if rod j is in group l and rod i is in group k.
c
      if(irod(j).ne.l .or. irod(i).ne.k) go to 60
```

```
      suma=suma+f(i,j)
60    continue
      if(irod(i).ne.k) go to 50
      sumb=sumb+a(i)*suma
50    continue
      fgrp(k,l)=sumb/agrp(k)
40    continue
30    continue
c
      return
      end
      subroutine fseg(b,nrod,p,d,i1,i2,itype,f,icrnr,jcrnr)
      real l1,l2,lhalf,l3(5),l24
      data pi/3.141593/
      l1=p
      l2=.5*(b-float(nrod-1)*p-d)
      lhalf=.5*l1
      radius=.5*d
      d24=.25*d*d
      c0=radius+l2
      deli=abs(float(i2-i1))
      d2=d*d
      l24=.25*l1*l1
      p2=p*p
      c02=c0*c0
      p24=.25*p2
      c05p=c0+.5*p
c
      go to (10,20,40,50,60,70,80,90 ), itype
c
10    continue
c
c     type 1 view factor
c
      if(icrnr.gt.0) go to 110
      f=atan(lhalf/(radius+l2))/pi
      go to 100
c
c     type 1 view factor, corner segment
c
110   continue
      x1=sqrt(2.*c02-d24)
      x2=x1
      x4=sqrt(c02+p24-d24)
      x3=x4
      c1=atan(1.0)
      c2=atan(x1/radius)
      c3=atan(x3/radius)
      c4=atan(.5*p/c0)
      a1=radius*(c1+c2-c3+c4)
      c5=atan(x4/radius)
      c6=atan(x2/radius)
      a2=radius*(c4+c5-c6+c1)
      f=(a1+a2)/(2.*pi*d)
      go to 100
20    continue
c
c     type 2 view factor
c
      l3(1)=(deli-.5)*l1
```

```
      y=(radius+l2)**2-d24
      x1=sqrt(l3(1)**2+y)
      l3(2)=abs(deli-1.5)*l1
      x2=sqrt(l3(2)**2+y)
      l3(3)=(deli+.5)*l1
      if(icrnr.gt.0) l3(3)=(deli-.5)*l1+c0+.5*p
      x3=sqrt(l3(3)**2+y)
      x5=x1
      if(icrnr.le.0) go to 120
      l3(5)=(deli-1.5)*l1+c0+.5*p
      x5=sqrt(l3(5)**2+y)
120   continue
      c1=atan(2.*x1/d)
      c2=atan(l3(1)/c0)
      c3=atan(2.*x3/d)
      c4=atan(l3(3)/c0)
      c5=atan(2.*x2/d)
      c6=atan(l3(2)/c0)
      gam1=c1-c2-c3+c4
      gam2=c5-c6-c1+c2
      if(icrnr.le.0) go to 130
      c1p=atan(x5/radius)
      c2p=atan(l3(5)/c0)
      gam2=c5-c6-c1p+c2p
130   continue
      x4=0.
      a3=0.
      if(deli.ne.1) go to 30
      x4=sqrt(p*p-d*d)
      c7=atan(x4/d)
      gam2=.5*pi-c7-c1+c2
      if(icrnr.le.0) go to 140
      c1=atan(x5/radius)
      gam2=.5*pi-c7-c1+atan(1.0)
140   continue
      gam3=c7-c5+.5*pi-c2
      a3=radius*gam3
30    continue
      a1=radius*gam1
      a2=radius*gam2
      f=(x2+x3+a1-x1-x5-a2-x4+a3)/(2.*pi*d)
      go to 100
c
c     type 3 view factor
c
40    continue
      radius=.5*d
      x1=p
      y1=radius+l2+deli*p
      y2=(deli-1.)*p+radius+l2
      ya=.5*l1
      yb=ya
      if(icrnr.gt.0) yb=c0
      ya2=ya*ya
      yb2=yb*yb
      x2=sqrt(ya2+y2*y2-d24)
      x3=sqrt(ya2+y1*y1-d24)
      c1=atan(2.*x3/d)
      c2=atan(.5*l1/y1)
      c3=atan(2.*x2/d)
```

```
      c4=atan(.5*l1/y2)
      a1=radius*(c1+c2-.5*pi)
      a2=radius*(c3+c4-.5*pi)
      x3p=sqrt(yb2+y1*y1-d24)
      x2p=sqrt(yb2+y2*y2-d24)
      c1p=atan(x3p/radius)
      c2p=atan(yb/y1)
      c3p=atan(x2p/radius)
      c4p=atan(yb/y2)
      a1p=radius*(c1p+c2p-.5*pi)
      a2p=radius*(c3p+c4p-.5*pi)
      f=(x2+x2p+2.*x1-(x3+x3p)+a1+a1p-(a2+a2p))/(2.*pi*d)
      go to 100
c
c     type 4 view factor
c
50    continue
      x1=sqrt(((deli-1.)*p+c0)**2+l24-d24)
      x2=sqrt((deli*p+c0)**2+l24-d24)
      x3=sqrt(((deli-1.)**2+1.)*p2-d2)
      x4=sqrt((deli*deli+1.)*p2-d2)
      c1=atan(x4/d)
      c2=atan(deli)
      c3=atan(x3/d)
      c4=atan(deli-1.)
      c5=atan(x1/radius)
      a1=radius*(c3-c4-c1+c2)
      c6=atan(((deli-1.)*p+c0)/(.5*l1))
      a2=radius*(c3-c4-c5+c6)
      c7=atan((deli*p+c0)/(.5*l1))
      c8=atan(x2/radius)
      a3=radius*(c1-c2-c8+c7)
      f=(x2+x3-x1-x4-a1-a2+a3)/(2.*pi*d)
      go to 100
c
c     type 5 view factor
c
60    continue
      x=sqrt(.25*l1*l1+c0*c0-d24)
      c1=atan(x/radius)
      c2=atan(.5*l1/c0)
      a1=d*(.25*pi-c1+c2)
      f=(c05p-x-.5*a1)/c05p
      go to 100
c
c     type 6 view factor
c
70    continue
      x1=p
      if(jcrnr.gt.0.and.icrnr.gt.0) x1=c05p
      x2=sqrt(((deli-.5)*p)**2+c02-d24)
      x3=sqrt(((deli-.5)*p+x1)**2+c02-d24)
      c1=atan(x2/radius)
      c2=atan((deli-.5)*p/c0)
      c3=atan(x3/radius)
      c4=atan(((deli-.5)*p+x1)/c0)
      a=radius*(c1-c2-c3+c4)
      denom=p
      if(icrnr.gt.0) denom=c05p
      f=.5*(x1+x2-x3-a)/denom
```

```
      go to 100
c
c     type 7 view factor
c
80    continue
      y=.5*p
      x1=sqrt((b-radius-l2)**2+y*y-d24)
      c1=atan(x1/radius)
      c2=atan(y/(b-radius-l2))
      a=radius*(c1+c2-.5*pi)
      denom=p
      f=2.*(x1-b+c0-a)/denom
      if(icrnr.le.0) go to 100
      fa=f
      x1=sqrt((b-c0)**2+c02-d24)
      c1=atan(x1/radius)
      c2=atan(c0/(b-c0))
      a=radius*(c1+c2-.5*pi)
      fb=(x1-b+c0-a)/c0
      f=(c0*fb+.5*p*fa)/c05p
      go to 100
c
c     type 8 view factor
c
90    continue
      x1=sqrt((b-c0)**2+l24-d24)
      x2=sqrt(p2+(b-d-2.*l2)**2-d2)
      c1=atan(x2/d)
      c2=atan((b-d-2.*l2)/p)
      c3=atan(2.*x1/d)
      c4=atan(2.*(b-c0)/l1)
      a=radius*(c1-c2-c3+c4)
      f=.5*(x2+b-2.*x1-2.*a)/l1
      if(icrnr.gt.0) f=l1*f/c05p
100   continue
      return
      end
      subroutine grplij(f,nd,fgrp,ngrp,a,agrp,irod,ndgrp,nmax,
     1 l,lgrp)
c     the purpose of this subroutine is to group the individual
c     beam lengths, l(i,j), into grouped values.
c
      real l,lgrp
      dimension f(nd,nd),a(nd), agrp(ndgrp),irod(nd)
      dimension fgrp(ndgrp,ndgrp)
      dimension l(nd,nd),lgrp(ndgrp,ndgrp)
c
c     initialize all grouped beam lengths to zero.
c
      do 5 i=1,ngrp
      do 5 j=1,ngrp
      lgrp(i,j)=0.
5     continue
c
c
c     group the beam lengths.
c
      do 30 k=1,ngrp
      do 40 ll=1,ngrp
      sumb=0.
```

```
      do 50 i=1,nmax
      suma=0.
      do 60 j=1,nmax
c
c     see if rod j is in group ll and rod i is in group k.
c
      if(irod(j).ne.ll .or. irod(i).ne.k) go to 60
      suma=suma+f(i,j)*l(i,j)
60    continue
      if(irod(i).ne.k) go to 50
      sumb=sumb+a(i)*suma
50    continue
      if(fgrp(k,ll).eq.0.) go to 40
      lgrp(k,ll)=sumb/(agrp(k)*fgrp(k,ll))
40    continue
30    continue
c
      return
      end
      subroutine mbl(lv,nfv,d,p)
c
c     the purpose of this subroutine is to calculate
c     the rod-rod geometrical mean beam lengths.
c
c     it is assumed that the mean beam length can be
c     approximated by an equivalent distance between
c     two flat plates.
c
c     written by
c               d. a. mandell
c               thermal reactor safety group, q-6
c               october, 1978
c
      real lv(8)
      data pi/3.141593/
c
c     initialize lv values to zero
c
      do 10 i=1,nfv
      lv(i)=0.
10    continue
      p2=p*p
      x=.25*pi*d
c
      do 20 i=1,nfv
      di=float(i-1)
      lv(i)=sqrt(di*di*p2+p2)-x
20    continue
      return
      end
      subroutine mbls(b,nrod,p,d,i1,i2,itype,bl,icrnr,jcrnr)
c
c     the purpose of this subroutine is to calculate the
c     geometrical mean beam lengths between the rods and
c     the channel segments and from one channel segment
c     to a second channel segment.
c
c     it is assumed that the beam lengths are equal to
c     an equivalent distance between two flat plates.
c
```

```
c      written by
c                d. a. mandell
c                thermal reactor safety group, q-6
c                october, 1978
c
       real l1,l2
       data pi/3.141593/
       l1=p
       l2=.5*(b-float(nrod-1)*p-d)
       c0=.5*d+l2
       deli=abs(float(i2-i1))
       di=deli
       c02=c0*c0
       x=.125*pi*d
       c05p=c0+.5*p
       p2=p*p
c
       go to (10,20,30,40,50,60,70,80), itype
c
10     continue
c
c      type 1 beam length
c
       bl=c0-x
       go to 90
20     continue
c
c      type 2 beam length
c
       bl=sqrt((di*l1)**2+c02)-x
       if(jcrnr.gt.0) bl=sqrt(((di-.25)*p+.5*c0)**2+c02)-x
       go to 90
30     continue
c
c      type 3 beam length
c
       bl=di*p+c0-x
       go to 90
40     continue
c
c      type 4 beam length
c
       bl=sqrt((di*p+c0)**2+p2)-x
       if(jcrnr.gt.0) bl=sqrt((di*p+c0)**2+(.5*c05p)**2)-x
       go to 90
50     continue
c
c      type 5 beam length
c      .70710678 = sqrt(2.0)/2.0
c
       bl=.70710678*c05p
       go to 90
60     continue
c
c      type 6 beam length
c
       bl=sqrt(.25*c05p**2+(c05p+(di-.5)*p)**2)
       if(jcrnr.gt.0) bl=sqrt(.25*c05p**2+(1.5*c05p+(di-1.)*p)**2)
       go to 90
70     continue
```

```
c
c     type 7 beam length
c
      bl=b
      go to 90
80    continue
c
c     type 8 beam length
c
      bl=sqrt(b*b+p2)
      if(icrnr.gt.0.or.jcrnr.gt.0) bl=sqrt(b*b+(.5*c0+.75*p)**2)
c
90    continue
c
      return
      end
      subroutine em(eg,ed,ag,ad,l,tw,tl,tv,ndrop,d,alpha,p)
c
c     calculation of properties following norcool methods.
c
c     ref. j. andersen et. al., norcool i a model for
c     analysis of a bwr under loca conditions, riso national
c     lab., denmark, rept. norhav-d-47, aug., 1977.
c
      real l,kl,kv,ndrop
c
      if(l.le.0.) go to 30
      acv=kv(tw,p,irang)
      ag0=1.-exp(-l*acv)
      acl=kl(ndrop,d)
      ad0=1.-exp(-l*acl)
      acv=kv(tv,p,irang)
      eg0=1.-exp(-l*acv)
      ed0=ad0
      ag0p=eg0
      if(alpha.le.0.) go to 10
      if(alpha.ge.1.0) go to 20
      if(ad0.eq.1..or.ed0.eq.1.) go to 40
      if(ag0.eq.1..or.eg0.eq.1..or.ag0p.eq.1.) go to 50
      c=alog(1.-ag0)/alog(1.-ad0)
      ag=c*(ag0+ad0-ag0*ad0)/(1.+c)
      ad=(ag0+ad0-ag0*ad0)/(1.+c)
      xkg=alog(1.-eg0)/alog(1.-ad0)
      xkd=alog(1.-ed0)/alog(1.-ag0p)
      eg=xkg*(eg0+ad0-eg0*ad0)/(1.+xkg)
      ed=xkd*(ed0+ag0p-ed0*ag0p)/(1.+xkd)
c
      return
c
10    continue
c
c     liquid only
c
      ag=0.
      eg=0.
      ad=ad0
      ed=ed0
      return
c
20    continue
```

```
c
c      vapor only
c
       ad=0.
       ed=0.
       ag=ag0
       eg=eg0
       return
30     continue
       ag=0.
       ad=0.
       eg=0.
       ed=0.
       return
40     continue
       ed=1.
       ad=1.
       ag=0.
       eg=0.
       return
50     continue
       eg=1.
       ed=0.
       ag=1.
       ad=0.
       return
       end
```

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