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**SWISSCHEESE:
A 7090 FORTRAN IV CODE
FOR THERMAL-HYDRAULIC ANALYSIS
OF GAS-COOLED NUCLEAR REACTORS**

GCR

C. E. LEACH

OCTOBER, 1965

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RICHLAND, WASHINGTON

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OF GAS-COOLED NUCLEAR REACTORS

By

C. E. Leach

Reactor Engineering Section
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October, 1965

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SWISSCHEESE
A 7090 FORTRAN IV CODE
FOR THERMAL-HYDRAULIC ANALYSIS
OF GAS-COOLED NUCLEAR REACTORS

INTRODUCTION

The SWISSCHEESE program was prepared as part of a study to evaluate plutonium and U^{233} fueled core designs for the 710 test reactor, a compact fast reactor. The study was sponsored by the Reactor Experiments Branch of the AEC Division of Reactor Development and Technology.

SWISSCHEESE is a one-dimensional, steady-state, compressible flow with heat addition and friction program for parametric and design point heat transfer and fluid flow analysis of gas-cooled axial flow nuclear heat sources. The equations used for finding the stream temperature and pressure are integrated in closed form thus obviating node stipulation for a step-by-step integration process.

The program has a range of applicability to axial flow geometries subject to the following conditions.

- *• The gas behaves as a perfect gas.
- The exit Mach number is less than 0.3.
- The fluid flow is turbulent.
- **• The reactor model consists only of fuel, coolant channel clad, and coolant voids.
- The reactor is a right-circular cylinder or a satisfactory mathematical model is a right-circular cylinder with coolant flow parallel to the cylinder's axis.

* Mean specific heats and ratio of specific heats are selected from a table.

** Moderator, spacing voids, etc., can be conveniently removed from the model by a process described on p. 32.

- The fuel can be of either the pinned cluster or inverted type but no interchannel mixing is provided. In the pinned cluster case the program assumes the coolant passages are tubes and, hence, a hydraulic diameter is specified.
- Axial heat addition profile is arbitrary and the shape is limited only by the quality of a four-term polynomial fit.
- Radial power shapes are permitted by a zoning process. The axial power shape in all zones is assumed to be geometrically similar. Up to eight radial zones are permitted.

SWISSCHEESE is a designer in the sense that, given certain criteria, the program will perform the thermal hydraulic core design. It will do the job quickly (about 2 sec per case in Mode 1 and 20 sec per case in Mode 2) and economically since most cross plots required in such parametric studies are eliminated. Comparison of results of sample problems with those obtained by step-by-step integration procedures shows essentially no difference in results.

SUMMARY

SWISSCHEESE performs the thermal-hydraulic analysis of a general class of gas-cooled nuclear reactor cores that can be equated, in terms of area, to right-circular cylinders pierced by an arbitrary number of coolant passages. The single passage case may also be considered. Axial power generation profiles are fit by a four-term polynomial. An option allows up to eight concentric radial zones with an assumed or calculated radial heat generation and void fraction profile. In this option the core is temperature flattened, meeting the condition of equal pressure over the entrance and exit plenums. Inlet and exit total pressure losses are calculated from input loss coefficients. One-dimensional compressible flow with heat addition and friction is assumed to prevail in the core.

Other than materials property data, input is minimal, thereby facilitating parametric studies. Output lists fluid, wall and fuel temperatures at eleven axial locations as well as entrance and exit total and static pressures and Mach numbers.

BRIEF DESCRIPTION OF PROGRAM OPERATION

The program, in essence, converts input weight-rate of coolant, power, inlet temperature, inlet pressure, gross geometry (void fraction and core size) and a specified maximum tube wall temperature to output coolant outlet temperature and outlet pressure, number and size of coolant passages (which can be converted by the user to the number and size of pins in the pin case) in addition to other significant parameters such as Reynolds number and fuel temperature.

Fuel temperatures are calculated by a subroutine. Two subroutines are included in the listing in this document, one of which calculates the maximum fuel temperature in an inverted element with uniform heat generation and thermal conductivity. The other is a dummy which may be used when fuel temperatures are not desired. The thermal conductivity is selected from a table according to the wall temperature. Clad-fuel resistance is not included in this subroutine but could be, if the accuracy were desired.

The following input is required:

- Inlet total pressure and temperature
- Reactor thermal power
- Reactor length and radius
- Coolant passage and clad volume fraction
- A guess of the proper coolant passage diameter
- Tube wall thickness
- Coolant weight flow rate
- Axial power profile characterized by eight normalized numbers
- A heat transfer parameter
- Molecular weight of coolant
- A relative convergence error
- Unheated entrance length
- Inlet and exit loss coefficients
- The maximum tube wall temperature desired in the core
- A volume fraction factor
- The fuel void fraction, and optionally, the number of coolant passages in the core and total pressure ratio.

In addition, coolant and fuel transport properties as well as several compressible flow functions are required in 10 tables.

The program operates in two modes, depending on the purpose of the study. In the first mode, the program adjusts the coolant tubing size and number of tubes to simultaneously meet the required void fraction and maximum temperature for reactors in which the radial power distribution and coolant channel size are assumed to be uniform. This mode of operation is primarily useful for parametric studies.

The second mode permits coolant channel size to be zoned to match an assumed or calculated nonuniform radial power distribution. The radial power profile may be adequately represented by from one to eight zones. Within each zone the radial power shape is assumed to be constant. In each zone the coolant passage diameter and coolant flow are adjusted while keeping the number of tubes constant, thereby simultaneously meeting pressure and maximum tube wall temperature conditions.

This second mode can be operated in two ways:

1. The program calculates the total pressure ratio and number of tubes by first calculating a uniform core case; or,
2. The user specifies the total pressure ratio and total number of tubes in the core.

THERMAL AND FLUID DYNAMIC ANALYSIS

One of the program requirements is that there be similarity between the reactor core nuclear and heat transfer models, thus allowing the use of common input parameters. The nuclear model for survey calculations to determine core sizes is most conveniently defined in terms of some regular geometry (cylinder or sphere) composed of a homogeneous mixture of materials (fuel, structural, coolant, etc.) and void space, which may be subdivided into regions of differing composition. The input parameters for SWISSCHEESE are based on a similar model allowing an almost direct abstraction of information from the nuclear study.

Model Definition

The heat transfer and fluid flow model considers only those surfaces and volumes where a significant portion of the reactor's heat is generated or transported. These portions are:

- The "fuel"*
- The coolant tube wall
- The coolant passages.

The portion of the core excluded from the model consists of:

- Void fraction in "fuel" ("fuel" not 100% of theoretical density)
- Spacing between elements or moderator
- "Fuel" rod cladding or other structural material
- Moderator.

The program assumes all coolant passages to be of uniform length and spacing. The model is nominally a right circular cylinder, but (as explained later) the radius defines only an area on which to base other gross parameters such as void fraction and heat generation. Hence, by suitably adjusting the radius and tube power, single coolant passages may be considered. A catalog of equations which serves to define the geometry of the model can now be considered.

Auxiliary Equations

The composition of the reactor can be broken down in terms of volume fractions. In the actual core the sum of the volume fractions must be 1, i.e.,

$$\alpha_F + \alpha_f + \alpha_m + \alpha_s + \alpha_{oc} + \alpha_{tc} = 1.0 \quad (1)$$

where

α_F = volume fraction of fuel (100% dense)

α_f = volume fraction of fuel voids

* "Fuel" - that portion of the core where the major amount of heat is generated. Gamma heating of clad is specifically excluded as the program allows for a distributed heat source in only one material.

- α_m = volume fraction of moderator
- α_s = volume fraction of spacing (miscellaneous)
- α_c = volume fraction of coolant void
- α_{oc} = volume fraction of fuel element clad
- α_{tc} = volume fraction of coolant tube clad.

It would have been entirely possible to provide for internal separation of these constituent volume fractions based on the core geometry. This internal separation would have required either cataloging the geometric equations associated with many designs or selecting a particular design, thus limiting the program scope. One geometry is worked out in the Sample Case (p. 25). A satisfactory compromise was to have the geometry work done by hand and to have the program assume that the core consists of fuel, tube clad, and coolant void. Rather than Equation (1) we have

$$\alpha_F' + \alpha_c' + \alpha_{tc}' = 1.0 \quad (2)$$

The coolant and tube clad are now grouped into a pseudo-void fraction such that

$$\alpha_F' + \alpha_v' = 1.0 \quad (3)$$

where

$$\alpha_v' = \alpha_c' + \alpha_{tc}'$$

α_v' is the "void" fraction introduced in the program. α_v' is internally separated into α_c' and α_{tc}' . Consideration of Equations (1), (2), and (3) obtains the model volume fractions in terms of the nuclear model

$$\alpha_F' = \frac{\alpha_F}{\alpha_F + \alpha_c + \alpha_{tc}}$$

Similarly,

$$\alpha_v' = \frac{\alpha_v}{\alpha_F + \alpha_c + \alpha_{tc}}$$

* Primes denote the heat transfer model.

The heat transfer and fluid flow equations require the following variables:

$$NP = \frac{\alpha_v' \pi r_{eq}'^2}{(.25 D_H + t_w)} \quad (4)$$

where

NP = total heat transfer perimeter of tubes in core

r_{eq}' = core radius, heat transfer model

D_H = hydraulic diameter of tubes = $\frac{4A}{P}$

t_w = wall thickness of tubes.

The denominator in Equation (4) contains a factor to correct for $\alpha_v' > \alpha_c'$ and is derived in Appendix A.

It is tacitly assumed that the tube wall is a long straight strip of thickness, t_w . As the diameter of a round coolant tube decreases, the error in this approximation becomes large, and a correction must be introduced.

$$t_{w \text{ effective}} = t_w + \frac{t_w^2}{D_H} \quad (5)$$

The actual wall thickness, t_w , is input to the program. Equation (4) then uses the results from Equation (5). If this correction is undesirable (square passages, for example), the fifth card after statement 3001 may be replaced by $XW = XW1$.

The mass-velocity is calculated as

$$G = \dot{w} \frac{1 + 4 \frac{t_w}{D_H}}{\left(\alpha_v' \pi r_{eq}'^2 \right)} \quad (6)$$

where

$\dot{w}$ = weight-rate of coolant

G = mass-velocity.

The fuel area is

$$A_{fu} = \pi r_{eq}'^2 (1 - \alpha_v') \quad (7)$$

The ratio of coolant to fuel area, $\frac{\alpha_c'}{\alpha_f'}$, is

$$\xi = \frac{A_c}{A_{fu}} = \frac{\alpha_c'}{\alpha_f'} = \frac{\alpha_v'}{(1 - \alpha_v') \left(1 + \frac{4t_w}{D_H}\right)} \quad (8)$$

The fluid flow area, A_c , is

$$A_c = \frac{\alpha_v' \pi r_{eq}'^2}{1 + \frac{4t_w}{D_H}} \quad (9)$$

The average volumetric heat generation rate

$$\bar{q}''' = \frac{Q}{\left[(\ell \pi r_{eq}'^2) (1 + \alpha_v') \right]} \quad (10)$$

where

ℓ = active core length

Q = total reactor power

$\bar{q}'''$ = average volumetric heat generation in the "fuel".

Finally, the number of equivalent* circular tubes in the core

$$N_t = \frac{4A_c}{\pi D_H^2} \quad (11)$$

This completes the cataloging of the auxiliary equations. The Equations used in the program in the form stated are Equations (4) through (11).

* Equivalent - only that the passages are not circular.

Method Used to Handle the Core Heat Balance

Consider a core with uniform distribution of cooling passages of a single size. Cognizance will be taken of the axial power shape. Axial conduction in the fuel and tube walls is negligible in comparison with the convective axial heat rate in the coolant passages. Finally, the radial power profile is fit by zoning the core into annular volumes separated by concentric adiabatic rings and temperature flattened by varying the void ratio while holding the number of tubes constant and changing their diameter. Temperatures are again calculated at 11 axial locations.

Heat Transfer Equations

The axial power profile is entered by fitting a four-term polynomial to a normalized shape. The normalization factor is the average volumetric heat generation which the program calculates by dividing the reactor power by the volume of "fuel" [Equation (10)].*

The core heat-transfer analysis begins with an elemental heat balance; then considers the tube wall temperature, heat transfer coefficients, and finally the fuel temperature.

For a heat source (infinite temperature source), neglecting axial conduction, the energy generated at location $\zeta = \frac{x}{L}$ in interval $d\zeta = \frac{dx}{L}$ results in a change in total temperature of the coolant dependent upon the coolant flow rate and its specific heat, i. e.,

$$\dot{w} \bar{C}_p dT_o = q'''(\zeta) A_{fu} d\zeta \quad (12)$$

where

$$\bar{C}_p = \text{average specific heat in interval } T_o \text{ to } T_o + dT_o.$$

Assume $q'''(\zeta)$ can be characterized by a polynomial expression

$$q'''(\zeta) = \bar{q}''' (A + B\zeta + C\zeta^2 + D\zeta^3) \quad (13)$$

* The calculation is further discussed in Power Profile Normalization, p. 17.

Equation (13) may be inserted into (12)

$$dT_o = \frac{A_{fu} \ell \bar{q}'''}{\dot{w} \bar{C}_p} (A + B\zeta + C\zeta^2 + D\zeta^3) d\zeta \quad (14)$$

It is more convenient to have the flow rate in terms of the mass-velocity, G , so that Equation (2) obtains

$$dT_o = \frac{\ell \bar{q}'''}{G \xi \bar{C}_p} (A + B\zeta + C\zeta^2 + D\zeta^3) d\zeta \quad (15)$$

Introduction of $\bar{C}_p = (C_{p1} + C_{p2})/2$ (1 - core entrance, 2 - core exit) should not introduce much error. With this assumption the constancy of $\bar{C}_p$ allows direct integration of Equation (15).

The expression for the coolant total temperature ratio is

$$\frac{T_o}{T_{o1}} = 1 + \frac{\ell \bar{q}'''}{G \xi \bar{C}_p T_{o1}} \left[A\zeta + B\frac{\zeta^2}{2} + C\frac{\zeta^3}{3} + D\frac{\zeta^4}{4} \right] \quad (16)$$

where

ℓ = core length

G = mass velocity

ξ = fluid flow area/fuel area

$\bar{C}_p$ = average specific heat of coolant

A, B, C, D = constants in polynomial fit

ζ = dimensionless axial distance, $\frac{x}{\ell}$

Similarly, the wall temperature may be found from an energy balance on a differential element by utilizing the definition of the heat-transfer coefficient

$$q = hA (T_W - T_B) \quad (17)$$

where

h = heat transfer coefficient

A = area for heat transfer

q = heat flux rate

W, B = denotes wall and fluid bulk, respectively.

A differential heat balance between the coolant and heat transferred gives

$$dq = h N_p l (T_w - T_o) d\zeta = \dot{w} \bar{C}_p dT_o \quad (18)$$

Inserting Equation (15) into (18) obtains

$$h N_p l [T_w - T_o] d\zeta = \dot{w} \bar{C}_p \frac{A_{fu} q'''}{G \xi C_p} (A + B\zeta + C\zeta^2 + D\zeta^3) d\zeta \quad (19)$$

Equation (19) can be rearranged and solved for T_w in terms of T_o .

$$\frac{T_w}{T_{o1}} = \frac{A_{fu} q'''}{h N_p T_{o1}} [A + B\zeta + C\zeta^2 + D\zeta^3] + \frac{T_o}{T_{o1}} \quad (20)$$

where

A_{fu} = fuel area

h = local heat transfer coefficient.

Film Coefficients

The correlation used in this program for determining local heat transfer coefficients is based on the bulk fluid temperature with correction for property changes by a bulk-to-wall temperature ratio proposed by Davenport, et al. ⁽¹⁾

$$N_{Nu} = .021 N_{Re}^{.8} N_{Pr}^{.4} \left(\frac{T_w}{T_b} \right)^{-m} \left[1 + \left(\frac{x}{D_H} \right)^{-7} \right] \quad (21)$$

Barnes and Jackson ⁽²⁾ suggested the same form and claim m is different for different gases while Davenport's results indicated (within experimental accuracy) $m = 0.5$ for air, nitrogen, and helium. Petukhov and Popov ⁽³⁾ find that a single factor of the following form may be used with 5 to 7% accuracy:

$$\frac{N_{ub}}{N_{uob}} = \left(\frac{T_w}{T_b} \right)^n \quad (22)$$

where

N_{ub} = bulk Nusselt number

N_{uob} = adiabatic bulk Nusselt number.

For hydrogen and air (the two gases investigated) Petukhov and Popov find $n = -0.47$ and -0.5 , respectively, which seems to confirm Davenport's proposition. The exponent m is part of the program input to permit the user freedom in its selection.

Fuel Temperature

The program provides boundary conditions and printout for a fuel temperature subroutine. It is anticipated that only the maximum fuel temperature is of interest. The boundary condition supplied is the tube wall temperature with the variables being tube spacing, heat generation rate, and a table of thermal conductivity versus temperature. A dummy and inverted element routine is included in the listing. It is expected that the user will formulate his own subroutine for other geometries.

System Pressure Loss

The core fluid dynamics is analyzed essentially by the method suggested by Shapiro.⁽⁴⁾ The selection of a one-dimensional compressible flow with friction and heat addition core model obtains the following differential statement for total pressure:

$$\frac{d \frac{P_o}{P_{o1}}}{\frac{P_o}{P_{o1}}} = - \frac{\gamma M^2}{2} \left[\frac{dT_o}{T_o} + \frac{4f\ell}{D_H} d\zeta \right] \quad (23)$$

Shapiro suggests the following method as valid for $M < .3$:

The Mach number at any point along the passage is

$$M^2 = \left(\frac{P_{o1}}{P_o} \right) \frac{T_o}{T_{o1}} \left(\frac{1 + \frac{\gamma-1}{2} M^2}{1 + \frac{\gamma-1}{2} M_1^2} \right)^{\frac{\gamma+1}{\gamma-1}} M_1^2 \quad (24)$$

Inserting Equation (24) into Equation (23) yields

$$\left(\frac{P_o}{P_{o1}} \right) d \left(\frac{P_o}{P_{o1}} \right) = - \frac{\gamma}{2} \left(\frac{1 + \frac{\gamma-1}{2} M^2}{1 + \frac{\gamma-1}{2} M_1^2} \right)^{\frac{\gamma+1}{\gamma-1}} \frac{T_o}{T_{o1}} \left[d \left(\frac{T_o}{T_{o1}} \right) + \frac{4f\ell}{D} d\zeta \right] \quad (25)$$

For low Mach numbers the first term in brackets on the right-hand side of Equation (25) remains nearly constant. He suggests, therefore, using the mean value of

$$\left(\frac{1 + \frac{\gamma-1}{2} M^2}{1 + \frac{\gamma-1}{2} M_1^2} \right)^{\frac{\gamma+1}{\gamma-1}}$$

which is

$$\overline{[f(M^2)]} = \frac{1}{2} \left[1 + \left(\frac{1 + \frac{\gamma-1}{2} M^2}{1 + \frac{\gamma-1}{2} M_1^2} \right)^{\frac{\gamma+1}{\gamma-1}} \right] \quad (26)$$

Inserting the appropriate portion of Equation (24) into Equation (26) yields

$$\overline{[f(M^2)]} = \frac{1}{2} \left[1 + \left(\frac{P_{o1}}{P_o} \right)^2 \left(\frac{T_{o1}}{T_o} \right) \frac{M^2}{M_1^2} \right] \quad (27)$$

Using the developed equations, the exit total pressure is

$$\left(\frac{P_{o_2}}{P_{o_1}}\right)^2 = 1 - \frac{\gamma M_1^2}{2} \left[1 + \left(\frac{P_{o_2}}{P_{o_1}}\right)^2 \left(\frac{T_{o_1}}{T_{o_2}}\right) \frac{M_2^2}{M_1^2} \right] \left\{ \frac{T_{o_2}}{T_{o_1}} - 1 + \frac{4f\ell}{D_H} \left[1 - \frac{\ell \bar{q}'''}{G_5 C_p T_{o_2}} \left(\frac{A}{2} + \frac{B}{6} + \frac{C}{12} + \frac{D}{20} \right) \right] \right\} \quad (28)$$

Solving Equation (28) for the total pressure ratio,

$$\left(\frac{P_{o_2}}{P_{o_1}}\right)^2 = \frac{1 - \frac{\gamma M_1^2}{2} \left\{ \frac{T_{o_2}}{T_{o_1}} - 1 + \frac{4f\ell}{D_H} \left[1 + \frac{\ell \bar{q}'''}{2G_5 C_p T_{o_1}} \left(A + \frac{B}{3} + \frac{C}{6} + \frac{D}{10} \right) \right] \right\}}{1 + \frac{\gamma M_1^2}{2} \left(\frac{T_{o_1}}{T_{o_2}}\right) \left(\frac{M_2}{M_1}\right)^2 \left\{ \frac{T_{o_2}}{T_{o_1}} - 1 + \frac{4f\ell}{D_H} \left[1 + \frac{\ell \bar{q}'''}{2G_5 C_p T_{o_1}} \left(A + \frac{B}{3} + \frac{C}{6} + \frac{D}{10} \right) \right] \right\}} \quad (29)$$

Inspection of Equation (29) reveals two unknowns, M_2 and P_{o_2} .

An additional relationship is

$$\frac{P_{o_2}}{P_{o_1}} \sqrt{\frac{T_{o_1}}{T_{o_2}}} = \frac{\left[\frac{A}{A^*}\right]_{s, M_2}}{\left[\frac{A}{A^*}\right]_{s, M_1}} \quad (30)$$

where

$\left[\frac{A}{A^*}\right]_{s, M_2}$ = isentropic expansion ratio to sonic velocity from state point 2.

The above system of equations is solved by assuming the quantity of fluid flow to be known and by calculating in the following order:

1. The coolant total temperature,

$$\frac{T_o}{T_{o_1}} = 1 + \frac{\ell \bar{q}'''}{G_5 C_p T_{o_1}} \left[A\zeta + B \frac{\zeta^2}{2} + C \frac{\zeta^3}{3} + D \frac{\zeta^4}{4} \right]$$

2. The coolant passage wall temperature,

$$\frac{T_w}{T_{o1}} = \frac{A_{fu} \bar{q}'''}{hp T_{o1}} \left[A + B\zeta + C\zeta^2 + D\zeta^3 \right] + \frac{T_o}{T_{o1}}, \text{ and}$$

3. The system total pressure loss,

$$\left(\frac{P_{o2}}{P_{o1}} \right)^2 = \frac{1 - \frac{\gamma M_1^2}{2} \left\{ \frac{T_{o2}}{T_{o1}} - 1 + \frac{4f\ell}{D_H} \left[1 + \frac{\ell \bar{q}'''}{2G\zeta C_p T_{o1}} \left(A + \frac{B}{3} + \frac{C}{6} + \frac{D}{10} \right) \right] \right\}}{1 + \frac{\gamma M_1^2}{2} \left(\frac{T_{o1}}{T_{o2}} \right) \left(\frac{M_2}{M_1} \right)^2 \left\{ \frac{T_{o2}}{T_{o1}} - 1 + \frac{4f\ell}{D_H} \left[1 + \frac{\ell \bar{q}'''}{2G\zeta C_p T_{o1}} \left(A + \frac{B}{3} + \frac{C}{6} + \frac{D}{10} \right) \right] \right\}}$$

The last is a trial-and-error solution accomplished by guessing M_2 and calculating $\frac{P_{o2}}{P_{o1}}$,

thence $\left[\frac{A}{A^*} \right]_{s, M_2}$

from

$$\left[\frac{A}{A^*} \right]_{s, M_2} = \left[\frac{A}{A^*} \right]_{s, M_1} \frac{P_{o2}}{P_{o1}} \sqrt{\frac{T_{o1}}{T_{o2}}}$$

then calculating M_2 from standard tables, and finally reinserting M_2 to calculate a new total pressure ratio while comparing the latest value of M_2 to its previous to determine convergence. This method analyzes arbitrary axial power profiles and is well suited to machine computation with minimal input information required.

The total pressure ratio across the core is calculated (as follows).

Thermodynamic stations are

- 0 - inlet plenum,
- 1 - inlet to core,
- 2 - core exit,
- 3 - exit plenum.

$$\frac{P_{o_3}}{P_{o_0}} = \frac{P_{o_3}}{P_{o_2}} \times \frac{P_{o_2}}{P_{o_1}} \times \frac{P_{o_1}}{P_{o_0}} \quad (31)$$

where $\frac{P_{o_2}}{P_{o_1}}$ is calculated (as outlined above) from Shapiro's approximation.

$\frac{P_{o_3}}{P_{o_2}}$ and $\frac{P_{o_1}}{P_{o_0}}$ are losses associated with the inlet and exit loss coefficients.

The loss coefficients are those typically associated with Bernoulli's equation and for the inlet are based on the downstream Mach number, M_1 , while the dump or exit loss coefficient is based on the upstream Mach number, M_2 ; this allows zero Mach number in upstream or downstream plenum.

Friction Coefficient

The appropriate friction factor to use is the isothermal average half-friction coefficient, $\frac{f}{2}$. f is defined in Equation (32).

$$f = \frac{h_L}{\frac{4\ell}{D_H} \frac{V^2}{2g}} \quad (32)$$

The half-friction factor is entered in tabular form along with the average Reynolds number. The program calculates the Reynolds number from Equation (33).

$$\bar{N}_{Re} = \frac{2 D_H G}{(\mu_1 + \mu_2)_B} \quad (33)$$

As previously defined, G has no density correction. [Suggested sources for $\frac{f}{2}$ are References (1-3) and (7)].

Power Profile Normalization

Axial Profile

In harmony with Equation (13) we desire

$$q_{(\zeta)}''' = \bar{q}''' \bar{P}_{(\zeta)} \quad (34)$$

where

$$\bar{q}''' = \frac{Q}{\pi r_{eq}'^2 (1 - \alpha_v') \ell}, \text{ and}$$

$\bar{P}_{(\zeta)}$ = normalized power shape.

A necessary condition [Equation (34)] is

$$\int_0^1 P \, d\zeta = 1.0 \quad (35)$$

If the power shape does not satisfy Equations (34) and (35), the following equation is utilized to achieve normalization:

$$\bar{P}_{(\zeta)} = \frac{P_{(\zeta)}}{\int_0^1 P_{(\zeta)} \, d\zeta} \quad (36)$$

For input, four values of ζ and corresponding values of $P_{(\zeta)}$ are selected. The program computes the coefficients in Equation (13).

Radial Profile

The program assumes the shape of $P_{(\zeta)}$ to be preserved throughout the core. Therefore, a product solution may be used, i. e.,

$$q'''(\zeta, r_{eq}') = \bar{q}''' \bar{P}_{(\zeta)} \overline{RP}_{(r_{eq}')} \quad (37)$$

where

$\overline{RP}_{(r_{eq}')} = \text{normalized radial power profile.}$

Just as $\bar{P}_{(\zeta)}$ is normalized on volume (area divides out because it is constant in axial direction), $\overline{RP}_{(r'_{eq})}$ must also be normalized in the same manner. Further complication besides that caused by cylindrical coordinates is introduced by the nonconstancy of α'_v with r'_{eq} and by the need to have the heat generation in the "fuel".

The radial profile usually resulting from nuclear calculations is normalized to volume regardless of core density, i. e.,

$$\overline{RP}_{(r)} = \frac{RP_{(r)}}{\frac{1}{\pi r_o^2} \int_0^{r_o} \pi RP_{(r)} r dr} \quad (38)$$

where

r_o = outer radius.

The radial profile normalized in this manner is entered into the program. If α'_{vI} is calculated as follows, the calculation and renormalization is internally handled. Setting $\bar{r} = r/r_o$ obtains Equation (39) from Equation (38).

$$\overline{RP}_{(r)} = \frac{RP_{(r)}}{\int_0^1 RP_{(r)} \bar{r} d\bar{r}} \quad (39)$$

If we now find the volumetric generation based on the total core volume, we can construct the proper picture.

$$\bar{q}''' = \frac{Q}{\pi R_o^2 \ell} \quad (40)$$

now

$$\bar{q}''' = \bar{q}''' / 1 - \alpha'_{vI} \quad (41)$$

where

I = zone index; 1, 2, 3, etc.

α'_{vI} = zone void fraction used in physics study to determine the radial power profile that has been corrected to the heat transfer model as stipulated by Equation (3). Thus,

$$\alpha'_{vI} = \left(\frac{\alpha_{vI}}{\alpha_f + \alpha_c + \alpha_{tc}} \right)_{\text{zone}}$$

The program then assumes $\bar{q}'''$ to be constant. The total heat generated in a zone is made proportional to the amount of fuel in the zone. As a consequence of Equation (41) the program requires a table of α'_{vI} versus r'_{eq} for input even if α'_{vI} is constant. In this instance the α'_v input for the uniform core case is ignored.

PROGRAM INPUT

The input can be broken down into three categories:

- Tabular
- Case input
- Zone input.

The mode of operation is controlled by the absence or presence of the pertinent number. In any case, all cards are required even if blank. Reference to the Listing, Nomenclature, and Sample Case input is desirable.

Tabular Data

Immediately following the transfer card (\$ DATA) are 10 tables. All table reading takes place in statement numbers 110-122.

Format 8F9.3

Each table consists of 4 cards making 40 cards in all. Hence, each table can contain a maximum of 32 numbers. A table need not be filled, but four cards per table are required even if some are blank*.

* Blank fields are read in as zero.

Program Table 1 is a temperature table, and units are °R. Tables 2 to 5 and Table 10 are:

Table

2*	Coolant dynamic viscosity, lb/(hr)(ft)
3	Coolant thermal conductivity, Btu/(hr)(ft)(°F)
4	Coolant specific heat, pressure constant, Btu/(lb)(°F)
5	Coolant ratio of specific heats, numeric
10	"Fuel" thermal conductivity, Btu/(hr)(ft)(°F).

Tables 2 to 5 and 10 are read in versus temperature (the temperature table). Values in these tables correspond by location in their respective tables to location in the temperature table. ** Hence, the temperature listed in Location 1 (first card, first field) of the temperature table is the argument for the first viscosity value (card 5, first field).

Table 6 is the compressible flow function $[A/A^*]_s$, where s denotes isentropic. Corresponding Mach numbers are entered in Table 7. A/A^* is the argument and must be entered in ascending order. Keenan and Kaye⁽⁵⁾ give tables of $[A/A^*]_s$ versus Mach number. The equation for calculating $[A/A^*]_s$ is given below:

$$[A/A^*]_s = \frac{1}{M} \left[\frac{2 \left(1 + \frac{\gamma - 1}{2} M^2 \right)}{\gamma + 1} \right]^{\frac{\gamma + 1}{2(\gamma - 1)}} \quad (42)$$

If γ changes with temperature, the basic premise of the total pressure calculations is violated. The author is not aware of any method to predict the error by any but finite difference integration for the particular problem in question. However, A/A^* is a weak function of the specific heat ratio, and any errors introduced should be negligible. The ratio of specific heats

* Tables 2 to 5 were generated by another program, "MIX". (6)

** Temperatures must be entered in ascending order beginning with the first location (field).

to be used to calculate $[A/A^*]$ for tabular input is the expected average γ and is selected from the γ table.

Inspection of Equation (42) reveals that it is transcendental and cannot be solved explicitly for M with A/A^* , the independent variable. The equation could be solved by trial and error, but entrance of tabular values proves better adapted to the trial-and-error method used to calculate the flow variables.

Tables 9 and 8 are the average isothermal half-fraction factor versus Reynolds number, respectively. f is defined in Equation (32) as

$$f = \frac{h_L}{\frac{4\ell}{D_H} \frac{V^2}{2g}}$$

The half-fraction factor, $f/2$, is entered in Table 9 corresponding by location to the appropriate Reynolds number in Table 8. The Reynolds number is entered in ascending order. References (1) and (7) give a correlation of $f/2$ versus N_{Re} . Tables are entered once in order 1 to 10.

Case Input - Uniform Core

Seven cards are required per case (zoned or uniform). For uniform core (flat radial power) studies the last four cards are left blank. The formats for the seven cards are as follows:

<u>Card</u>	<u>Format</u>
1	7F8.3, 2E8.3
2	9F8.3
3	9F8.3
4	F8.3
5	9F8.3
6	9F8.3
7	8F9.3

The case input will now be discussed in detail.

Card	First Column in Field	Variable	Comments	Units
1	1	Core Inlet Total Temperature	Coolant	°R
	9	Inlet Plenum Total Pressure	Coolant	psia
	17	Net Core Power		MW
	25	Core Length (Actual)		ft
	33	Core Radius (Model)	See Sample Case	ft
	41	Coolant + Tube Cladding Volume Fraction		numeric
	49	Guess of Proper Tube Hydraulic Diameter		ft
	57	Actual Tube Wall Thickness		ft
	65	Desired Core Coolant Flow		lb/hr
2	1	*Normalized Axial Power Profile (NAPP)	See Sample Case	numeric
	9	Normalized Axial Location (NAL)		numeric
	17	NAPP		numeric
	25	NAL		numeric
	33	NAPP		numeric
	41	NAL		numeric
	49	NAPP		numeric
	57	NAL		numeric
	65	Heat Transfer Temperature Correlation Exponent	See Analysis, p. 11 and 12	numeric
3	1	Coolant Molecular Weight		lb lb-mole
	9	Desired Convergence Error	See Below	
	17	Unheated Entrance Length		ft
	25	**Number of Inlet Velocity-Head Losses	$\frac{2g\Delta P}{\rho V_1^2}$	numeric
	33	†Number of Exit Velocity-Head Losses	$\frac{2g\Delta P}{\rho V_2^2}$	numeric
	41	Maximum Desired Tube Wall Temperature		°R
	49	A Factor for Converting Model to Actual	(Optional)	numeric
	57	Volume Fraction of "Fuel" Voids	(Optional) See Sample Case, p. 32	numeric
	65	Number of Tubes in Core	Zone Case Only - Option 3	numeric
4	1	Desired Coolant Total Pressure Ratio	Zone Case Only - Option 3 Otherwise Blank	numeric

* Beginning at core front face.

** Based on downstream velocity.

† Based on upstream velocity.

If the convergence error equals E, then convergence is:

Variable	Relative Error
Heat Transfer Coefficient	E
Inlet Mach Number - Uniform	E
- Zoned	.1E
Exit Mach Number - Uniform	E
- Zoned	.1E
Total Pressure Ratio - Zoned	.1E
Maximum Desired Wall Temperature	.5E
Average Coolant Specific Heat	E

Before discussing the zone calculations input, a review should be made of the program modes of operation.

Mode 1 - Uniform Core. The program adjusts the number of coolant passages and their hydraulic diameters, within allowable "void" to desired maximum average wall temperature. Coolant flow and "void" remain constant while total pressure ratio changes. Hence, some cases "blow up" for two reasons:

- Mach number exceeds that allowed by the approximation.
- There is not enough pressure to force the required flow through the core.

Results are considered to be wholly unreliable when $M_2 > .5$. Iterations are in general limited to 20 with on-line error return.

Mode 2 - Zoned Core. The program calculates uniform model. Number of tubes (last location, third card) and total pressure ratio specification (Card 4) are left blank. Entry of detailed zone data (radial power shape, radial location, and "void")(Cards 5, 6, and 7) with other than zeros causes the program to zone the core with any number of zones specified up to 8. The average tube walls in each zone will have the same maximum temperature and the total pressure ratio is the same (within .1E) over the core. The core coolant flow rate, tube diameter, power, and void change from the uniform case while the number of coolant passages remain constant.

Mode 3 - Same as Mode 2 except:

- Number of tubes and total pressure ratio are specified.
- A uniform core case is not calculated but printout of anything that happens to be in memory takes place labeled as zone 0.

If total pressure ratio and number of tubes are specified and Cards 5 to 7 are blank (attempt to specify total pressure ratio on uniform core), the program will print whatever happens to be in memory and call the next case.

Zone Input

Card	First Column in Field	Variable	Units
5	1	Radial Power Ratio Zone 1	numeric
	9	Inner Radius of Zone 1 (Usually Zero)	ft
	17	Radial Power Ratio (RPR) Zone 1	numeric
	25	*Outer Radius (OR) of Zone 1	ft
	33	RPR Zone 2	
	41	OR Zone 2	ft
	49	RPR Zone 3	
	57	OR Zone 3	ft
6	65	RPR Zone 4	
	1	OR Zone 4	ft
	9	RPR Zone 5	
	17	OR Zone 5	ft
	25	RPR Zone 6	
	33	OR Zone 6	ft
	41	RPR Zone 7	
	49	OR Zone 7	ft
	57	RPR Zone 8	
	65	OR Zone 8	ft

* These radii are corrected to the heat transfer model radius. The number of zones is specified by the number of zone inputs.

Card	First Column in Field	Variable	Units
Note the different format on Card 7.			
7	1	*Model "Void Fraction" Zone 1	numeric
	10	Model "Void Fraction" Zone 2	numeric
	19	Model "Void Fraction" Zone 3	numeric
	28	Model "Void Fraction" Zone 4	numeric
	37	Model "Void Fraction" Zone 5	numeric
	46	Model "Void Fraction" Zone 6	numeric
	53	Model "Void Fraction" Zone 7	numeric
	64	Model "Void Fraction" Zone 8	numeric

This completes the input. Successive cases are run by stacking (sequentially) after the tables, the seven cards per case for as many cases as are desired. Tables are read in but one time (each time the program is read into the machine).

Program Stop

This program is stopped by stacking three or more blank cards after the case runs.

SAMPLE CASES

Three sample cases are illustrated to demonstrate the three modes of operation:

Case 1 - Uniform core

Case 2 - Zoned core from uniform core model

Case 3 - Zoned core specifying the coolant total pressure ratio and number of coolant passages.

The core to be investigated in this example is a fast spectrum, cermet fueled, inverted element reactor; therefore, the core contains no moderator.

* "Void Fraction" $\alpha'_{vl} = \alpha'_{cl} + \alpha'_{tcl}$ (see pp. 18 and 19)

Model Calculations

The "fuel" rods are hexagonal and consist of finely divided fissile material immersed in a continuous matrix of refractory metal. The coolant passages are circular and uniformly spaced within the "fuel" rod.

The differences between the actual core, physics model, and heat transfer model are illustrated in Figure 1. The physics model is a right circular cylinder whose diameter and sectional area corresponds to the sectioned area of the core. The physics model then includes the cermet voids, spacing of elements, clad, as well as the "fuel" and coolant tubes, all distributed in a homogeneous manner.

FIGURE 1

Physics and Heat Transfer Models

Constituent Volume Fractions

In determining whether a critical core of given size, void fraction, and power has sufficient coolant voids available to meet thermal design conditions, the voids must be allotted according to geometry, to tube walls, tubes, element spacing, clad and void fraction in cermet. The allotment is based upon the following development.

By definition, for the actual core:

$$\alpha_F + \alpha_f + \alpha_s + \alpha_c + \alpha_{oc} + \alpha_{tc} = 1.0 \quad (43)$$

where

- α_F = volume fraction of 100% dense cermet
- α_f = volume fraction of cermet voids
- α_s = volume fraction of element spacing
- α_c = volume fraction of coolant voids
- α_{oc} = volume fraction of fuel element clad
- α_{tc} = volume fraction of coolant passage clad.

For a given fractional spacing, P , and flats dimension, L , the area of each element (including spacing) is

$$A_E = .867 L^2 (1 + P)^2 \quad (44)$$

With N fuel elements in the core, the total reactor area normal to its axis is

$$A_T \cong N A_E = .867 N L^2 (1 + P)^2 \quad (45)$$

This equation also includes the spacing area on the core periphery, introduces a negligible but conservative error, and will be retained because of its simplicity.

The spacing area, A_s , is

$$\begin{aligned} A_s &= \text{total area} - \text{area of elements} \\ &= N[.867 L^2 (1 + P)^2 - .867 L^2] \\ &= .867 N L^2 (2P + P^2) \end{aligned} \quad (46)$$

If t_{oc} is the clad thickness then the outer clad area, A_{oc} , is

$$\begin{aligned} A_{oc} &= .867 N [L^2 - (L - 2t_{oc})^2] \\ &= 3.46 N t_{oc} (L - t_{oc}) \end{aligned} \quad (47)$$

For N_t tubes of inner diameter, D_H , in the core the coolant area, A_c , is

$$A_c = N_t D_H^2 \frac{\pi}{4} \quad (48)$$

For a tube wall thickness, t , and corresponding equivalent tube thickness, t_e , the area associated with the tube wall is

$$A_{tc} = N_t D_H \pi t_e \quad (49)$$

where

$$t_e = t \left(1 + \frac{t^2}{D_H^2} \right)$$

From Equation (43) the average void area in the cermet, A_f , is

$$A_f = (A_T - A_s - A_{oc} - A_c - A_{tc}) \left(1 - \frac{\rho}{\rho_t} \right) \quad (50)$$

where $\frac{\rho}{\rho_t}$ is the fraction of theoretical density of the cermet.

The actual cermet area of 100% theoretical density is

$$A_F = (A_T - A_s - A_{oc} - A_c - A_{tc}) \frac{\rho}{\rho_t} \quad (51)$$

The core is symmetric and of uniform area so the volume fractions are the ratio of the area in question to the total core cross-sectional area. Doing this obtains

$$\alpha_s = \frac{A_s}{A_T} = \frac{.867 N L^2 (2P + P^2)}{.867 N L^2 (1 + P)^2} = \frac{(2P + P^2)}{(1 + P^2)} \quad (52)$$

$$\alpha_{oc} = \frac{4 t_{oc} (L - t_{oc})}{L^2 (1 + P)^2} \quad (53)$$

$$\alpha_c = \frac{N_t D_H^2 \pi}{3.46 L^2 (1 + P)^2 N} \quad (54)$$

$$\alpha_{tc} = \frac{N_t D_H \pi t_e}{.867 L^2 (1 + P^2) N} \quad (55)$$

$$\begin{aligned}\alpha_f &= \left(1 - \frac{\rho}{\rho_t}\right) \left(1 - \frac{A_s}{A_T} - \frac{A_{oc}}{A_T} - \frac{A_c}{A_T} - \frac{A_{tc}}{A_T}\right) \\ &= \left(1 - \frac{\rho}{\rho_t}\right) (1 - \alpha_s - \alpha_{oc} - \alpha_c - \alpha_{tc})\end{aligned}\quad (56)$$

Similarly,

$$\alpha_F = \frac{\rho}{\rho_t} (1 - \alpha_s - \alpha_{oc} - \alpha_c - \alpha_{tc}) \quad (57)$$

In the physics model, the neutronics are assumed to be the same for a smooth cylinder of cross-sectional area and length equal to that of a roughly cylindrical core made from hexagonal rods of length identical to the cylinder. Thus, we can define a core of equivalent area (volume) to that of the actual core:

$$\pi r_{eq}^2 = A_T = .867 N L^2 (1 + P)^2 \quad (58)$$

where r_{eq} is the radius described in Figure 1 (Physics Model). The denominators in Equations (54) and (55) can be replaced by πr_{eq}^2 and a constant.

Group the volume fractions into a gross void fraction, α_G , and coolant tube and tube wall volume fraction, α_v .

$$\alpha_G = \alpha_s + \alpha_{oc} + \alpha_f + \alpha_c + \alpha_{tc} \quad (59)$$

and

$$\alpha_v = \alpha_c + \alpha_{tc} \quad (60)$$

For a given size reactor and associated gross void fraction, α_G , α_s , α_{oc} , and α_f are constant (fixed spacing, "fuel density", and clad thickness); consequently, α_v is constant. When designing to a fixed wall or fuel temperature, α_c and α_{tc} are not separately constant because of the ability to change tube diameter (and consequently number of tubes) and arrive at the appropriate temperature. The important thing to note is that α_v is constant during this process.

Now mathematically define a new reactor (the heat transfer model) with 100% theoretical density "fuel" and without element clad or spacing. In this reactor

$$\alpha_F' + \alpha_V' = 1.0 \quad (61)$$

As a consequence of this definition:

$$\alpha_F' = \frac{\alpha_F}{\alpha_F + \alpha_V} \quad (62)$$

and

$$\alpha_V' = \frac{\alpha_V}{\alpha_F + \alpha_V} \quad (63)$$

The area of the heat transfer core may now be found by requiring that the area for coolant flow be the same in the physics and heat transfer cores, i.e.,

$$\alpha_V \pi r_{eq}^2 = \alpha_V' \pi r_{eq}'^2 \quad (64)$$

so that

$$r_{eq}' = r_{eq} \sqrt{\frac{\alpha_V}{\alpha_V'}} \quad (65)$$

r_{eq}' is the radius described in Figure 1 (Heat Transfer Model).

With some simplifying assumptions the criticality survey can be performed neglecting clad material effects and assuming the clad to be void. Hence, α_G or α_F are independent and constrained so that

$$\alpha_F + \alpha_G = 1.0 \quad (66)$$

Once $\frac{\rho}{\rho_t}$, L , α_G , r_{eq} , t_{oc} , t , and P are named the allotment of the remaining quantities (except α_c and α_{tc}) may be found as follows:

* Prime denotes heat transfer model.

$$\alpha_s = \frac{2P + P^2}{(1 + P)^2} \quad (52)$$

$$\alpha_{oc} = \frac{4 t_{oc} (L - t_{oc})}{L^2 (1 + P)^2} \quad (53)$$

From Equations (57) and (59)

$$\alpha_v = 1 - \frac{\rho_t}{\rho} \alpha_F - \alpha_s - \alpha_{oc} \quad (67)$$

α_v is broken into its constituents after determining the number and diameter of tubes by using Equations (54), (55), and (58) (and, consequently, a trial and error process).

The two factors entered on Card 3, columns 49 and 57, will now be found. These factors for converting heat transfer model to actual may be found in Equation (65). To obtain the actual core radius from the model rearrange Equation (65):

$$r_{eq} = r'_{eq} \sqrt{\frac{\alpha'_v}{\alpha_v}} \quad (68)$$

From Equation (63)

$$\frac{\alpha'_v}{\alpha_v} = \frac{1}{\alpha_F + \alpha_v} \quad (69)$$

To find the expression $\alpha_F + \alpha_v$, insert Equation (56) into Equation (57) and rearrange to give this factor:

$$\alpha_F + \alpha_v = 1 - \alpha_s - \alpha_{oc} - \alpha_f \quad (70)$$

α_f must now be removed as it changes with α_F . Doing this obtains

$$\alpha_F + \alpha_v = \frac{\rho}{\rho_t} (1 - \alpha_s - \alpha_{oc}) + (1 - \frac{\rho}{\rho_t}) \alpha_v \quad (71)$$

The first factor (column 49) is then

$$VF = \frac{\rho}{\rho_t} (1 - \alpha_s - \alpha_{oc}) \quad (72)$$

The second factor (column 57) is

$$VFF = 1 - \frac{\rho}{\rho_t} \quad (73)$$

A moderated core may be treated in one of several ways, e.g., the amount of moderator in the core may be considered constant while α_v does the same and α_c and α_{tc} change. In this instance, α_M is lumped with α_s and α_{oc} .

Fuel Temperatures

The sample case fuel temperatures were calculated, using a truncated series equation derived in Schneider's⁽⁸⁾ text and incorporated in subroutine FUTEMP. He solves the problem of uniform tube spacing, thermal conductivity and heat generation with homogeneous boundary conditions. The sample case neglects the difference in thermal conductivity of the tube and clad, and assumes the thermal conductivity is that of the cermet.

Input Preparation

Assume the appropriate tables have been prepared as shown on pp. 19, 20, 21, and 39 and consider the case input. The design point (Table I) for all three cases is essentially the same.

From Equation (66),

$$\alpha_F = 1 - \alpha_G = .73$$

From Equation (67) the core void left for the coolant tubes is

$$\begin{aligned} \alpha_v &= 1 - \frac{\rho_t}{\rho} \alpha_F - \alpha_s - \alpha_{oc} \\ &= 1 - (1.05) (.73) - .1 \\ &= .131 \end{aligned}$$

TABLE I
SAMPLE CASE INPUT

<u>Design Point</u>	
Coolant	10 He-90 Ne
Mean Molecular Weight	18.565 $\frac{\text{lb}}{\text{lb-mole}}$
Coolant Inlet Temperature	600 °F (1060 °R)
Coolant Exit Temperature	1300 °F (1760 °R)
Required Coolant Flow	4.46 x 10 ⁴ lb/hr
Inlet Total Pressure	800 psia
Coolant Tube Maximum Temperature	1500 °F (1960 °R)
Core Net Thermal Power	2.444 MW
Entrance Loss Coefficient	1.5
Dump Loss Coefficient	1.0
<u>Core Characteristics</u>	
Length	1.308 ft
Diameter	1.322 ft
Gross Void Fraction-- α_G	27%
Coolant Tube Clad Thickness	7.14 x 10 ⁻⁴ ft
$\alpha_{oc} + \alpha_s$	10.04%
ρ/ρ_t	95%
Unheated Tube Entrance Length	8.3 x 10 ⁻⁴ ft (none)

The Normalized Axial Power Profile
Is Characterized by the Following Eight Numbers

$\bar{P}_1$	0.7730
$(x/l)_1$	0
$\bar{P}_2$	1.2880
$(x/l)_2$	0.4000
$\bar{P}_3$	0.9990
$(x/l)_3$	0.7000
$\bar{P}_4$	0.2030
$(x/l)_4$	1.0000

From Equation (69),

$$\frac{\alpha'_v}{\alpha_v} = \frac{1}{\alpha_F + \alpha_v} = \frac{1}{.861}$$

From Equation (72)

$$VF = \frac{\rho}{\rho_t} (1 - \alpha_s - \alpha_{oc}) = (.95)(.8996) = .8546$$

and Equation (73)

$$VFF = .05$$

The "volume fraction" and core radius must be corrected to the heat transfer model.

From above

$$\alpha'_v = \frac{.131}{.861} = .152$$

From above and Equation (65),

$$r'_{eq} = \frac{1.322}{2} \sqrt{.861} \\ = .614 \text{ ft}$$

The heat transfer model, excluding fuel void, element clad and spacing, has a diameter of 1.228 ft in comparison with the actual core diameter of 1.322 ft and a tube volume fraction of .152 compared to .131. A convergence error of .005 is desired. A coolant tube ID of .00594 ft was guessed.

Case I - Uniform Core

Input

The above input information is entered on Cards 1, 2, and 3 in the fields and format as discussed on p. 22, and shown in the input listings on p. 39. Zoning is not desired so Cards 4, 5, 6, and 7 are left blank.

Output

Output is shown on p. 41.

The headings are interpreted as follows:

ICASE	Case Number
ITERATION	Number of Loops to Converge on Proper Wall Temperature
INPUT TMAXWALL	Desired Maximum Wall Temperature
ZONE	Zero (0) Designates Uniform Core
T01/R	Inlet Total Temperature, °R
P00/PSI	Inlet Total Pressure, psia
Q/MW	Core Power, MW
QB/B/HCUFT	Fuel Volumetric Heat Generation Rate, Btu/(hr)(ft ³)
XL/FT	Core Length, ft
RAD/FT	Model Radius, ft
HYD D/F	Coolant Tube Hydraulic Diameter to Achieve Required Tube Wall Temperature, ft
WALL TH/FT	Equivalent Tube Wall Thickness, ft (not actual as entered)
EQV N	Equivalent Number of Circular Tubes in Core
WDOT/LB/H	Coolant Flow Rate, lb/hr
G/LB/HSF	Mass Coolant Velocity, lb/hr-ft ²
VOID F	α_v
COOL FR	Ratio of Coolant to Fuel Area
A, B, C, D	Coefficients in Axial Power Shape Fit
FUEL FRACTION	Volume Fraction of Fuel in Actual Core
TUBE CLAD FR	Volume Fraction of Tube Clad in Actual Core
COOLANT VOID	Volume Fraction of Tube Coolant Area in Actual Core
ZONE OUTER RAD	Actual Outer Radius of Zone, ft
XNRE	Bulk Average Reynolds Number
ZETA	Dimensionless Axial Distance
T0	Coolant Total Temperature at ZETA, °R
TW	Tube Wall Temperature at ZETA, °R
TMAX	Fuel Temperature as Calculated by Subroutine FUTEMP, °R
IN MACH	Mach Number in Tubes at Core Front Face Based on Fully Developed, Wholly Turbulent Flow

EXIT MACH	Mach Number in Tubes at Core Back Face
P01	Total Pressure in Tubes at Core Front Face, psia
PS1	Static Pressure in Tubes at Core Front Face, psia
PS2	Static Pressure in Tubes at Core Back Face, psia
P02	Total Pressure in Tubes at Core Back Face, psia
P03/P00	Plenum-to-Plenum Total Pressure Ratio

At the end of zoning the zoned core total coolant flow and power is printed out.

Note: The error trace appearing on the first page of output is due to processing the radial zone input. It arises because the program first finds the fractional area in each zone by the following equation in FORTRAN notations.

$$DQ(IZ) = 1, 9$$

$$REQ(IZ) = (RZ(IZ + 1) ** 2. - RZ(IZ) ** 2.) / RAD ** 2.$$

Since 9 values of RZ are read in and 11 locations allotted, location 10 contains a - .0. When $IZ = 9$, $IZ + 1 = 10$, the error return is caused. This in no way affects the ensuing calculations.

The output is now self-explanatory. It is seen that 2070 tubes of $ID = .00918$ ft are required to meet design conditions. The tube clad fraction and coolant void are split up (as shown) and their sum is, of course, .131. The total pressure ratio is .98514 under these conditions. Since both entrance and dump plenums are stagnation points, $P00 = PS0$ and $P03 = PS3$.

Case II - Uniform Model of Same Geometry as Case I Is Zoned into 8 Zones. Same Design Point

Input

Cards 1, 2, and 3 are identical to Case I. Total pressure ratio is not specified so Card 4 and the last field on 3 are left blank.

The normalized radial power ratio, radial location, and α_v' , used to obtain the radial power profile, are shown in Table II.

TABLE II
ZONED CORE POWER RATIO
AND VOID FRACTION

<u>Zone</u>	<u>Inner Radius (Model) of Zone, ft.</u>	<u>Outer Radius (Model) of Zone, ft</u>	<u>Normalized Power Ratio, Numeric</u>	<u>α_v'</u>
1	0	0.2456	1.1250	0.152
2	0.2456	0.3684	1.0250	0.152
3	0.3684	0.4912	0.8850	0.152
4	0.4912	0.5526	0.8190	0.152
5	0.5526	0.5680	0.8480	0.152
6	0.5680	0.5833	0.9080	0.152
7	0.5833	0.5987	1.0100	0.152
8	0.5987	0.6140	1.4800	0.152

Entry of this data on Cards 5, 6, and 7, as shown on the input listing and input directions, causes the program to zone the core into zones of equal maximum tube wall temperature.

Output

The output is shown on pp. 42 to 50. Zone zero (0), p. 42, is the uniform core model for zoning and is identical to Case I. All zones have a nominal total pressure ratio of .985 and maximum wall temperature of 1960 °R. The zone outer radius is the actual O.R. of the zone in the real core. RAD is the radius of a circle whose area is equal to the zone area.

Note: Zone 8 - The core power, after zoning, is 2.36 MW rather than 2.44 MW. The coolant flow is 12.06 lb/sec while design was 12.4 lb/sec.

Case III - Same as II Except 3500 Tubes Are Required at Total Pressure Ratio of .95

Input

The input cards are the same as Case II except 3500 is entered in field 9, Card 3, and .95 is entered on Card 4 as shown on p. 22 and 40.

Output (pp. 51 to 59).

As previously mentioned, the program prints out whatever happens to be in memory for Zone ZERO since Zone ZERO calculation is not required. Therefore, with the exception of EQV N and P03/P00 (3500. and .95), the output is identical to Zone 8, Case II. The differences between Cases III and II are readily apparent.

SAMPLE CASE INPUT LISTING

```

SDATA
-----
400.0    600.0    800.0    1000.0    1200.0    1400.0    1600.0    1800.0    11TEMP
2000.0    2200.0    2400.0    2600.0    2800.0    3000.0    3200.0    3400.0    12
3600.0    3800.0    4000.0    4200.0    4400.0    4600.0    4800.0    5000.0    13
10000.0                                     14
0.06332270.08066130.09702690.11262910.12325030.14084280.15412500.1665205000000803
0.17945390.19168690.20341610.21514520.22652720.23762330.24865220.2595580000000903
0.27004900.28041720.29096950.30139920.31046060.31856740.32798430.3374609000001003
0.34535650.00000000.00000000.00000000.00000000.00000000.00000000.0000000000001103
0.02672660.03441640.04145440.04790230.05371820.05953730.06527340.0708056000001203
0.07623540.08156270.08654370.09148520.09633860.10104910.10561790.1101860000001303
0.11471620.11925460.12368800.12797450.13233840.13545570.14074320.1447871000001403
0.15428400.00000000.00000000.00000000.00000000.00000000.00000000.0000000000001503
0.2672    0.2672    0.2672    0.2672    0.2672    0.2672    0.2672    0.2672000000010
0.2672    0.2672    0.2672    0.2672    0.2672    0.2672    0.2672    0.2672000000110
0.2672    0.2672    0.2672    0.2672    0.2672    0.2672    0.2672    0.2672000000210
0.2672    -0.0000    -0.0000    -0.0000    -0.0000    -0.0000    -0.0000    -0.00000000000310
1.6670    1.6670    1.6670    1.6670    1.6670    1.6670    1.6670    1.66700000000403
1.6670    1.6670    1.6670    1.6670    1.6670    1.6670    1.6670    1.66700000000503
1.6670    1.6670    1.6670    1.6670    1.6670    1.6670    1.6670    1.66700000000603
1.6670    -0.0000    -0.0000    -0.0000    -0.0000    -0.0000    -0.0000    -0.00000000000703
1.058     1.085     1.125     1.176     1.239     1.320     1.425     1.560    61A/A*
1.740     1.985     2.340     2.885     3.602     5.660     11.27     56.25    62
112.50    562.5    9999999.0                                     63
-----
.75       .70       .65       .60       .55       .50       .45       .40    71MACH
.35       .30       .25       .20       .15       .10       .05       .01    72
.005     .001     .000                                     73
-----
100.     1000.     2000.     3000.     4000.     5000.     6000.     7000.    NRE81
8000.     9000.     10000.     20000.     30000.     40000.     50000.     60000.    82
70000.     80000.     90000.     100000.     1000000.                                     83
-----
.135     .0675     .0135     .00999     .00945     .00935     .0081     .0076 F/2 91
.0069     .0065     .0062     .0045     .0039     .0036     .0035     .0034    92
.0032     .0031     .0030     .0028     .0020                                     93
-----
21.6     20.5     19.6     18.8     18.1     17.6     17.0     16.5    101KM
16.1     15.8     15.4     15.2     14.9     14.8     14.6     14.5    102
14.3     14.2     14.0     13.9     13.7     13.6     13.5     13.5    103
13.5                                     104
1060.     800.     2.444    1.308     .614     .152     .00594    6.66E-044.46E+04 10
.7730    0.000     1.288     .4000     .9990     .7000     .2030     1.000     .5000    20
18.565    .005     .00083    1.5       1.0       1960.     .8546     .05       0.       30
-----
40
50
60
70

```

[illegible]

SWISSCHEESE 2

1060.0 800.0 2.4440.635E 07 1.308 0.6140 0.009180.000714 2073.

[illegible]

0.730 0.034 0.100 0.

ZETA =	0.0	.1	.2	.3	.4	.5	.6
--------	-----	----	----	----	----	----	----

T0	1060.0	1122.7	1199.1	1284.4	1374.0	1463.3	1547.9
----	--------	--------	--------	--------	--------	--------	--------

TW	=	1105.7	1451.2	1602.9	1730.2	1831.0	1902.5	1945.5
----	---	--------	--------	--------	--------	--------	--------	--------

TMAX =	1121.7	1473.1	1629.0	1759.0	1860.8	1931.8	1972.6
--------	--------	--------	--------	--------	--------	--------	--------

ZETA = .7 .8 .9 1.0

T0	=	1623.6	1686.4	1732.5	1758.1
----	---	--------	--------	--------	--------

TW = 1959.9 1943.7 1898.7 1821.2

TMAX = 1983.4 1962.2 1910.8 1825.9

IN MACH	EXIT MACH	P01	PS1	PS2	P02	P03/P00
---------	-----------	-----	-----	-----	-----	---------

0.04431 0.04795 798.04349 796.73911 788.18096 789.69215 0.98523

ERROR TRACE. CALLS IN REVERSE ORDER.

CALLING ROUTINE	IFN OR LINE NO.	ABSOLUTE LOCATION
--------------------	--------------------	----------------------

FXP3	00036	23273
------	-------	-------

DECK2 00071 03352

EXPONENTIATION ERROR (-B)***C

EVALUATE FOR +8

SWISSCHEESE 2

ICASE = 2 ITERATION 4 INPUT TMAXWALL= 1960.00 ZONE 0							
T01/R P00/PSI Q/MW QR/B/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N							
1060.0	800.0	2.4440.635E 07	1.308	0.6140	0.009180.000714	2073.	
WDOT/LB/H;G/LB/HSF VOID F COOL FR A B C D							
0.446E 05	0.325E 06	0.152	0.137	0.7730	2.6854	-3.6542	0.3988
FUEL FRACTION TUBE CLAD FR COOLANT VOID ZONE OUTER RAD							
0.730	0.031	0.100	-0.				
XNRE = 0.21328E 05							
ZETA =	0.0	.1	.2	.3	.4	.5	.6
T0 =	1060.0	1122.7	1199.1	1284.4	1374.0	1463.3	1547.9
TW =	1105.7	1451.2	1602.9	1730.2	1831.0	1902.5	1945.5
TMAX =	1121.7	1473.1	1629.0	1759.0	1860.8	1931.8	1972.6
ZETA =	.7	.8	.9	1.0			
T0 =	1623.6	1686.4	1732.5	1758.1			
TW =	1959.9	1943.7	1898.7	1821.2			
TMAX =	1983.4	1962.2	1910.8	1825.9			
IN MACH EXIT MACH P01 PS1 PS2 P02 P03/P00							
0.04431	0.04795	798.04349	796.73911	788.18096	789.69215	0.98523	

SWISSCHEESE 2

ICASE = 2 ITERATION				0 INPUT TMAXWALL = 1960.00 ZONE 1			
T01/R P00/PS1 Q/MW QR/B/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N							
1060.0	800.0	0.4360	714E-07	1.308	0.2456	0.009450	0.000713 332.
WDOT/LB/H,G/LB/HSE		VOID F	COOL FR	A	B	C	D
0.811E 04	0.348E-06	0.160	0.146	0.7730	2.6854	-3.6542	0.3988
FUEL FRACTION		TUBE CLAD FR	COOLANT VOID	ZONE OUTER RAD			
0.724		0.032	0.106	0.265			
XNRE = 0.23613E 05							
ZETA =	0.0	.1	.2	.3	.4	.5	.6
T0 =	1060.0	1121.5	1196.5	1280.2	1368.1	1455.6	1538.6
TW =	1106.5	1460.1	1613.5	1740.8	1840.5	1909.9	1949.8
TMAX =	1123.7	1483.9	1641.8	1772.0	1872.8	1941.6	1979.1
ZETA =	.7	.8	.9	1.0			
T0 =	1612.9	1674.5	1719.7	1744.9			
TW =	1960.5	1940.2	1891.3	1809.9			
TMAX =	1986.0	1960.2	1904.4	1815.0			
IN MACH	EXIT MACH	P01	PS1	PS2	P02	P03/P00	
0.04537	0.04872	797.94884	796.58118	788.17706	789.73753	0.98522	

SWISSCHEESE 2

ICASE = 2 ITERATION 0 INPUT TMAXWALL= 1960.00 ZONE 2							
T01/R P00/PSI Q/MW QR/B/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N							
1060.0	800.0	0.4970	0.651E 07	1.308	0.2746	0.009400	0.000713 415.
WDOT/LB/H,G/LB/HSF VOID F COOL FR A B C D							
0.917E 04	0.318E 06	0.158	0.144	0.7730	2.6854	-3.6542	-0.3988
FUEL FRACTION TUBE CLAD FR COOLANT VOID ZONE OUTER RAD							
0.725	0.032	0.105	0.397				
XNRE = 0.21436E 05							
ZETA =	0.0	.1	.2	.3	.4	.5	.6
T0 =	1060.0	1122.0	1197.7	1282.2	1370.8	1459.2	1542.9
TW =	1105.8	1455.1	1607.6	1734.9	1835.1	1905.5	1947.0
TMAX =	1121.7	1476.9	1633.5	1763.4	1864.7	1934.6	1973.9
ZETA = .7 .8 .9 1.0							
T0 =	1617.9	1680.1	1725.7	1751.0			
TW =	1959.6	1941.4	1894.4	1815.1			
TMAX =	1982.9	1959.7	1906.5	1819.7			
IN MACH EXIT MACH P01 PS1 PS2 P02 P03/P00							
0.04399	0.04767	798.07158	796.78602	788.53589	790.03034	0.98567	

SWISSCHEESE 2

ICASE = 2 ITERATION			0 INPUT TMAXWALL= 1960.00 ZONE 3					
T01/R P00/PS1 Q/MW QB/B/HCUFT XL/FT RAD/FT			HYD D/FWALL TH/FT EQV N					
1060.0	800.0	0.6100	562E 07	1.308	0.3249	0.008950	0.00716	580.
WDOT/LR/H.G/LB/HSF			VOID F	COOL FR	A	B	C	D
0.109E 05	0.300E 06	0.145	0.129	0.7730	2.6854	-3.6542	0.3988	
FUEL FRACTION			TUBE CLAD FR	COOLANT VOID	ZONE OUTER RAD.			
0.736	0.030	0.095	0.529					
XNRE = 0.19121E 05								
ZETA =	0.0	.1	.2	.3	.4	.5	.6	
T0 =	1060.0	1123.8	1201.6	1288.5	1379.7	1470.6	1556.7	
TW =	1104.9	1442.5	1592.7	1720.0	1822.0	1895.5	1941.5	
TMAX =	1119.6	1462.6	1616.6	1746.3	1849.3	1922.3	1966.3	
ZETA =	.7	.8	.9	1.0				
T0 =	1633.8	1697.8	1744.7	1770.8				
TW =	1959.4	1947.1	1905.8	1832.0				
TMAX =	1980.9	1964.0	1917.0	1836.3				
IN MACH			EXIT MACH	P01	PS1	PS2	P02	P03/P00
0.04299	0.04698	798.15749	796.92939	788.18029	789.63132	0.98523		

SWISSCHEESE 2

ICASE = 2 ITERATION 0 INPUT TMAXWALL= 1960.00 ZONE 4							
T01/R P00/PSI Q/MW QP/B/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N							
1060.0	800.0	0.3430	520E 07	1.308	0.2532	0.008950	0.000716 352.
WDOT/LB/H,G/LB/HSF VOID F COOL FR A B C D							
0.610E 04	0.275E 06	0.145	0.129	0.7730	2.6854	3.6542	0.3988
FUEL FRACTION TUBE CLAD FR COOLANT VOID ZONE OUTER RAD							
0.736	0.030	0.095	0.596				
XNRE = 0.17551E 05							
ZETA =	0.0	.1	.2	.3	.4	.5	.6
T0 =	1060.0	1124.3	1202.6	1290.2	1382.0	1473.5	1560.3
TW =	1104.4	1439.4	1589.3	1716.7	1819.2	1893.5	1940.6
TMAX =	1118.0	1458.0	1611.4	1741.1	1844.4	1918.3	1963.5
ZETA =	.7	.8	.9	1.0			
T0 =	1637.9	1702.3	1749.5	1775.8			
TW =	1959.8	1948.8	1908.9	1836.4			
TMAX =	1979.7	1964.5	1919.2	1840.4			
IN MACH EXIT MACH P01 PS1 PS2 P02 P03/P00							
0.04148	0.04585	798.28349	797.13966	788.45454	789.83682	0.98557	

SWISSCHEESE 2

ICASE = 2 ITERATION 0 INPUT TMAXWALL = 1960.00 ZONE 5									
T01/R P00/PS1 Q/MW OR/B/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N									
1060.0	800.0	0.0960	530E 07	1.308	0.1814	0.008950	0.000716	95.	
WDOT/LB/H,G/LB/HSF VOID F COOL FR A B C D									
0.171E 04	0.287E 06	0.145	0.129	0.7730	2.6854	-3.6542	0.3988		
FUEL FRACTION TUBE CLAD FR COOLANT VOID ZONE OUTER RAD									
0.736	0.030	0.095	0.612						
XNRE = 0.18299E 05									
ZETA =	0.0	.1	.2	.3	.4	.5	.6		
T0 =	1060.0	123.9	1201.8	1288.8	1380.1	1471.1	1557.3		
TW =	1104.6	1439.8	1589.5	1716.5	1818.5	1892.3	1938.7		
TMAX =	1118.6	1459.1	1612.4	1741.7	1844.6	1917.9	1962.5		
ZETA =	.7	.8	.9	1.0					
T0 =	1634.4	1698.5	1745.4	1771.5					
TW =	1957.2	1945.7	1905.2	1832.3					
TMAX =	1977.9	1961.9	1915.9	1836.4					
IN MACH EXIT MACH P01 PS1 PS2 P02 P03/P00									
0.04223	0.04640	798.22193	797.03692	788.31321	789.72871	0.98539			

SWISSCHEESE 2

ICASE = 2 ITERATION 0 INPUT TMAXWALL= 1960.00 ZONE 6									
T01/R P00/PSI Q/MW QR/B/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N									
1060.0	800.0	0.1050	5.77E 07	1.308	0.1327	0.008950	0.000716	97.	
WDOT/LB/H,G/LB/HSF VOID F COOL FR A B C D									
0.186E 04	0.306E 06	0.145	0.129	0.7730	2.6854	-3.6542	0.3988		
FUEL FRACTION TUBE CLAD FR COOLANT VOID ZONE OUTER RAD									
0.736	0.030	0.095	0.629						
XNRE = 0.19518E 05									
ZETA =	0.0	.1	.2	.3	.4	.5	.6		
T0 =	1060.0	1124.1	1202.3	1289.5	1381.1	1472.4	1558.9		
TW =	1105.4	1445.9	1597.2	1725.3	1827.7	1901.3	1947.2		
TMAX =	1120.4	1466.5	1621.7	1752.3	1855.7	1928.8	1972.7		
ZETA =	.7	.8	.9	1.0					
T0 =	1636.4	1700.6	1747.7	1773.9					
TW =	1964.9	1952.1	1910.2	1835.7					
TMAX =	1987.0	1969.5	1921.7	1840.1					
IN MACH EXIT MACH P01 PS1 PS2 P02 P03/P00									
0.04335	0.04727	798.12683	796.87823	788.11440	789.58306	0.98514			

SWISSCHEESE 2

ICASE = 2 ITERATION 0 INPUT TMAXWALL= 1960.00 ZONE 7							
T01/R P00/PSI Q/MW QR/R/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N							
1060.0	800.0	0.1190.641E 07	1.308	0.1349	0.009210.000714	100.	
WDOT/LB/H.G/LB/HSF VOID F COOL FR A B C D							
0.218E 04	0.327E 06	0.153	0.137	0.7730	2.6854	-3.6542	0.3988
FUEL FRACTION TUBE CLAD FR COOLANT VOID ZONE OUTER RAD							
0.730	0.031	0.100	0.645				
XNRE = 0.21516E 05							
ZETA =	0.0	.1	.2	.3	.4	.5	.6
T0 =	1060.0	1122.6	1198.9	1284.1	1373.5	1462.6	1547.0
TW =	1105.8	1451.9	1603.7	1731.0	1831.7	1903.1	1945.8
TMAX =	1121.9	1474.0	1630.0	1760.0	1861.8	1932.5	1973.1
ZETA =	.7	.8	.9	1.0			
T0 =	1622.6	1685.4	1731.3	1756.9			
TW =	1959.9	1943.3	1898.0	1820.2			
TMAX =	1983.6	1961.9	1910.2	1824.9			
IN MACH EXIT MACH P01 PS1 PS2 P02 P03/P00							
0.04440	0.04802	798.03497	796.72491	788.17611	789.69176	0.98522	

SWISSCHEESE 2

```

ICASE =      2  ITERATION      0  INPUT TMAXWALL= 1960.00  ZONE      8
T01/R  P00/PSI  Q/MW  QR/B/HCUFT  XL/FT  RAD/FT  HYD D/FWALL  TH/FT  EQV N

```

1060.0 800.0 0,1720,940F 07 1.308 0.1362 0.010160.000710 102.

WDOT/LB/H,G/LB/HSF	VOID F	COOL FR	A	B	C	D
--------------------	--------	---------	---	---	---	---

0.336E 04 0.406E 06 0.182 0.173 0.7730 2.6854 -3.6542 0.3988

FUEL FRACTION TUBE CLAD FR COOLANT VOID ZONE OUTER RAD

0.706 0.034 0.122 0.661

XNRE = 0.29779E 05

ZETA = 0.0 .1 .2 .3 .4 .5 .6

T0	=	1060.0	1118.5	1189.9	1269.7	1353.3	1436.7	1515.7
----	---	--------	--------	--------	--------	--------	--------	--------

TW	=	1108.1	1481.8	1639.4	1766.8	1863.6	1928.1	1960.3
----	---	--------	--------	--------	--------	--------	--------	--------

TMAX =	1128.6	1510.1	1673.2	1803.9	1902.0	1965.7	1995.1
--------	--------	--------	--------	--------	--------	--------	--------

ZETA = .7 .8 .9 1.0

T0	=	1586,4	1645,1	1688,2	1712,1
----	---	--------	--------	--------	--------

TW	=	1962.0	1933.0	1872.8	1782.0
----	---	--------	--------	--------	--------

TMAX = 1992.1 1956.7 1888.3 1788.0

IN MACH	EXIT MACH	P01	PS1	PS2	P02	P03/P00
---------	-----------	-----	-----	-----	-----	---------

0.04745 0.05225 797.75851 796.26359 788.11448 789.90907 0.98514
COOLANT FLOW LB/SEC 12.0632 POWER,MW 2.3775

ERROR TRACE. CALLS IN REVERSE ORDER.

CALLING ROUTINE

LINE OR
LINE NO.

ABSOLUTE
LOCATION

FXP3

00036

23273

DECK 2

00071

03352.

SWISSCHEESE 2

ICASE = 3		ITERATION 0		INPUT TMAXWALL= 1960.00		ZONE 0	
T01/R	P00/PSI	Q/MW	QR/R/HCUFT	XL/FT	RAD/FT	HYD D/FWALL	TH/FT EQV N
1060.0	800.0	2.4440.940E 07	1.308	0.6140	0.005940.000666	3500.	
WDOT/LB/H.G/LB/HSF		VOID F		COOL FR	A	B	C D
0.446E 05	0.406E 06	0.152	0.173	0.7730	2.6854	-3.6542	0.3988
FUEL FRACTION		TUBE CLAD FR		COOLANT VOID		ZONE OUTER RAD	
0.706		0.034		0.122		0.661	
XNRE = 0.29779E 05							
ZETA =	0.0	.1	.2	.3	.4	.5	.6
T0 =	1060.0	1118.5	1189.9	1269.7	1353.3	1436.7	1515.7
TW =	1108.1	1481.8	1639.4	1766.8	1863.6	1928.1	1960.3
TMAX =	1125.4	1505.7	1668.0	1798.1	1896.1	1959.9	1989.7
ZETA =	.7	.8	.9	1.0			
T0 =	1586.4	1645.1	1688.2	1712.1			
TW =	1962.0	1933.0	1872.8	1782.0			
TMAX =	1987.5	1953.1	1885.9	1787.0			
IN MACH		EXIT MACH		P01	PS1	PS2	P02 P03/P00
0.04745		0.05225		797.75851	796.26359	788.11448	789.90907 0.95000

SWISSCHEESE 2

ICASE = 3 ITERATION 0 INPUT TMAXWALL= 1960.00 ZONE 1							
T01/R P00/PSI Q/MW GR/B/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N							
1060.0	800.0	0.4640	7.14E 07	1.308	0.2456	0.005430	0.000748 560.
WDOT/LB/H.G/LB/HSF VOID F COOL FR A B C D							
0.731E 04	0.563E 06	0.106	0.077	0.7730	2.6854	-3.6542	0.3988
FUEL FRACTION TUBE CLAD FR COOLANT VOID ZONE OUTER RAD							
0.768	0.032	0.059	0.265				
XNRE = 0.21328E 05							
ZETA =	0.0	.1	.2	.3	.4	.5	.6
T0 =	1060.0	1132.6	1221.1	1319.9	1423.6	1527.0	1624.9
TW =	1100.9	1359.8	1494.5	1618.8	1728.5	1819.3	1888.8
TMAX =	1115.4	1379.4	1517.7	1644.5	1755.1	1845.6	1913.2
ZETA =	.7	.8	.9	1.0			
T0 =	1712.6	1785.3	1838.7	1868.3			
TW =	1937.0	1958.9	1951.5	1911.5			
TMAX =	1958.2	1975.7	1962.6	1915.9			
IN MACH	EXIT MACH	P01	PS1	PS2	P02	P03/P00	
0.05973	0.08486	796.47158	794.10786	759.98095	764.55029	0.94999	

SWISSCHEESE 2

ICASE = 3 ITERATION 0 INPUT TMAXWALL= 1960.00 ZONE 2							
T01/R P00/PS1 Q/MW QB/B/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N							
1060.0	800.0	0.5320	651E 07	1.308	0.2746	0.005210	0.00751 700.
WDOT/LB/H,G/LB/HSF VOID F COOL FR A B C D							
0.826E 04	0.553E 06	0.099	0.070	0.7730	2.6854	3.6542	0.3988
FUEL FRACTION TUBE CLAD FR COOLANT VOID ZONE OUTER RAD							
0.773	0.031	0.054	0.398				
XNRE = 0.20059E 05							
ZETA =	0.0	.1	.2	.3	.4	.5	.6
T0 =	1060.0	1133.6	1223.4	1323.7	1428.9	1533.8	1633.2
TW =	1100.2	1352.1	1485.9	1610.5	1721.3	1814.1	1886.3
TMAX =	1113.9	1370.7	1508.0	1634.9	1746.6	1839.1	1909.6
ZETA = .7 .8 .9 1.0							
T0 =	1722.1	1795.9	1850.0	1880.1			
TW =	1937.5	1962.6	1958.5	1921.7			
TMAX =	1957.7	1978.6	1969.0	1925.8			
IN MACH EXIT MACH P01 PS1 PS2 P02 P03/P00							
0.05813	0.08396	790.65559	794.41649	759.64679	764.11776	0.94957	

SWISSCHEESE 2

ICASE = 3 ITERATION 0 INPUT TMAXWALL= 1960.00 ZONE 3							
T01/R P00/PSI Q/MW QR/B/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N							
1060.0	800.0	0.6490	5.62E 07	1.308	0.3249	0.004940	0.000756 980.
WDOT/LB/H,G/LB/HSF VOID F COOL FR A B C D							
0.997E 04	0.530E 06	0.091	0.062	0.7730	2.6854	-3.6542	0.3988
FUEL FRACTION TUBE CLAD FR COOLANT VOID ZONE OUTER RAD							
0.780	0.030	0.049	0.530				
XNRE = 0.18182E 05							
ZETA =	0.0	.1	.2	.3	.4	.5	.6
T0 =	1060.0	1134.4	1225.3	1326.7	1433.1	1539.1	1639.6
TW =	1098.7	1339.6	1471.4	1595.4	1706.9	1801.7	1877.0
TMAX =	1111.2	1356.5	1491.4	1617.5	1729.8	1824.4	1898.1
ZETA =	.7	.8	.9	1.0			
T0 =	1729.6	1804.2	1859.0	1889.4			
TW =	1931.6	1960.7	1960.8	1928.5			
TMAX =	1950.0	1975.2	1970.4	1932.2			
IN MACH EXIT MACH P01 PS1 PS2 P02 P03/P00							
0.05401	0.08119	797.10552	795.17096	760.03735	764.22015	0.95006	

SWISSCHEESE 2

ICASE = 3 ITERATION 0 INPUT TMAXWALL= 1960.00 ZONE 4							
T01/R P00/PSI Q/MW QR/B/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N							
1060.0	800.0	0.3660	520E 07	1.308	0.2532	0.0048	0.000758 595.
WDOT/LB/H.G/LB/HSF		VOID F COOL FR		A	B	C	D
0.561E 04	0.521E 06	0.087	0.059	0.7730	2.6854	3.6542	0.3988
FUEL FRACTION		TUBE CLAD FR		COOLANT VOID		ZONE OUTER RAD	
0.783		0.029		0.046		0.596	
XNRE = 0.17350E 05							
ZETA =	0.0	.1	.2	.3	.4	.5	.6
T0 =	1060.0	1134.6	1225.7	1327.3	1434.0	1540.3	1641.0
TW =	1097.8	1332.4	1462.6	1586.0	1697.5	1791.8	1869.6
TMAX =	1109.7	1348.5	1481.6	1607.0	1719.3	1813.3	1889.7
ZETA =	.7	.8	.9	1.0			
T0 =	1731.2	1806.0	1860.9	1891.4			
TW =	1925.8	1956.8	1959.1	1929.1			
TMAX =	1943.2	1970.6	1968.2	1932.6			
IN MACH		EXIT MACH		P01	PS1	PS2	P02 P03/P00
0.05229		0.08002		797.28383	795.46987	760.00524	764.06818 0.95001

SWISSCHEESE 2

ICASE = 3 ITERATION 0 INPUT TMAXWALL= 1960.00 ZONE 5									
T01/R P00/PSI Q/MW QR/R/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N									
1060.0	800.0	0.1020	538E 07	1.308	0.1314	0.004870	0.000757	160.	
WDOT/LB/H,G/LB/HSF VOID F COOL FR A B C D									
0.157E 04	0.525E 06	0.089	0.060	0.7730	2.6854	-3.6542	0.3988		
FUEL FRACTION TUBE CLAD FR COOLANT VOID ZONE OUTER RAD									
0.782	0.029	0.047	0.613						
XNRE = 0.17754E 05									
ZETA =	0.0	.1	.2	.3	.4	.5	.6		
T0 =	1060.0	1134.4	1225.1	1326.5	1432.8	1538.8	1639.2		
TW =	1098.1	1335.2	1465.8	1589.2	1700.5	1794.3	1871.4		
TMAX =	1110.3	1351.6	1485.3	1610.7	1722.8	1816.3	1891.9		
ZETA =	.7	.8	.9	1.0					
T0 =	1729.1	1803.7	1858.4	1888.8					
TW =	1926.7	1956.8	1958.1	1927.0					
TMAX =	1944.6	1970.9	1967.4	1930.7					
IN MACH EXIT MACH P01 PS1 PS2 P02 P03/P00									
0.05318	0.08061	797.19154	795.31515	759.95194	764.07447	0.94995			

SWISSCHEESE 2

ICASE = 3 ITERATION 0 INPUT TMAXWALL= 1960.00 ZONE 6									
T01/R P00/PSI Q/MW QR/B/HCUFT XL/FT RAD/FT HYD D/FWALL TH/FT EQV N									
1060.0	800.0	0.1110	5.77E 07	1.308	0.1327	0.004990	0.000755	164.	
WDOT/LB/H,G/LB/HSF VOID F COOL FR A B C D									
0.171E 04	0.535E 06	0.093	0.064	0.7730	2.6854	-3.6542	0.3988		
FUEL FRACTION TUBE CLAD FR COOLANT VOID ZONE OUTER RAD									
0.779	0.030	0.050	0.630						
XNRE = 0.18544E 05									
ZETA =	0.0	.1	.2	.3	.4	.5	.6		
T0 =	1060.0	1134.1	1224.6	1325.5	1431.5	1537.1	1637.1		
TW =	1098.9	1341.2	1473.0	1596.9	1707.9	1802.2	1876.8		
TMAX =	1111.6	1358.4	1493.4	1619.3	1731.3	1825.3	1898.2		
ZETA =	.7	.8	.9	1.0					
T0 =	1726.7	1801.0	1855.5	1885.8					
TW =	1930.7	1959.0	1958.4	1925.3					
TMAX =	1949.3	1973.7	1968.1	1929.1					
IN MACH EXIT MACH P01 PS1 PS2 P02 P03/P00									
0.05492	0.08178	797.00893	795.00900	759.83336	764.07645	0.94980			

SWISSCHEESE 2

ICASE = 3 ITERATION				0 INPUT TMAXWALL= 1960.00 ZONE 7			
T01/R P00/PSI Q/MW QR/B/HCUFT XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N							
1060.0	800.0	0.1270	.641E 07	1.308	0.1349	0.005190	.000751 169.
WDOT/LB/H,G/LB/HSF		VOID F	COOL FR	A	B	C	D
0.197E 04	0.550E 06	0.099	0.069	0.7730	2.6854	-3.6542	0.3988
FUEL FRACTION		TUBE CLAD FR	COOLANT VOID	ZONE OUTER RAD			
0.774		0.031	0.054	0.646			
XNRE = 0.19843E 05							
ZETA =	0.0	.1	.2	.3	.4	.5	.6
T0 =	1060.0	1133.7	1223.5	1323.9	1429.2	1534.1	1633.6
TW =	1100.0	1350.9	1484.5	1609.1	1719.8	1812.8	1885.3
TMAX =	1113.6	1369.3	1506.4	1633.2	1744.9	1837.5	1908.3
ZETA =	.7	.8	.9	1.0			
T0 =	1722.6	1796.4	1850.6	1880.7			
TW =	1936.7	1962.2	1958.4	1922.0			
TMAX =	1956.7	1978.0	1968.9	1926.1			
IN MACH		EXIT MACH	P01	PS1	PS2	P02	P03/P00
0.05750		0.08350	796.72579	794.53422	759.94402	764.36831	0.94994

ICASE =		3 ITERATION		0 INPUT TMAXWALL=		1960.00 ZONE		8	
T01/R		P00/PSI		Q/MW		QR/B/HCUFT		XL/FT RAD/FT, HYD D/FWALL TH/FT EQV N	
1060.0		800.0		0.1830.940E 07		1.308		0.1362 0.006070.000739 172.	
WDOT/LB/H.G/LB/HSF		VOID F COOL FR		A		B		C D	
0.299E 04		0.600E 06		0.127		0.098		0.7730 2.6854 -3.6542 0.3988	
FUEL FRACTION		TUBE CLAD FR		COOLANT VOID		ZONE OUTER RAD			
0.751		0.036		0.073		0.662			
XNRE =		0.25552E 05							
ZETA =		0.0		.1		.2		.3 .4 .5 .6	
T0 =		1060.0		1130.1		1215.6		1311.1 1411.3 1511.2 1605.8	
TW =		1103.5		1384.6		1523.2		1648.0 1755.4 1841.0 1904.8	
TMAX =		1120.4		1407.6		1550.5		1678.1 1786.6 1871.8 1933.3	
ZETA =		.7		.8		.9		1.0	
T0 =		1690.6		1760.8		1812.4		1841.1	
TW =		1943.1		1956.0		1939.0		1889.4	
TMAX =		1967.9		1975.6		1951.9		1894.4	
IN MACH		EXIT MACH		P01		PS1		PS2 P02 P03/P00	
0.06544		0.08845		795.77844		792.94509		759.85634 764.82126 0.94983	
COOLANT FLOW LB/SEC		10.9395		POWER, MW		2.5336			

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BNWL-147

APPENDIXES

APPENDIX A
SWISSCHEESE LOGIC DIAGRAM

APPENDIX B

SWISSCHEESE FORTRAN IV LISTING

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$ IDENT CUS433 XDC C.E.LEACH 328 300 SWISS CHEESE 2
$JOB C.E.LEACH SWISS CHEESE 2
$EXECUTE IBJOB
$IBJOB DLOGIC,MAP
$IBFTC DECK2 FULIST,REF
C SWISSCHEESE 2
C C.E. LEACH 328 300
  DIMENSION XUB(32),XT(32),XKB(32),XCP(32),XGAMMA(32),XXM(32),
  1XASTAR(32),ALPHI(11), XZKM(32),CP2(22),TO(11),H(22),TW(11),
  2XXM2(22),TMAX(11),XXUB(11),XXNRE(32),XXF1(32),TDIFR(21),DHH(21),
  3 RZ(11),RP(11),WDOTS(11),POD(21),WDOTZ(21),PWRB(11),REQ(11),WDOTSS
  4(11)
  COMMON TW,XT,XZKM,TMAX,RAD,EN,TW1,QB,A,B,C,D,DH
100 CONTINUE
110 READ (2,1010)(XT(KK),KK=1,32)
111 READ (2,1010)(XUB(KK),KK=1,32)
112 READ (2,1010)(XKB(JJ),JJ=1,32)
114 READ (2,1010)(XCP(LL),LL=1,32)
116 READ (2,1010)(XGAMMA(MM),MM=1,32)
117 READ (2,1010)(XASTAR(NN),NN=1,32)
118 READ (2,1010)(XXM(NN), NN=1,32)
123 READ(2,1010)(XXNRE(MN),MN=1,32)
121 READ(2,1010)(XXF1(MN),MN=1,32)
122 READ (2,1010)(XZKM(KL),KL=1,32)
  ICASE = 0
124 CONTINUE
130 READ (2,1020)T01,P00,Q,XL,RAD,ALPHA,DH,XW,WDOT,QB1,ZETA1
  1,QB2,ZETA2,QB3,ZETA3,QB4,ZETA4,EXP,XMW,E,XL1,VKL01,VKL23,TMAXCI,VF
  2,VFF,EN,P03P00
132 CONTINUE
C END PROGRAM WHEN ZERO OR BLANK ENTERED FOR RAD
134 IF(RAD)2000,2000,138
138 CONTINUE
  READ(2,1022)(RP(I),RZ(I),I=1,9)
  READ(2,1010)(ALPHI(I),I=1,8)
  DO 4002 IZ=1,9
    REQ(IZ) = (RZ(IZ+1)**2.-RZ(IZ)**2.)/RAD**2.
    WDOTS(IZ) = WDOT*REQ(IZ)
4002 CONTINUE
C SET INDECES TO ZERO
  ICASE = ICASE + 1
3000 N1 = 0
  WDOTT = 0.
  PSR = 0.
  IZ = 0
  IZ2 = 0
  PWR = 0.
  XW1 = XW

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C      SOLVE FOR CONSTANTS A,B,C,D
      ZETA12 = ZETA1**2.0
      ZETA13 = ZETA1**3.0
      ZETA22 = ZETA2**2.0
      ZETA23 = ZETA2**3.0
      ZETA32 = ZETA3**2.0
      ZETA33 = ZETA3**3.0
      ZETA42 = ZETA4**2.0
      ZETA43 = ZETA4**3.0
      DELTA = (ZETA2 - ZETA1)* (ZETA3 - ZETA1)* (ZETA4 - ZETA1)* ((ZETA42 +
1 ZETA4*ZETA1 + ZETA12) * (ZETA3 - ZETA2) + (ZETA32 + ZETA3*ZETA1 + ZETA12
2) * (ZETA2 - ZETA4) + (ZETA22 + ZETA2*ZETA1 + ZETA12) * (ZETA4 - ZETA3))
      B = ((QB2 - QB1)*(ZETA3 - ZETA1)*(ZETA4 - ZETA1) * ((ZETA3 + ZETA1)*(ZET
1A42 + ZETA4*ZETA1 + ZETA12) - (ZETA4 + ZETA1) * (ZETA32 + ZETA3*ZETA1
2 + ZETA12)) + (QB4 - QB1)*(ZETA3 - ZETA1)*(ZETA2 - ZETA1) * ((ZETA2 +
3 ZETA1) * (ZETA32 + ZETA3*ZETA1 + ZETA12) - (ZETA3 + ZETA1)*(ZETA2
42 + ZETA2*ZETA1 + ZETA12)) + (QB3 - QB1)*(ZETA4 - ZETA1)*(ZETA2 -
5 ZETA1) * ((ZETA4 + ZETA1)* (ZETA22 + ZETA2*ZETA1 + ZETA12) - (
6 ZETA2 + ZETA1) * (ZETA42 + ZETA4 *ZETA1 + ZETA12)))/DELTA
      C = ((ZETA2 - ZETA1)* (QB3 - QB1) * (ZETA43 - ZETA13) + (QB2 - QB1)*
1 (ZETA33 - ZETA13)*(ZETA4 - ZETA1) + (ZETA23 - ZETA13)*(ZETA3 - ZETA1
2) * (QB4 - QB1) - (ZETA4 - ZETA1) * (QB3 - QB1) * (ZETA23 - ZETA13)
3 - (QB4 - QB1)*(ZETA33 - ZETA13) * (ZETA2 - ZETA1) - (ZETA43 - ZETA13
4) * (ZETA3 - ZETA1)*(QB2 - QB1))/DELTA
      D = ((QB4 - QB1) - B*(ZETA4 - ZETA1) - C*(ZETA42 - ZETA12))/(ZETA43
1 - ZETA13)
      A = QB1 - B*ZETA1 - C*ZETA12 - D*ZETA13
      IF(P03P00)3001,3001,3200
3001 CONTINUE
      I=0
      J=0
      K=0
      L=0
      XW = XW1 + XW1**2./DH
C      CALCULATE AUXILIARY EQUATIONS
      IF(PSR)140,140,142
140  PI = 3.14159
      XNP = ALPHA * PI * RAD**2.0/(.25*Dh + XW)
      G = WDOT * (1.0 + 4.0*XW/DH)/(ALPHA * PI * RAD**2.0)
      AFU = PI * RAD**2.0 * (1.0 - ALPHA)
      XI = ALPHA/((1.0 - ALPHA)*(1.0 + 4.0*XW/DH))
      AFL = ALPHA * PI * RAD **2.0 /(1.0 + 4.0*XW/DH)
      QB = 3.413E+6 * Q/((XL *PI* RAD**2.0)* (1.0 - ALPHA))
      R = 1545.0/XMW
      EN = 4.0 *AFL/(PI *DH**2.0)
      GO TO 150
142  CONTINUE
      ENZ = ENS*REQ(IZ)

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EN = ENZ
AFL = .25*ENZ*PI*DH**2.
RAD = SQRT(RZ(IJ+1)**2. - RZ(IJ)**2.)
ALPHA = AFL*(1.+4.*XW/DH)/(PI*RAD**2.)
XNP = ALPHA * PI * RAD**2.0/(.25*DH +XW)
G = WDOT*(1.0 + 4.0*XW/DH)/(ALPHA * PI *RAD** 2.0)
AFU = PI * RAD**2.0 *(1.0 -ALPHA)
XI = ALPHA/((1.0 -ALPHA)*(1.0 +4.0*XW/DH))
QB = QBS*RP(IJ+1)/(1.-ALPHI(IJ))
Q = QB*AFU*XL/3.413E+6
150 CONTINUE
ALPHAT = ALPHA/(1.+DH/(4.*XW))
ALPHAC = ALPHA-ALPHAT
ALPHV = VF / (1./ALPHA- VFF)
ALPHC = ALPHAC*(VF+VFF*ALPHV)
ALPHT = ALPHAT*(VF+VFF*ALPHV)
ALPFU = (1.- ALPHA)*(VF+VFF*ALPHV)
ERAD = RZ(IJ+1)/(SQRT(VF+VFF*ALPHV))
C TABLE LOOK UP FOR SPECIFIC HEAT
IJ =1
170 IF(T01-XT(IJ))176,174,172
172 IJ =IJ +1
GO TO 170
174 CP1 =XCP(IJ)
XXUB(1)=XUB(IJ)
GO TO 178
176 TINT1= (T01 -XT(IJ-1))/(XT(IJ)-XT(IJ-1))
CP1 = XCP(IJ-1) +(XCP(IJ) - XCP(IJ-1))* TINT1
XXUB(1)=XUB(IJ-1)+(XUB(IJ)-XUB(IJ-1))*TINT1
178 CP =CP1
IX =1
EE90 = QB*XL/(G*XI)
EE80 = (A +B/2.0 +C/3.0 + D/4.0)
180 CONTINUE
C CALCULATE T02
EE91 = EE90/CP
T02 = T01 + EE91 *EE80
184 CONTINUE
IK = IJ
C TABLE LOOK UP FOR CP2
186 IF(T02 -XT(IK))192,190,188
188 IK = IK +1
GO TO 186
190 CP2(IX) = XCP(IK)
GO TO 193
192 TINT2 =(T02 - XT(IK-1))/(XT(IK)-XT(IK -1))
CP2(IX) = XCP(IK -1) +(XCP(IK) -XCP(IK-1))* TINT2
193 IF (IX-1)1500,198,194

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194 IF( ABS((CP2(IX)-CP2(IX-1))/CP2(IX)) -E)200,200,198
198 CP =(CP1 + CP2(IX))/2.0
-----IX=IX+1-----
IF(IX -20 )199,199,1510
199 GO TO 180
200 CONTINUE
C CALCULATE TO AT 11 PLACES USE AVG VALUE OF CP
ZETA = 0.0
EE91 = 2.*EE90/(CP1 + CP2(IX))
I = 1
204 CONTINUE
TO(I) = TO1 + EE91 * ( A*ZETA + B*ZETA**2.0/2.0 +C*ZETA**3.0/3.
10 + D* ZETA **4.0/4.0)
ZETA = ZETA +.1
I = I +1
IF ( ZETA -1.05)204,205,205
205 ZETA = 0.0
J = 1
206 CONTINUE
C H/HAVG LOOK UP
ZETA = ZETA +.1
XXL =(XL/DH)* ZETA + XL1/DH
207 IF (ZETA -1.05)208,246,246
208 XH=1.+(1./XXL)**.7
C CALCULATE H
216 CONTINUE
J =J +1
TB = TO(J)
C PROPERITES LOOK UP
IM =1
218 IF(TB -XT(IM))224,222,220
220 IM =IM+1
GO TO 218
222 UB = XUB(IM)
ZKB= XKB(IM)
CP= XCP(IM)
GAMMA= XGAMMA(IM)
GO TO 226
224 XT Bint = (TB -XT(IM-1))/(XT(IM) - XT(IM -1))
UB = XUB(IM-1) + (XUB(IM) - XUB(IM-1)) *XT Bint
ZKB = XKB(IM-1) + (XKB(IM) - XKB(IM-1)) *XT Bint
CP = XCP(IM-1) + (XCP(IM) - XCP(IM-1)) *XT Bint
GAMMA = XGAMMA(IM-1)+(XGAMMA(IM) -XGAMMA(IM -1))*XT Bint
226 CONTINUE
XXUB(J)=UB
COE = .021* G**.8 *ZKB**.6 *CP**.4 *XH/(DH**.2 * UB**.4)
JL =1
H(JL) =COE

```

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C   CALCULATE TW AT ZETA=0,.1,.2,.3,.4,.5,.6,.7,.8,.9,1.0
230  CONTINUE
    TW(J)=AFU* QB*(A +B*ZETA +C*ZETA**2.0 + D*ZETA**3.0)/(H(JL)*XNP)
1 + TO(J)
    IF(J-2)1500,234,236
234  TW1 = AFU*QB*A*XH/(H(JL)*XNP*(1.+(DH/XL1)**.7))+TO(1)
236  TWB = TW(J)
    JL =JL+ 1
    H(JL) = COE *( TR/TWR) ** EXP
    IF(ABS((H(JL)-H(JL-1))/H(JL)) - E)206,206,240
240  IF(JL -20)230,230,1515
246  CONTINUE
    XNREAV= 2.*DH*G/(XXUB(1) + XXUB(11))
C   TABLE LOOK UP FOR ISOTHERMAL FRICTION FACTOR BASED ON BULK
C   AVERAGE TEMP.
    IM=1
500  IF(XNREAV-XXNRE(IM))506,504,502
502  IM= IM+1
    GO TO 500
504  XF= XXF1(IM)*2.
    GO TO 503
506  XF =2.*XXF1(IM-1)+2.*(XXF1(IM)-XXF1(IM-1))*(XNREAV-XXNRE(IM-1))/
1(XNRE(IM)-XXNRE(IM-1))
C   CALCULATE P02 AND M2
503  CONTINUE
    XM1G=.05
    XM1=XM1G
507  P01 = P00/(1.+GAMMA*.5*XM1**2.*VKL01*(1.+.5*(GAMMA-1.)*XM1**2.))
1 ** (GAMMA/(1.-GAMMA)))
508  ASTAR1 = ( 2.0/(GAMMA +1.))**((GAMMA +1.)/(2.*(GAMMA-1.)))*
1 3600.*144.*P01 * SQRT( GAMMA *32.196/(R* T01)) / G
    K =1
248  IF( ASTAR1 -XASTAR(K))256,254,250
250  K = K +1
    GO TO 248
254  XM1 = XXM(K)
    GO TO 260
256  XM1 = XXM(K-1) + (XXM(K) - XXM(K-1))*(ASTAR1 - XASTAR(K-1))/
1 (XASTAR(K) -XASTAR(K-1))
260  CONTINUE
    IF(ABS(1.-XM1G/XM1) -E)261,261,265
265  XM1G =XM1
    GO TO 507
261  CONTINUE
    EE95 =.5* GAMMA * (T0(11)/T01 -1. + 4.*XF* XL * ( 1.+ QB*XL
1 * (A + B/3. + C/6. + D/ 10.)/(2. * G * XI * CP * T01)) /DH)
    XM2 = XM1
262  CONTINUE

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```

      L = 1
      XXM2(L) = XM1
270  CONTINUE
      PO2PO1 = SQRT( (1. - XM1**2. * EE95) / (1. + XM2**2. * EE95 * T01 /
1    TO(11)))
      ASTAR2 = ASTAR1 * PO2PO1 * SQRT( T01 / TO(11))
      L = L + 1
      K = 1
274  IF (ASTAR2 - XASTAR(K)) 280, 278, 276
276  K = K + 1
      GO TO 274
278  XXM2(L) = XXM(K)
      GO TO 283
280  XXM2(L) = XXM(K-1) + (XXM(K) - XXM(K-1)) * (ASTAR2 - XASTAR(K-1)) /
1    (XASTAR(K) - XASTAR(K-1))
283  CONTINUE
      IF (ABS((XXM2(L) - XXM2(L-1)) / XXM2(L)) - E) 286, 286, 284
284  XM2 = XXM2(L)
      IF (L - 20) 270, 270, 1520
286  CONTINUE
      XM2 = XXM2(L)
      PO2PO1 = SQRT( (1. - XM1**2. * EE95) / (1. + XM2**2. * EE95 * T01 / TO(11)
1    ))
C    CALCULATE STATIC PRESSURE, TEMP, ETC.
      PS1 = P01 * (1. + ((GAMMA - 1.) / 2.) * XM1 **2.) ** (GAMMA / (1. - GAMMA))
      P02 = PO2PO1 * P01
      PS2 = PO2PO1 * P01 * (1. + ((GAMMA - 1.) / 2.) * XM2**2.) ** (GAMMA / (
1    1. - GAMMA))
      P03 = (1. - .5 * GAMMA * XM2**2. * VKL23 * PS2 / P02) * P02
      P03P00 = P03 / P00
      IF (PSR) 3010, 3010, 3015
3015 IF (ABS(1. - P03P00 / PSR) - E * .1) 4605, 3020, 3020
3010 TMAXC = AMAX1(TW(1), TW(2), TW(3), TW(4), TW(5), TW(6), TW(7), TW(8), TW(9
1    ), TW(10), TW(11))
      IF (ABS(1. - TMAXC / TMAXCI) - E * .5) 3005, 3020, 3020
3020 N1 = N1 + 1
      IT = 0
      POD(N1) = PSR - P03P00
      TDIFR(N1) = TMAXCI - TMAXC
      IF (N1 - 20) 3030, 3030, 3025
3025 PRINT 15111, ICASE, IZ
      PRINT 3026, (TDIFR(N1), N1 = 1, 20)
3026 FORMAT(58H COULD NOT CONVERGE ON MAX TEMP - TEMP DIFFERENCES FOLL
1    OW // 10F8.3 / 10F8.3 //)
      GO TO 287
3030 CONTINUE
3032 IF (N1 - 1) 1500, 3035, 3070
3035 DHH(1) = DH

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      IF(PSR) 3037,3037,3039
3037 IF(TDIFR(N1))3060,3005,3040
3039 IF(POD(N1))3060,4605,3040
3040 DHH(2) = DH*1.005
      DH = DHH(2)
      GO TO 3001
3060 DHH(2) = DH*.995
      DH = DHH(2)
      GO TO 3001
3070 CONTINUE
      DHH(N1) = DH
      IF(PSR)3072,3072,3074
3072 DH = DHH(N1-1) - ( DHH(N1-1)-DHH(N1))/(1.-TDIFR(N1)/TDIFR(N1-1))
      GO TO 3001
3074 DH = DHH(N1)-(DHH(N1)-DHH(N1-1))/(1.-POD(N1-1)/POD(N1))
      GO TO 3001
3005 CONTINUE
      IF(PSR)3200,3200,3220
3200 PSR = P03P00
      QBS = Q*3.413E+6/(PI*RAD**2.*XL)
      ENS = EN
3220 CONTINUE
      IF(ABS(1.-P03P00/PSR) - E*.1) 287,3015,3015
C      CALCULATE CORE MAX TEMP INVERTED MATRIX
287 CONTINUE
      CALL FUTEMP
350 CONTINUE
C      OUTPUT ROUTINE NEXT
360 WRITE (3,1700)
      WRITE (3,1710) ICASE,N1,TMAXCI,IZ
      WRITE (3,1100) T01,P00,Q,QB,XL,RAD,DH,XW,EN
      WRITE (3,1110) WDOT,G,ALPHA,XI,A,B,C,D
      WRITE(3,6110)
      WRITE(3,6112)ALPFU,ALPHT,ALPHC,ERAD
      WRITE (3,1755)XNREAV
      WRITE (3,1720)
      WRITE (3,1725)(T0(I),I=1,7)
      WRITE (3,1728)(TW(I),I=1,7)
      WRITE (3,1730)(TMAX(I),I=1,7)
      WRITE (3,1734)
      WRITE (3,1736)(T0(I),I=8,11)
      WRITE (3,1738)(TW(I),I=8,11)
      WRITE (3,1740)(TMAX(I),I=8,11)
      WRITE (3,1750)XM1,XM2,P01 ,PS1,PS2,P02,P03P00
      IF(IZ)364,364,362
362 WDOTSS(IZ) = WDOT/3600.
      PWRB(IZ) = Q
364 IZ = IZ + 1

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      IT = 0
      N1 = 0
      WDOT = WDOTS(IZ)
3225 IF(RZ(IZ+1)) 3226,3226,3235
3226 IF(IZ=1) 1500,124,3228
3228 DO 3229 N2 = 1,9
      WDOTT = WDOTSS(N2) + WDOT
      PWR = PWR+PWRB(N2)
3229 CONTINUE
      WRITE(3,3230)WDOTT,PWR
3230 FORMAT(21H COOLANT FLOW LB/SEC F8.4,10H POWER,MW F8.4)
      GO TO 124
1700 FORMAT(45H1 SWISSCHEESE 2 ///)
1710 FORMAT(11H ICASE = I5,11H ITERATION I5,17H INPUT TMAXWALL= F8.
      12.6H ZONE I5)
1720 FORMAT(72H ZETA = 0.0 .1 .2 .3 .4
      1 .5 .6 ///)
1725 FORMAT(9H TO = 7F9.1//)
1728 FORMAT(9H TW = 7F9.1//)
1730 FORMAT(9H TMAX = 7F9.1//)
1734 FORMAT(45H ZETA = .7 .8 .9 1.0 ///)
1736 FORMAT(9H TO = 4F9.1//)
1738 FORMAT(9H TW = 4F9.1//)
1740 FORMAT(9H TMAX = 4F9.1//)
1750 FORMAT(72H IN MACH EXIT MACH P01 PS1 PS2 P
      102 P03/P00 //F12.5,6F10.5)
1755 FORMAT(10H XNRE = E12.5//)
C DIAGNOSTICS
1500 PRINT 1501
1501 FORMAT(60H OPERATOR MACHINE GOOF NEG FIXED POINT INTEGER REFUND
      1MONEY)
      GO TO 350
1510 PRINT 1511
1511 FORMAT(46H COULD NOT FIND CP2 FOR T02 LOC 180 ,NEXT ZONE)
15110 PRINT 15111,ICASE,IZ
1512 PRINT 1513,(CP2(IX),IX=1,19)
1513 FORMAT(9H CP(IX) =/19F6.4//)
      GO TO 350
1515 PRINT 1516
1516 FORMAT(53H COULD NOT FIND HEAT TRANSFER COEFFICIENT , NEXT ZONE)
      PRINT 15111,ICASE,IZ
1517 PRINT 1518,(H(L),L=1,19)
1518 FORMAT(10H H(IL) =/19F6.1//)
      GO TO 350
1520 PRINT 1521
1521 FORMAT(39H COULD NOT FIND MACH NUMBER , NEXT ZONE)
      PRINT 15111,ICASE,IZ
1522 PRINT 1523,(XXM2(L),L=1,19)

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1523 FORMAT(10H XXM2(L)=/19F6.4/)
      GO TO 350
15111 FORMAT(10H ICASE = 15/8H ZONE = 15)
1000 FORMAT(8E9.3)
1010 FORMAT(8F9.3)
1020 FORMAT(7F8.3,2E8.3/9F8.3/9F8.3/F8.3)
1022 FORMAT(9F8.3/9F8.3)
1100 FORMAT(72H T01/R P00/PSI O/MW QB/R/HCUFT XL/FT RAD/FT, HYD D/F
1WALL TH/FT EQV N//2F8.1,F8.3,E9.3,F7.3,F8.4,F8.5,F8.6,F8.0///)
1110 FORMAT(72H WDOT/LB/H.G/LB/HSE VOID F COOL FR A B
1 C D //2E10.5,2F8.3,4F9.4///)
6110 FORMAT( 64H FUEL FRACTION
1TUBE CLAD FR COOLANT VOID ZONE OUTER RAD//)
6112 FORMAT(4(F10.3,6X)///)
C SET INDEGES TO ZERO
3235 CONTINUE
I=0
J=0
K=0
L=0
C CALCULATE AUXILIARY EQUATIONS
ENZ = ENS*REG(IZ)
EN = ENZ
AFL = .25*ENZ*PI*DH**2.
RAD = SQRT(RZ(IZ+1)**2. -RZ(IZ)**2.)
ALPHA = AFL*(1.+4.*XW/DH)/(PI*RAD**2.)
XNP = ALPHA * PI * RAD**2.0/(.25*DH +XW)
G = WDOT * (1.0 + 4.0*XW/DH)/(ALPHA * PI *RAD** 2.0)
AFU = PI * RAD**2.0 *(1.0 -ALPHA)
XI = ALPHA/((1.0 -ALPHA)*(1.0 +4.0*XW/DH))
QB = QBS*RP(IZ+1)/(1.-ALPHI(IZ))
Q = QB*AFU*XL/3.413E+6
ALPHAT = ALPHA/(1.+DH/(4.*XW))
ALPHAC = ALPHA-ALPHAT
ALPHV = VF /((1./ALPHA- VFF)
ALPHC = ALPHAC*(VF+VFF*ALPHV)
ALPHT = ALPHAT*(VF+VFF*ALPHV)
ALPFU = (1.- ALPHA)*(VF+VFF*ALPHV)
ERAD = RZ(IZ+1)/(SQRT(VF+VFF*ALPHV))
C TABLE LOOK UP FOR SPECIFIC HEAT
IJ =1
4170 IF(T01-XT(IJ))4176,4174,4172
4172 IJ =IJ +1
      GO TO 4170
4174 CP1 =XCP(IJ)
      XXUB(1)=XUB(IJ)
      GO TO 4178
4176 TINT1= (T01 -XT(IJ-1))/(XT(IJ)-XT(IJ-1))

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      CP1 = XCP(IJ-1) + (XCP(IJ) - XCP(IJ-1)) * TINT1
      XXUB(1) = XUB(IJ-1) + (XUB(IJ) - XUB(IJ-1)) * TINT1
4178 CP = CP1
      IX = 1
      EE90 = QB * XL / (G * XI)
      EE80 = (A + B/2.0 + C/3.0 + D/4.0)
4180 CONTINUE
C      CALCULATE T02
      EE91 = EE90 / CP
      T02 = T01 + EE91 * EE80
4184 CONTINUE
      IK = IJ
C      TABLE LOOK UP FOR CP2
4186 IF (T02 - XT(IK)) 4192, 4190, 4188
4188 IK = IK + 1
      GO TO 4186
4190 CP2(IK) = XCP(IK)
      GO TO 4193
4192 TINT2 = (T02 - XT(IK-1)) / (XT(IK) - XT(IK-1))
      CP2(IK) = XCP(IK-1) + (XCP(IK) - XCP(IK-1)) * TINT2
4193 IF (IX-1) 1500, 4198, 4194
4194 IF (ABS((CP2(IK) - CP2(IK-1)) / CP2(IK)) - E) 4200, 4200, 4198
4198 CP = (CP1 + CP2(IK)) / 2.0
      IX = IX + 1
      IF (IX - 20) 4199, 4199, 1510
4199 GO TO 4180
4200 CONTINUE
C      CALCULATE TO AT 11 PLACES USE AVG VALUE OF CP
      ZETA = 0.0
      EE91 = 2. * EE90 / (CP1 + CP2(IK))
      I = 1
4204 CONTINUE
      T0(I) = T01 + EE91 * (A * ZETA + B * ZETA ** 2.0 / 2.0 + C * ZETA ** 3.0 / 3.0
      + D * ZETA ** 4.0 / 4.0)
      ZETA = ZETA + .1
      I = I + 1
      IF (ZETA - 1.05) 4204, 4205, 4205
4205 ZETA = 0.0
      J = 1
4206 CONTINUE
C      H/HAVG LOOK UP
      ZETA = ZETA + .1
      XXL = (XL / DH) * ZETA + XL1 / DH
4207 IF (ZETA - 1.05) 4208, 4246, 4246
4208 XH = 1. + (1. / XXL) ** .7
C      CALCULATE H
4216 CONTINUE
      J = J + 1

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      TB = T0(J)
C     PROPERITES LOOK UP
      IM = 1
4218  IF(TB - XT(IM))4224,4222,4220
4220  IM = IM+1
      GO TO 4218
4222  UB = XUB(IM)
      ZKB = XKB(IM)
      CP = XCP(IM)
      GAMMA = XGAMMA(IM)
      GO TO 4226
4224  XTBTINT = (TB - XT(IM-1))/(XT(IM) - XT(IM-1))
      UB = XUB(IM-1) + (XUB(IM) - XUB(IM-1)) * XTBTINT
      ZKB = XKB(IM-1) + (XKB(IM) - XKB(IM-1)) * XTBTINT
      CP = XCP(IM-1) + (XCP(IM) - XCP(IM-1)) * XTBTINT
      GAMMA = XGAMMA(IM-1) + (XGAMMA(IM) - XGAMMA(IM-1)) * XTBTINT
4226  CONTINUE
      XXUB(J) = UB
      COE = .021 * G**0.8 * ZKB**0.6 * CP**0.4 * XH / (DH**0.2 * UB**0.4)
      JL = 1
      H(JL) = COE
C     CALCULATE TW AT ZETA=0,.1,.2,.3,.4,.5,.6,.7,.8,.9,1.0
4230  CONTINUE
      TW(J) = AFU * QB * (A + B * ZETA + C * ZETA**2.0 + D * ZETA**3.0) / (H(JL) * XNP)
      1 + T0(J)
      IF(J-2)1500,4234,4236
4234  TW1 = AFU * QB * A * XH / (H(JL) * XNP * (1. + (DH/XL1)**0.7)) + T0(1)
4236  TWB = TW(J)
      JL = JL + 1
      H(JL) = COE * (TB/TWB) ** EXP
      IF(ABS((H(JL) - H(JL-1))/H(JL)) - E)4206,4206,4240
4240  IF(JL - 20)4230,4230,1515
4246  CONTINUE
      XNREAV = 2. * DH * G / (XXUB(1) + XXUB(11))
C     TABLE LOOK UP FOR ISOTHERMAL FRICTION FACTOR BASED ON BULK
C     AVERAGE TEMP.
      IM = 1
4500  IF(XNREAV - XXNRE(IM))4506,4504,4502
4502  IM = IM+1
      GO TO 4500
4504  XF = XXF1(IM) * 2.
      GO TO 4503
4506  XF = 2. * XXF1(IM-1) + 2. * (XXF1(IM) - XXF1(IM-1)) * (XNREAV - XXNRE(IM-1)) /
      1 * (XXNRE(IM) - XXNRE(IM-1))
C     CALCULATE P02 AND M2
4503  CONTINUE
      XM1G = .05
      XM1 = XM1G

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4507 P01 = P00/(1.+GAMMA*.5*XM1**2.*VKL01*(1.+5*(GAMMA-1.)*XM1**2.))
1 ** (GAMMA/(1.-GAMMA)))
4508 ASTAR1 = (-2.0/(GAMMA+1.))*((GAMMA+1.)/(2.*(GAMMA-1.)))*
1 3600.*144.*P01 * SQRT( GAMMA *32.196/(R* T01)) / G
K=1
4248 IF( ASTAR1 -XASTAR(K))4256,4254,4250
4250 K = K +1
GO TO 4248
4254 XM1 = XXM(K)
GO TO 4260
4256 XM1 = XXM(K-1) + (XXM(K) - XXM(K-1))* (ASTAR1 - XASTAR(K-1))/
1 (XASTAR(K) - XASTAR(K-1))
4260 CONTINUE
IF(ABS(1.-XM1G/XM1) -E*.1)4261,4261,4265
4265 XM1G = XM1
GO TO 4507
4261 CONTINUE
EE95 =.5* GAMMA * (T0(11)/T01 -1. + 4.*XF* XL * ( 1.+ QB*XL
1 * (A + B/3. + C/6. + D/ 10.)/(2. * G * XI * CP * T01)) /DH)
XM2 = XM1
4262 CONTINUE
L = 1
XXM2(L) = XM1
4270 CONTINUE
P02P01 = SQRT( (1. -XM1**2. *EE95)/(1. + XM2**2.*EE95 *T01/
1 T0(11)))
ASTAR2 = ASTAR1 * P02P01 * SQRT( T01/T0(11))
L = L +1
K =1
4274 IF (ASTAR2 - XASTAR(K))4280,4278,4276
4276 K =K+1
GO TO 4274
4278 XXM2(L)=XXM (K)
GO TO 4283
4280 XXM2(L)= XXM(K-1) + (XXM(K) -XXM(K-1)) * (ASTAR2 -XASTAR(K-1))/
1 ( XASTAR(K) - XASTAR(K-1))
4283 CONTINUE
IF ( ABS((XXM2(L)- XXM2(L-1))/XXM2(L)) - E*.1)4286,4286,4284
4284 XM2 = XXM2(L)
IF(L -20)4270,4270,1520
4286 CONTINUE
XM2 = XXM2(L)
P02P01 = SQRT( (1. -XM1**2. *EE95)/(1. +XM2**2. *EE95 *T01/T0(11
1)))
C CALCULATE STATIC PRESSURE,TEMP,ETC.
PS1 = P01 * ( 1. +((GAMMA -1.)/2.)*XM1 **2.))* ( GAMMA/(1.-GAMMA))
P02 = P02P01 *P01
PS2 = P02P01 *P01 * ( 1.+((GAMMA -1.)/2.)*XM2**2.))* (GAMMA/(

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1      1. - GAMMA))
      P03= (1.-.5*GAMMA*XM2**2.*VKL23*PS2/P02)*P02
      P03P00 = P03/P00
4605  IT = IT + 1
      IF(IT-20) 4608,4608,4606
4606  WRITE(3,4607) IT,P03P00
4607  FORMAT(11H ITERATION 15/53H COULD NOT CONVERGE ON TOTAL PRESSURE R
      ATIO NEXT ZONE/21H LAST PRESSURE RATIO F8.4)
      GO TO 287
C      FLOW CHANGE
4608  N1 = 0
      TMAXC= AMAX1(TW(1),TW(2),TW(3),TW(4),TW(5),TW(6),TW(7),TW(8),TW(9
      1),TW(10),TW(11))
      IF(ABS(1.-TMAXC/TMAXCI) -E*.5)4700,4609,4609
4609  TDIFR(IT) = TMAXCI - TMAXC
      IF(IT-1)1500,4600,4614
4600  WDOTZ(1) = WDOT
      IF(TDIFR(IT))4610,3220,4612
4610  WDOTZ(2) = WDOTZ(1)*1.05
      WDOT = WDOTZ(2)
      GO TO 3235
4612  WDOTZ(2) = WDOTZ(1) * .95
      WDOT = WDOTZ(2)
      GO TO 3235
4614  WDOTZ(IT) = WDOT
      WDOT = WDOTZ(IT)-(WDOTZ(IT)-WDOTZ(IT-1))/(1.-TDIFR(IT-1)/TDIFR(I
      1))
      GO TO 3235
4700  IZ2=IZ2 +1
      IF(IZ2-20)3220,3220,4606
C      PROGRAM TERMINATION
2000  CALL SSWTCH(1,JJ)
      IF(JJ-1)2020,2010,2020
2010  PRINT 2012
2012  FORMAT(53H OPERATOR PLEASE RESTORE SSW1 AND RESTART AFTER PAUSE)
      PAUSE
2020  PRINT 2022
2022  FORMAT(15H END OF PROGRAM)
2024  STOP
      END

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APPENDIX C

SUBROUTINE FUTEMP LISTING

Uniform Spacing
with Uniform Heat Generation
Fuel Temperature Subroutine

\$IBFTC DECK3 FULIST,REF

SUBROUTINE FUTEMP

DIMENSION TW(11),XT(32),XZKM(32),TMAX(11)

COMMON TW,XT,XZKM,TMAX,RAD,EN,TW1,QB,A,B,C,D,DH

287 S = 1.1 * RAD * SQRT(1./EN)

ZETA = 0.

TW(1) = TW1

J = 1

288 CONTINUE

K=1

290 IF(TW(J) - XT(K)) 296,294,292

292 K = K+1

GO TO 290

294 ZKM = XZKM(K)

GO TO 300

296 ZKM = XZKM(K-1) + (XZKM(K) - XZKM(K-1)) * (TW(J) - XT(K-1)) / (XT(K) - XT(K-1))

300 CONTINUE

TMAX(J) = TW(J) + QB * (A + B * ZETA + C * ZETA**2.0 + D * ZETA**3.0) *

1 S** 2.0 * (-.23535 + .25 * (1.65 * ALOG(2.*S/DH)

2 + (DH / (2.*S))**2.0) / ZKM

J = J + 1

ZETA = ZETA + .1

IF(J-11) 288,288,350

350 CONTINUE

RETURN

END

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APPENDIX D
DUMMY FUTEMP LISTING

```
-----  
$IBFTC DECK3 FULIST,REF  
C DUMMY ROUTINE FOR FUTEMP  
-----  
SUBROUTINE FUTEMP  
-----  
  DIMENSION TMAX(11)  
  COMMON TW,XT,XZKM,TMAX,RAD,EN,TW1,QB,A,B,C,D,OH  
-----  
  DO 350 J=1,11  
  TMAX(JJ)=0.  
-----  
350 CONTINUE  
-----  
  RETURN  
-----  
  END
```

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APPENDIX E

DERIVATION OF DENOMINATOR IN EQUATION (4)

The denominator of Equation (4) contains a factor to correct for the fact that $\alpha'_v > \alpha'_c$.

The coolant area in the core is

$$A_c = \alpha'_c \pi r_{eq}'^2 \quad (A-1)$$

As a consequence of the hydraulic diameter definition the perimeter of all tubes is

$$NP = \frac{4A_c}{D_H} \quad (A-2)$$

Substituting Equation (A-1) into Equation (A-2)

$$NP = \frac{\alpha'_c \pi r_{eq}'^2}{.25 D_H} \quad (A-3)$$

Now, from definition of α'_v ,

$$\alpha'_c = \alpha'_v - \alpha'_{tc} \quad (A-4)$$

Consider a tube and its wall:

$$\frac{\alpha'_{tc}}{\alpha'_c} \cong \frac{NP t_w}{A_c} = \frac{4NP t_w}{NP D_H} \quad (A-5)$$

Insert Equation (A-5) into Equation (A-4)

$$\alpha'_c = \frac{\alpha'_v}{1 + \frac{4t_w}{D_H}} \quad (A-6)$$

Insert Equation (A-6) into Equation (A-3) to arrive at Equation (4).

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APPENDIX F
NOMENCLATURE

Analysis	FØRTRAN	Description	Units
A	A	Coefficient in Power Expansion	numeric
A/A*	ASTAR	Compressible Flow Function	numeric
A _c	AFL	Coolant Flow Area	ft ²
A _{fu}	AFU	"Fuel" Area (Principal Heat Generating Area in Core)	ft ²
B	B	Same as "A"	numeric
C	C	Same as "A"	numeric
C _p	CP	Specific Heat at Constant Pressure of Coolant	Btu/(lb)(°F)
$\bar{C}_p$	---	Average Specific Heat	Btu/(lb)(°F)
---	CØE	Local Film Coefficient Without Temperature Correction Factor	Btu/(hr)(ft ²)(°F)
D	D	Same as "A"	numeric
---	DELTA	Master Determinant in Finding A, B, C, D from Input	numeric
D _H	DH	Hydraulic Diameter of Coolant Passages	ft
---	DHH	Same as DH Except Used as Dummy	ft
---	E	Relative Convergence Criteria	numeric
---	ENZ	Number of Tubes in Zone	numeric
f	XF	Average Friction Factor Defined in Equation (32)	numeric
G	G	Mass Velocity	lb/(hr)(ft ²)
g	---	Acceleration Due to Gravity	32.17 ft/sec ²
h	H	Local Film Coefficient	Btu/(hr)(ft ²)(°F)
---	I	Axial Location Matrix Index	
---	ICASE	Case Index	
	IJ	Table Look-Up Index	
	IK	Table Look-Up Index	
	IM	Table Look-Up Index	
	IT	Iteration Index	
	IZ	Zone Index	

Analysis	FORTTRAN	Description	Units
	IZ2	Zone Iteration Limit Index	
	J THRU N	About Same as Above	
l	XL	Core Length	ft
M	XM	MACH Number	numeric
m	EXP	Film Coefficient Temperature Correction Exponent	numeric
NP	XNP	Total Inner Perimeter of Coolant Passages	ft
N_t	EN	Equivalent Number of Circular Tubes	
N_{NU}	---	Local Nusselt Number	numeric
N_{RE}	---	Local Reynolds Number	numeric
$\bar{N}_{Re}$	XNREAV	Average Reynolds Number Calculated by Equation (33), Analysis	numeric
Po	P0	Total Coolant Pressure (0-ZERØ)	psia
Po2/Po1	P02P01	Total Pressure Ratio Station 2 to Station 1	numeric
Po3/Po0	P03P00	Total Core Pressure Ratio Station 3 to Station 0	numeric
---	P0D	Difference Between Core Total Pressure Ratio Desired and that Calculated	numeric
---	PS	Coolant Static Pressure	psia
---	PSR	Desired Core Total Pressure Ratio	numeric
---	PWR	Core Zoned Total Thermal Power	MW
---	PWRB	Zone Thermal Power	MW
Q	Q	Core Total Thermal Power	MW
q'''	---	Local Volumetric Heat Generation Rate	$\frac{\text{Btu}}{(\text{hr})(\text{ft}^3)}$
---	QB1-4	Normalized Axial Power Profile (Those in Conjunction with ZETA 1-4 YIELD A, B, C, and D)	numeric
$\bar{q}'''$	QB	Average Volumetric Heat Generation Rate in "Fuel"	$\text{Btu}/(\text{hr})(\text{ft}^3)$
r	ERAD	Actual Radius of Core Including All Voids	ft
r'	RAD	Radius of Core Including Just Tube Clad, Coolant Void and "Fuel"	ft
	REQ	Ratio of the Square of the Radius of a Circle Equivalent in Area to an Annulus to the Square of Core Radius	numeric
---	RP	Average Normalized Power Profile in Zone	numeric
---	RZ	Outer Radius of Annular Zone	ft

Analysis	FORTTRAN	Description	Units
T_0	T0	Coolant Total Temperature (O-ZERO)	$^{\circ}\text{R}$
T_B	TB	Bulk Average Total Temperature	$^{\circ}\text{R}$
---	TDIFR	Difference Between Maximum Desired Tube Wall Temperature and Actual Temperature	$^{\circ}\text{R}$
---	TMAXCI	Maximum Desired Input Wall Temperature	$^{\circ}\text{R}$
---	TMAXC	Maximum Wall Temperature	$^{\circ}\text{R}$
---	TMAX	Fuel Temperature as Calculated by Subroutine FUTEMP	$^{\circ}\text{R}$
T_w	TW	Wall Temperature	$^{\circ}\text{R}$
t_{we}	XW	Effective Tube Wall Thickness (Enter Actual Thickness in Input)	ft
V	---	Fluid Velocity	ft/sec
x	---	Axial Distance Along Core from Point of First Heat Generation	ft
<u>Greck</u>			
α_c	ALPHC	Actual Volume Fraction of Coolant Voids	numeric
α_F	ALPFU	Actual Volume Fraction of "Fuel"	numeric
α_{tc}	ALPHT	Actual Volume Fraction of Tube Clad	numeric
α_v	ALPHV	Actual Volume Fraction of Tube Clad and Coolant Void	numeric
α'_c	ALPHAC	Volume Fraction of Coolant Voids in Heat Transfer Model $\alpha'_c \geq \alpha_c$	numeric
α'_{tc}	ALPHAT	Volume Fraction of Tube Clad in Heat Transfer Model $\alpha'_{ta_t} > \alpha_{ta_t}$	numeric
α'_v	ALPHA	$\alpha'_c + \alpha'_{ta_t}$	numeric
γ	GAMMA	Ratio of Specific Heats, C_p/C_v	numeric
μ	UB	Dynamic Viscosity	lb/(hr)(ft)
ξ	XI	Fluid Flow Area/Fuel Area (Coolant Fraction)	numeric
π	PI	3.14159	numeric
$\dot{w}$	WDQT	Total Coolant Weight Flow in Core	lb/hr
ζ	ZETA	x/l	numeric

Analysis	FØRTRAN	Description	Units
<u>Subscripts*</u>			
0	0	Zero - Inlet Plenum	
1	1	Active Core Front Face	
2	2	Active Core Back Face	
3	3	Dump Plenum	
<u>Important Program Variables Not Listed in Nomenclature</u>			
α_{vI}	ALPHI	Zone α_v^S -- Same as ALPHA	numeric
	VKL01	Loss Coefficient Station 0 to Station 1 (0-ZERO)	numeric
	VKL23	Loss Coefficient Station 2 to Station 3	numeric
	WDØTS	First Approximation to Coolant Flow in Zone - Internally Generated	$\frac{lb}{hr}$
	WDØTT	Total Coolant Flow Through Core	lb/sec
	XASTAR	A/A* Table from Standard Compressible Flow Functions (Table should cover range from M = .001 to .75)	numeric
	XCP	Coolant Specific Heat Table versus Temperature	Btu/(lb)(°F)
	XGAMMA	Coolant Ratio of Specific Heats Table versus Temperature	numeric
	XKB	Coolant Thermal Conductivity Table versus Temperature	$\frac{B}{(hr)(ft)(°F)}$
	XT	Properties Temperature Table	°R
	XUB	Coolant Viscosity Table versus Temperature	lb/(hr)(ft)
	XXF1	Half-Friction Factor Table versus Reynolds number	numeric
	XXM	MACH Number Table for XASTAR	numeric
	XXNRE	Reynolds Number Table for XXF1	numeric
	XZKM	"Fuel" Thermal Conductivity Table versus XT	$\frac{B}{(hr)(ft)(°F)}$
	ZETA1-4	Dimensionless Axial Locations to Which QB1-4 Correspond	numeric

* FØRTRAN variables are terminated in subscript, i.e., $Po_3 = P03$.

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