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ORINC—A One-Dimensional Implicit Approach to the Inverse Heat Conduction Problem

L. J. Ott
R. A. Hedrick

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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ORINC — A ONE-DIMENSIONAL IMPLICIT APPROACH
TO THE INVERSE HEAT CONDUCTION PROBLEM

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ABSTRACT

This report develops an implicit solution technique to determine both the transient surface temperature and the transient surface heat flux of electrically heated rods given the power input and an "indicated" internal temperature during a simulated loss-of-coolant accident. A digital computer program ORINC (ORNL Inverse Code) is developed which solves a one-dimensional, transient, lumped parameter, implicit formulation of the conduction equation at each bundle thermocouple position in the Thermal-Hydraulic Test Facility (THTF).

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LIST OF SYMBOLS

<u>Symbol</u>	<u>Definition</u>
A	Area of integration, in^2
A	Constant of proportionality [Eq. (II.15)]
$\bar{B}_F$	Column vector of knowns in the forward conduction model [Eq. (II.46)]
$\bar{B}_I$	Column vector of knowns in the inverse conduction model [Eq. (II.70)]
b_{-}	Elements of $\bar{B}_{-}$
C_p	Specific heat, $\text{Btu/lb} \cdot ^\circ\text{F}$
f	Geometric view factor
$\bar{H}_F$	Tridiagonal coefficient matrix of the forward conduction model [Eq. (II.36)]
$\bar{H}_I$	Tridiagonal coefficient matrix of the inverse conduction model [Eq. (II.63)]
h_{-}	Elements of $\bar{H}_{-}$
h_f	Surface convective heat transfer coefficient, $\text{Btu/sec-ft}^2 \cdot ^\circ\text{F}$
h_b	ORINC-calculated heat transfer coefficient based on T_b , $\text{Btu/sec-ft}^2 \cdot ^\circ\text{F}$
h_{sat}	ORINC-calculated heat transfer coefficient based on T_{sat} , $\text{Btu/sec-ft}^2 \cdot ^\circ\text{F}$
h_{gap}	Gap convective heat transfer coefficient, $\text{Btu/sec-ft}^2 \cdot ^\circ\text{F}$
h_r	Gap radiation heat transfer coefficient, $\text{Btu/sec-ft}^2 \cdot ^\circ\text{F}$
k_{-}	Thermal conductivity, $\text{Btu/sec} \cdot ^\circ\text{F} \cdot \text{ft} / \text{ft}$
$\bar{k}_{i,i+1}$	Average thermal conductivity (i.e., $k_i + k_{i+1}/2$), $\text{Btu/sec} \cdot ^\circ\text{F} \cdot \text{ft} / \text{ft}$
l	Unit distance in the axial direction, ft
n	Number of nodes (subvolumes) in a substrate
$\bar{n}$	Unit vector normal to dA
$\dot{q}_{-}$	Volumetric heat generation rate, Btu/sec-ft^3
$\dot{q}$	Heat generation rate, Btu/sec
q_{-}	Heat flow between nodes, Btu/sec
r	Radial distance, ft

Δr^2	Nodal area, ft ² [defined by Eq. (II.10) or (B-20)]
r_1	Node 1 interface radius, ft [defined by Eq. (II.11) or (B-18)]
$\bar{r}_1$	Node 1 center of mass, ft [defined by Eq. (II.12) or (B-19)]
r_I	Inside radius of heat source, ft
r_H	Outside radius of heat source, ft
r_S	Radius of rod surface, ft
Δr_{gap}	Radial gap at the substrata interface, ft
t	Time, sec
T	Temperature, °F
$\bar{T}_F$	Column vector of unknowns in the forward conduction model, [Eq. (II.45)] (nodal temperatures)
$\bar{T}_I$	Column vector of unknowns in the inverse conduction model, [Eq. (II.69)]
T_b	Average local fluid bulk temperature, °F
T_{sat}	Local fluid saturation temperature, °F
T_{surf}	Rod surface temperature, °F
Δv	Subvolume of a substrate, defined by Eq. (II.9) (nodal volume), ft ³
V	Volume of integration, ft ³
z	Axial distance, ft
θ	Azimuthal angle, radians
ρ	Density, lb _m /ft ³
σ	Stefan-Boltzmann constant
ϕ	Time-averaged linear surface heat rate (divided by π), Btu/sec-ft
ψ	Time-averaged surface heat flux, Btu/sec-ft ²

SubscriptsDefinition

NMGO	Number of nodes in magnesium oxide
MgO	Magnesium oxide substrate
NH	First node in Inconel substrate (NMGO + 1)
Heat (heater)	Inconel heater substrate

NHT	Number of nodes in Inconel substrate
NOD2	Last node in Inconel substrate ($NMGO + NHT$)
NH	First node in the Cupro Nickel substrate ($NOD2 + 1$)
Cu	Cupro Nickel substrate
NCU	Number of nodes in Cupro Nickel substrate
NOD3	Last node in the heater ($NOD2 + NCU$)
NC	First node in the boron nitride substrate ($NOD3 + 1$)
BN	Boron nitride substrate
NBN	Number of nodes in boron nitride substrate
NOD4	Last node in the boron nitride ($NOD3 + NBN$)
NB	First node in the inner stainless steel sheath substrate ($NOD4 + 1$)
SS1	Inner stainless steel sheath substrate
NSS1	Number of nodes in inner stainless steel sheath
NOD5	Last node in the inner stainless steel sheath ($NOD4 + NSS1$)
NS	First node in the outer stainless steel sheath ($NOD5 + 1$)
SS2	Outer stainless steel sheath substrate
NSS2	Number of nodes in outer stainless steel sheath
NOD6	Last node in the outer stainless steel sheath ($NOD5 + NSS2$)
SS	Stainless steel
gap ₁	Radial gap at the magnesium oxide - Inconel interface
gap ₂	Radial gap at the heater - boron nitride interface
gap ₃	Radial gap at the boron nitride - inner stainless steel sheath interface
gap ₄	Radial gap at the inner stainless steel sheath - outer stainless steel sheath interface
gap ₀	Bias gap for gap ₄

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CHAPTER I

INTRODUCTION

Background¹

The Oak Ridge National Laboratory (ORNL) Pressurized-Water-Reactor Blowdown Heat Transfer (PWR-BDHT) Separate-Effects Program is part of the overall light-water-reactor (LWR) safety research program of the Nuclear Regulatory Commission (NRC). Other parts of the program cover a wide range of experimental and analytical efforts from laboratory- to small-scale experimental nuclear plants; the separate-effects studies, which fall between these two, are designed to answer specific questions relevant to the hypothetical loss-of-coolant accident (LOCA).

Specific objectives of the ORNL PWR-BDHT Separate-Effects Program are to determine for a wide range of parameters time to CHF (critical heat flux) and the following variables for both pre- and post-CHF: heat fluxes, ΔT (temperature difference between pin surface and fluid), heat transfer coefficients, and local fluid properties. The program also seeks to test the ability of existing codes, such as RELAP, to predict the behavior of the single- and 49-rod loops under blowdown conditions.

The parameters to be studied include

1. single- and double-ended coolant line breaks of varying area ratios;
2. fast to slow depressurization rates;
3. combinations of system power and pressure to obtain different values of the departure from nuclear boiling ratio (DNBR);
4. a range of power cutoff delays;
5. a range of power decay rates;
6. a range of power-to-system volume ratios.

Secondary objectives are (1) to obtain CHF data under steady-state conditions over a range of coolant pressures, inlet and exit subcooling, and an inlet flow rate appropriate to PWR interests; (2) to evaluate the thermal-hydraulic behavior of the test loops during simulated operational upsets that include variations in local power, system pressure, or coolant

flow using the anticipated transient without scram (ATWS) as a guide;² and (3) to determine the effect of different spacer grids and power distribution profiles on both transient and steady-state CHF.

Test Facilities¹

Primary test results are obtained from the Thermal-Hydraulic Test Facility (THTF), a large nonnuclear experimental loop with a test section that contains a 7×7 array of 12-ft stepped, chopped-cosine heater rods with an outside diameter of 0.422 in.

A schematic view of the THTF is shown in Fig. 1-1. Fluid discharged from the pump flows through two control valves, where excess pump head is dissipated and flow adjusted to the desired level by diverting a portion through the bypass line. Heat generated in the fluid by the pump is removed in the small Graham "Heliflow" heat exchanger in the bypass line. The primary flow then passes through inlet instrumented spool pieces 1 and 2, where flow conditions are monitored by a combination of a drag disk, gamma densitometer, turbine meter, and temperature and pressure sensors in each spool piece. Flow enters the test section at the top of the rectangular shroud box, flows down its length, and enters the bottom of the rod bundle. The fluid exits the bundle through outlet spool pieces 1 and 2, which are identical to those on the inlet. The energy added by the test section heater rods is removed by Graham "Heliflow" heat exchangers A, B, and C. Finally, the fluid returns to the pump section past the line from the pressurizer, which provides the primary pressure control for the loop and at the same time serves as a surge tank.

At the instant of blowdown, the contents of the primary loop may be discharged through either of two rupture disk assemblies and appropriately sized orifices into the pressure-suppression system. For approximately 15 sec before and approximately 300 sec after blowdown, over 500 sensors throughout the loop will be scanned by a computer-controlled digital-data-acquisition system (CCDAS) at a rate of 20 times per second. These sensors include approximately 320 thermocouples in the heater rods of the test section.

Fig. I-1. Thermal-Hydraulic Test Facility (ORNL-PWR Blowdown Heat Transfer Separate-Effects Program).

Supporting experiments are carried out in the Forced Convection Test Facility (FCTF). A schematic view of the principal FCTF loop components is illustrated in Fig. I-2. The primary purpose of the FCTF is to qualify prototype heaters for use in the THTF and to obtain blowdown heat transfer and steady-state CHF results for single rods in an annular geometry. In

Fig. I-2. Forced convection depressurization loop.

its present configuration, the FCTF is capable of conducting only single-ended break tests.

Objectives

One of the primary objectives of the analysis is to determine the transient surface temperature and heat flux of the THTF heater rods from internal thermocouple signals obtained during a blowdown. This analysis requires the solution of the inverse heat conduction problem.

The first purpose of this report is to develop a method for calculating the surface heat flux and surface temperature given the power input and the "indicated" internal temperature. The second objective is to develop and present the inverse computer program ORINC (ORNL Inverse Code), which solves a one-dimensional, transient, lumped-parameter, implicit formulation of the conduction equation at each thermocouple position.

Literature Survey

An extensive review of the literature on the inverse heat conduction problem has been made by Muzzy, Avila, and Root.³ The following draws heavily from that study.

The problem can be posed mathematically as follows: determine an unknown function $b(t)$ which may be either the temperature or flux at the boundary $\bar{D}$ of a domain D if the temperature distribution $T(x,t)$ satisfies

$$\bar{\nabla} \cdot k \bar{\nabla} T + \dot{q}''' = \rho C_p \frac{\partial T}{\partial t} \quad \text{for } x \in D \quad (\text{I.1})$$

and the conditions

$$T(x,0) = f(x) \quad x \in D \quad (\text{I.2})$$

$$T(x_0,t) = g(t) \quad x_0 \in D, t \geq 0, \quad (\text{I.3})$$

where ρ denotes density, C_p is specific heat, k is thermal conductivity, $\dot{q}'''$ is the heat generation rate, and f and g are known functions. Most numerical techniques for solving Eqs. (I.1) through (I.3) are inherently unstable since small changes in the data can cause large changes in the

solution. All numerical techniques that solve this problem successfully require an explicit or implicit reduction in the space of functions in which the solution will be sought.

There are four basic approaches to the numerical solution of the inverse heat conduction problem: integral equation techniques, transform techniques, series techniques, and techniques involving minimization over a multiparameter family of functions. All of these methods overlap considerably.

The integral equation approach exploits the fact that for linear problems (i.e., where the material properties are temperature and time invariant), the solution to Eqs. (I.1) through (I.3) employs an integral equation. For example, if $b(t)$ denotes the surface heat flux on $\bar{D}$, then

$$g(t) = g(0) + \int_0^t G(S,t) b(S) dS, \quad (I.4)$$

where $G(S,t)$ is an appropriate "kernel."

Stoltz⁴ used Eq. (I.4) to obtain numerical solutions for b equal to the surface heat flux. By considering $t_i = i \Delta t$ ($i = 0, 1, 2, \dots, n$), he approximated the integral using a simple integration scheme. By assuming b constant on each interval (t_i, t_{i+1}) , he was able to solve for b recursively, starting from $i = 0$. Even when restricting the class of possible solutions to step functions, instabilities were observed if Δt became too small. Beck⁵ also used Eq. (I.4), but improved on Stoltz's method by considering t_i ahead of the value for which b was presently sought. Applying a least-squares technique to obtain the optimum solution for Eq. (I.4) over several values of t_i simultaneously, Beck was able to solve b for a much smaller Δt . In a more recent work, Agee⁶ also reduced the nonlinear problem to an equivalent linear problem via a relationship similar to Eq. (I.4) and then used an adjoint solution technique to solve the equivalent linear problem for either the surface temperature or heat flux. The integral equation approach is restricted to linear problems and can become difficult if the geometry is irregular.

The second approach is characterized by the use of Laplace or Fourier transforms to obtain transfer functions which relate the input data $g(t)$ to

the output function $b(t)$. Sparrow, Haji-Sheikh, and Lundgren,⁷ Kendall,⁸ and Imber⁹ have used this approach. Again, the linearity assumption is crucial; if the domain is irregular or composed of many regions — each with different material properties — the application of these techniques may be difficult.

The third approach involves the use of infinite series with the values of $g(t)$ and its derivatives to solve Eqs. (I.1) through (I.3). Burggraf¹⁰ first developed this technique, and his results were later extended to other cases of interest by Makhin and Shmukin.¹¹ In more recent work, Plummer et al.¹² have employed this method numerically with apparent success. Linearity and a regular geometry are essential.

The fourth approach is that of minimization over a multiparameter family of functions. In this technique the solution is assumed to be of a certain form, for example, step or polynomial functions which depend on several parameters. These are chosen such that, with the resulting $b(t)$ as input, a best match of the data $g(t)$ in a least-squares sense is obtained. The major proponent of this method is Beck,¹³ but others had considered it earlier (Frank¹⁴ and Davies¹⁵). In this technique the process is an iterative one; for each proposed set of parameters the forward problem [Eqs. (I.1) and (I.2)] is solved, in addition to

$$-k \frac{\partial T}{\partial n} = b(t) \quad \text{for } x \in \bar{D}, \quad (\text{I.5})$$

where $b(t)$ represents the heat flux and $\bar{n}$ the direction normal to the surface. After the forward problem is solved, the adjustable parameters are altered by some strategy and the process is repeated. The best parameters are those for which Eq. (I.3) is most nearly satisfied.

Beck¹³ considered b to be a low-order polynomial or constant over the analysis interval (several time steps in the discretized data). The coefficients in the polynomial expansion are adjusted to most nearly satisfy Eq. (I.3) in the least-squares sense over the analysis interval. The solution is taken as the accepted value of b over the next single time step only. The analysis interval is shifted by one step and the entire process is repeated.

In the mathematical literature inverse heat conduction is usually referred to as a parabolic continuation problem that is related to solving the heat equation backward in time. There are several approaches that may be taken to solve these problems. The first, described by Douglas,¹⁶ is to solve an integral equation of the form of Eq. (I.4) subject to auxiliary conditions, such as requiring the solution to be bounded. Linear programming techniques are used to optimize the agreement in Eq. (I.3). Linearity is essential, but for regular geometries this approach may be easier to implement than those described above. As the complexity of the domain increases (such as multiple regions within the domain with varying thermal properties), it may not be possible to find the kernel function in Eq. (I.4), and the difficulties of this method increase.

A second approach, similar to the least-squares ideas described above, has been employed by Miller and Viano¹⁷ and by Miller.¹⁸ Assume that for any $b(t)$, $T(x_0, t)$ can be calculated by

$$A(b) = T(x_0, t) . \quad (I.6)$$

The following is then minimized

$$||A(b) - g|| , \quad (I.7)$$

(where $||\cdot||$ denotes some convenient vector norm), subject to the condition

$$||B(b)|| \leq E , \quad (I.8)$$

where $B(b)$ expresses some operation on the function b . For example, $B(b)$ might be the derivative of b , and Eq. (I.8) would restrict the acceptable solutions to those functions whose derivatives remained bounded by E over the time step under consideration. This approach is applicable to nonlinear problems and offers the advantages of some theoretical background. So far, the applications in the literature have not included the problem given in Eqs. (I.1) through (I.3).

Muzzy, Avila, and Root³ concluded that the most promising technique for solving the inverse heat conduction problem, as shown in the literature, is Beck's second method,¹³ Miller's method,¹⁸ or some combination of the

two. The other techniques are restricted by the linearity assumption and the requirements of simple geometries and/or simple domains.

The original algorithm for Beck's second method was implemented in the INVERS subroutine of the Aerojet Nuclear HEATLA code.¹⁹ This technique has also been incorporated in Energy Incorporated's LEPER code.²⁰ Muzzy, Avila, and Root³ also used a variant of Beck's second method in General Electric's HCODE. Muzzy introduced several improvements and additions to this method: (1) the "trend" of the solution for b was anticipated in the formulation for $b(t_{i+1})$; (2) the formulation for $b(t_{i+1})$ allowed a one-parameter rather than a polynomial (multiparameter) minimization; (3) by restricting the maximum change in $b(t_{i+1})$ over the analysis interval, the possibility of oscillation in the heat flux for rapid transients was minimized; (4) the minimization algorithm was not entered until there was reasonable (within preset error criterion) agreement between the indicated and calculated temperatures; (5) HCODE used a weighted least-squares technique; and (6) HCODE forced the computed temperature to lie alternately on either side of the indicated temperature, reducing the accumulated error in b .

However, there are drawbacks in applying Beck's second method. The first is excessive computational time. Except for the improvements noted in HCODE, the least-squares error function may have local minima to which the iterative minimization process converges (these local minima may be relatively distant from the true minimum) and by applying the process recursively, the computed solution may "drift."

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CHAPTER II

MODEL DERIVATION

Consider the governing differential equation for the conduction of heat in a solid with an internal heat source:

$$\bar{\nabla} \cdot k \bar{\nabla} T + \dot{q}''' = \rho C_p \frac{\partial T}{\partial t} \quad (II.1)$$

Volume integration of Eq. (II.1) yields

$$\int_V (\bar{\nabla} \cdot k \bar{\nabla} T + \dot{q}''') dV = \int_V \rho C_p \frac{\partial T}{\partial t} dV \quad (II.2)$$

With the assumption that $\rho C_p (\partial T / \partial t)$ is constant over V and with the application of the divergence theorem to the left side of Eq. (II.2), the result is

$$\int_A k \bar{\nabla} T \cdot \bar{n} dA + \int_V \dot{q}''' dV = \rho C_p V \frac{\partial T}{\partial t} \quad (II.3)$$

Restricting the model application to cylindrical coordinates allows expansion for the gradient of T ,

$$\int_A k \left(\frac{\partial T}{\partial r} \bar{r} + \frac{1}{r} \frac{\partial T}{\partial \theta} \bar{\theta} + \frac{\partial T}{\partial z} \bar{z} \right) \cdot \bar{n} dA + \int_V \dot{q}''' dV = \rho C_p V \frac{\partial T}{\partial t} \quad (II.4)$$

Assuming there is no azimuthal temperature dependence and no axial conduction (i.e., $\partial T / \partial \theta = \partial T / \partial z = 0$), Eq. (II.4) reduces to

$$\int_A k \frac{\partial T}{\partial r} (\bar{r} \cdot \bar{n}) dA + \int_V \dot{q}''' dV = \rho C_p V \frac{\partial T}{\partial t} \quad (II.5)$$

With the further assumption that $k(\partial T / \partial r)$ is a function of r and t only, then

$$-2\pi k \ell \left| r_i \frac{\partial T}{\partial r} \right|_{r_i} + 2\pi k \ell \left| r_o \frac{\partial T}{\partial r} \right|_{r_o} + \int_V \dot{q}''' dV = \rho C_p V \frac{\partial T}{\partial t} \quad (II.6)$$

for the radial interval (r_i, r_o) .

Equation (II.6) can be further simplified with the assumptions that k is constant on the interval (r_i, r_0) and that $\dot{q}$ is constant for all regions:

$$\int_V \dot{q} dV = \dot{q} V. \quad (\text{II.7})$$

Therefore, Eq. (II.6) reduces to

$$-2\pi k l r_i \left. \frac{\partial T}{\partial r} \right|_{r_i} + 2\pi k l r_0 \left. \frac{\partial T}{\partial r} \right|_{r_0} + \dot{q} = \rho C_p V \frac{\partial T}{\partial t}. \quad (\text{II.8})$$

The next step in the derivation is dependent on the assumption of the nature of the heat flow between two radial positions. However, it is appropriate to first discuss the manner in which a continuous homogeneous domain (substrate) is replaced by a pattern of discrete points (nodes) within the domain. Given a substrate of domain (r_{i-1}, r_{i-1+n}) , the substrate is divided into a finite number (n) of equal subvolumes where

$$\Delta v = \frac{\pi r_{i-1+n}^2 \ell - \pi r_{i-1}^2 \ell}{n}. \quad (\text{II.9})$$

Replacing Δv with $\pi \ell \Delta r^2$ and eliminating $\pi \ell$ from both sides of Eq. (II.9) yields

$$\Delta r^2 = \frac{r_{i-1+n}^2 - r_{i-1}^2}{n}. \quad (\text{II.10})$$

Therefore, the interface radius of each subvolume can be defined by

$$r_{i-1+j} = (r_{i-1}^2 + j \Delta r^2)^{1/2}, \quad (\text{II.11})$$

where $j = 0, n$. Also, the center of mass of each subvolume is

$$\bar{r}_{i-1+j} = (r_{i-1+j}^2 - 0.5 \Delta r^2)^{1/2}, \quad (\text{II.12})$$

where $j = 1, n$. The nodal points for a substrate over the domain (r_{i-1} , r_{i-1+n}) are defined by the centers of mass of the subvolumes; the temperature of a subvolume is associated with its center of mass. A better understanding of the element notation (node i , r_i , $\bar{r}_i$) can be gained by referring to Fig. II-1.

Given the cylinder depicted in Fig. II-2 with internal heat source over the radial domain of (r_I , r_H), heat flow between internal nodes [i.e., radial domain of (0 , r_H)] is proportional to r^2 (or capacitance dominated); however, in the radial domain of (r_H , r_s) the heat flow between two nodes is constant at any r between the nodes, making it flux dominated. Derivation of the model, starting with Eq. (II.8), requires two branches which will be joined later.

Over the domain $0 < r < r_H$ (Figs. II-1 and II-2), assume that heat flow between the nodes is proportional to r^2 , or

$$q \propto r^2 ; \quad (\text{II.13})$$

also

$$q = -k2\pi r l \frac{\partial T}{\partial r} . \quad (\text{II.14})$$

Fig. II-1. Schematic denoting element notation.

Fig. II-2. Schematic of a cylindrical rod with an internal heat source ($r_I < r < r_H$).

Combining Eqs. (II.13) and (II.14) with a constant of proportionality A yields

$$q = -k2\pi r \ell \frac{\partial T}{\partial r} = Ar^2 . \quad (\text{II.15})$$

With separation of variables,

$$-2k\pi \ell \partial T = Ar \partial r , \quad (\text{II.16})$$

and integration of Eq. (II.16) from $\bar{r}_{i-1}$ to $\bar{r}_i$, we have

$$-2k\pi \ell (T_i - T_{i-1}) = \frac{A}{2} (\bar{r}_i^2 - \bar{r}_{i-1}^2) . \quad (\text{II.17})$$

Therefore,

$$A = - \frac{4k\pi \ell (T_i - T_{i-1})}{(\bar{r}_i^2 - \bar{r}_{i-1}^2)} . \quad (\text{II.18})$$

Substituting Eq. (II.18) into Eq. (II.15) yields

$$q_{i-1,i} = - \frac{4k\pi \ell}{(\bar{r}_i^2 - \bar{r}_{i-1}^2)} (T_i - T_{i-1}) \bar{r}_{i-1}^2 . \quad (\text{II.19})$$

Applying Eqs. (II.8) and (II.19) to the i th node (Fig. II-1) with ρ constant and C_p and k evaluated at the present nodal temperatures results in

$$\begin{aligned} - \frac{\bar{k}_{i-1,i} 4\pi \ell \bar{r}_{i-1}^2}{(\bar{r}_i^2 - \bar{r}_{i-1}^2)} (T_i - T_{i-1}) + \frac{\bar{k}_{i,i+1} 4\pi \ell \bar{r}_i^2}{(\bar{r}_{i+1}^2 - \bar{r}_i^2)} (T_{i+1} - T_i) \\ + \dot{q}_i = \rho C_p V_i \frac{\partial T_i}{\partial t} . \end{aligned} \quad (\text{II.20})$$

Expanding $\dot{q}_1$ and the right side of Eq. (II.20) yields

$$\begin{aligned}
 & -\frac{\bar{k}_{i-1,i} 4\pi\ell r_{i-1}^2}{(\bar{r}_1^2 - \bar{r}_{i-1}^2)} (T_i - T_{i-1}) + \frac{\bar{k}_{i,i+1} 4\pi\ell r_i^2}{(\bar{r}_{i+1}^2 - \bar{r}_i^2)} (T_{i+1} - T_i) \\
 & + \dot{q}_1''' \pi\ell (r_i^2 - r_{i-1}^2) = \rho C p_i \pi\ell (r_i^2 - r_{i-1}^2) \\
 & \times \frac{T_i(t + \Delta t) - T_i(t)}{\Delta t} . \quad (II.21)
 \end{aligned}$$

Factoring out $\pi\ell$ and using an implicit formulation, Eq. (II.21) becomes

$$\begin{aligned}
 & -\frac{4\bar{k}_{i-1,i} r_{i-1}^2}{(\bar{r}_1^2 - \bar{r}_{i-1}^2)} [T_i(t + \Delta t) - T_{i-1}(t + \Delta t)] \\
 & + \frac{4\bar{k}_{i,i+1} r_i^2}{(\bar{r}_{i+1}^2 - \bar{r}_i^2)} [T_{i+1}(t + \Delta t) - T_i(t + \Delta t)] + \dot{q}_1''' (r_i^2 - r_{i-1}^2) \\
 & = \rho C p_i (r_i^2 - r_{i-1}^2) \frac{T_i(t + \Delta t) - T_i(t)}{\Delta t} . \quad (II.22)
 \end{aligned}$$

Collecting terms in Eq. (II.22) yields

$$\begin{aligned}
 & \left[\frac{4\bar{k}_{i-1,i} r_{i-1}^2}{(\bar{r}_1^2 - \bar{r}_{i-1}^2)} \right] T_{i-1}(t + \Delta t) + \left[-\frac{4\bar{k}_{i-1,i} r_{i-1}^2}{(\bar{r}_1^2 - \bar{r}_{i-1}^2)} - \frac{\rho C p_i (r_i^2 - r_{i-1}^2)}{\Delta t} \right. \\
 & \left. - \frac{4\bar{k}_{i,i+1} r_i^2}{(\bar{r}_{i+1}^2 - \bar{r}_i^2)} \right] T_i(t + \Delta t) + \left[\frac{4\bar{k}_{i,i+1} r_i^2}{(\bar{r}_{i+1}^2 - \bar{r}_i^2)} \right] T_{i+1}(t + \Delta t) \\
 & = -\dot{q}_1''' (r_i^2 - r_{i-1}^2) - \left[\frac{\rho C p_i (r_i^2 - r_{i-1}^2)}{\Delta t} \right] T_i(t) . \quad (II.23)
 \end{aligned}$$

Over the domain of $r_H < r < r_S$ (Figs. II-1 and II-2) assume that the heat flow between nodes is constant at any r between the nodes; therefore, in Eq. (II.14) the variables can be separated to yield

$$\frac{\partial r}{r} = -\frac{k2\pi\ell}{q} \partial T . \quad (II.24)$$

Upper integration of Eq. (II.24) from $\bar{r}_{i-1}$ to $\bar{r}_i$

$$\ln \left(\frac{\bar{r}_i}{\bar{r}_{i-1}} \right) = - \frac{k_{2\pi\ell}}{q_{i-1,i}} (T_i - T_{i-1}) ; \quad (\text{II.25})$$

rearranging Eq. (II.25) gives

$$q_{i-1,i} = - \frac{k_{2\pi\ell} (T_i - T_{i-1})}{\ln (\bar{r}_i / \bar{r}_{i-1})} . \quad (\text{II.26})$$

Applying Eqs. (II.8) and (II.26) to the i th node (Fig. II.1), with ρ constant, C_p and k evaluated at the present nodal temperatures, and with expansion of $\dot{q}_i$ and the right side of Eq. (II.8) yields

$$\begin{aligned} & - \frac{\bar{k}_{i-1,i} 2\pi\ell}{\ln (\bar{r}_i / \bar{r}_{i-1})} (T_i - T_{i-1}) + \frac{\bar{k}_{i,i+1} 2\pi\ell}{\ln (\bar{r}_{i+1} / \bar{r}_i)} (T_{i+1} - T_i) \\ & + \dot{q}_i'''' \pi\ell (r_i^2 - r_{i-1}^2) = \rho C_p \pi\ell (r_i^2 - r_{i-1}^2) \frac{T_i(t + \Delta t) - T_i(t)}{\Delta t} . \quad (\text{II.27}) \end{aligned}$$

Factoring out $\pi\ell$ and using an implicit formulation, Eq. (II.27) becomes

$$\begin{aligned} & - \frac{2\bar{k}_{i-1,i}}{\ln (\bar{r}_i / \bar{r}_{i-1})} [T_i(t + \Delta t) - T_{i-1}(t + \Delta t)] \\ & + \frac{2\bar{k}_{i,i+1}}{\ln (\bar{r}_{i+1} / \bar{r}_i)} [T_{i+1}(t + \Delta t) - T_i(t + \Delta t)] + \dot{q}_i'''' (r_i^2 - r_{i-1}^2) \\ & = \rho C_p (r_i^2 - r_{i-1}^2) \frac{T_i(t + \Delta t) - T_i(t)}{\Delta t} . \quad (\text{II.28}) \end{aligned}$$

Collecting terms in Eq. (II.28) yields

$$\begin{aligned}
 & \left[\frac{2\bar{k}_{i-1,i}}{\ln(\bar{r}_i/\bar{r}_{i-1})} \right] T_{i-1}(t + \Delta t) + \left[-\frac{2\bar{k}_{i-1,i}}{\ln(\bar{r}_i/\bar{r}_{i-1})} - \frac{\rho C p_i (r_i^2 - r_{i-1}^2)}{\Delta t} \right] \\
 & - \left[\frac{2\bar{k}_{i,i+1}}{\ln(\bar{r}_{i+1}/\bar{r}_i)} \right] T_i(t + \Delta t) + \left[\frac{2\bar{k}_{i,i+1}}{\ln(\bar{r}_{i+1}/\bar{r}_i)} \right] T_{i+1}'(t + \Delta t) \\
 & = -\dot{q}_i''''(r_i^2 - r_{i-1}^2) - \left[\frac{\rho C p_i (r_i^2 - r_{i-1}^2)}{\Delta t} \right] T_i(t) . \quad (II.29)
 \end{aligned}$$

The inverse conduction model is basically a manipulation of the forward conduction model where the boundary conditions are specified and the rod temperature profile is desired. The forward conduction model will be set up using the equations developed previously, and the inverse conduction model will be derived from the forward conduction model.

Given the cylindrical rod in Fig. II-2 with a known internal heat source over the radial domain (r_I, r_H) of

$$\begin{aligned}
 \dot{q}_i''''(t) & \quad r_I < r < r_H \text{ and } t \geq 0 \\
 \dot{q}_i''''(t) & = 0 \quad 0 < r < r_I \text{ and } r_H < r < r_S , \quad (II.30)
 \end{aligned}$$

a known convective heat transfer coefficient at $r = r_S$ of

$$h_f(t) \quad t \geq 0 , \quad (II.31)$$

a known sink temperature of

$$T_b(t) \quad t \geq 0 , \quad (II.32)$$

and a known steady-state temperature profile of

$$T(r,0) \quad 0 < r < r_S \text{ and } t = 0 , \quad (II.33)$$

solve for

$$T(r,t) \quad 0 < r < r_s \text{ and } t > 0. \quad (\text{II.34})$$

Using n nodes and applying Eq. (II.23) over $(0, r_H)$ and Eq. (II.29) over (r_H, r_s) , the matrix formulation of the forward conduction model is

$$\bar{H}_F \bar{T}_F = \bar{B}_F, \quad (\text{II.35})$$

where $\bar{H}_F$ is the tridiagonal coefficient matrix of the system:

$$\bar{H}_F = \begin{bmatrix} h_{1,1} & h_{1,2} & 0 & 0 & \dots & 0 & 0 & 0 & 0 & 0 \\ h_{2,1} & h_{2,2} & h_{2,3} & 0 & \dots & 0 & 0 & 0 & 0 & 0 \\ 0 & h_{3,2} & h_{3,3} & h_{3,4} & \dots & 0 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \dots & h_{n-3,n-4} & h_{n-3,n-3} & h_{n-3,n-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 & h_{n-2,n-3} & h_{n-2,n-2} & h_{n-2,n-1} & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & h_{n-1,n-2} & h_{n-1,n-1} & h_{n-1,n} \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 & h_{n,n-1} & h_{n,n} \end{bmatrix}$$

(II.36)

with interior nodes [i.e., within domain $(0, r_H)$]

$$h_{1,1} = -\frac{\rho C p_1 (r_1^2 - 0)}{\Delta t} - \frac{4\bar{k}_{1,2} r_1^2}{(\bar{r}_2^2 - \bar{r}_1^2)}, \quad (\text{II.37})$$

$$h_{i,i} = -\frac{4\bar{k}_{i-1,i} r_{i-1}^2}{(\bar{r}_i^2 - \bar{r}_{i-1}^2)} - \frac{\rho C p_1 (r_i^2 - r_{i-1}^2)}{\Delta t} - \frac{4\bar{k}_{i,i+1} r_i^2}{(\bar{r}_{i+1}^2 - \bar{r}_i^2)}, \quad (\text{II.38})$$

$$h_{i,i+1} = \frac{4\bar{k}_{i,i+1} r_i^2}{(\bar{r}_{i+1}^2 - \bar{r}_i^2)}, \quad (\text{II.39})$$

$$h_{i,i-1} = \frac{4\bar{k}_{i-1,i} r_{i-1}^2}{(\bar{r}_i^2 - \bar{r}_{i-1}^2)}; \quad (\text{II.40})$$

and with exterior nodes [i.e., within domain (r_H, r_S)]

$$h_{i,i} = -\frac{2\bar{k}_{i-1,i}}{\ln(\bar{r}_i/\bar{r}_{i-1})} - \frac{\rho C p_i (r_i^2 - r_{i-1}^2)}{\Delta t} - \frac{2\bar{k}_{i,i+1}}{\ln(\bar{r}_{i+1}/\bar{r}_i)}, \quad (\text{II.41})$$

$$h_{i,i+1} = \frac{2\bar{k}_{i,i+1}}{\ln(\bar{r}_{i+1}/\bar{r}_i)}, \quad (\text{II.42})$$

$$h_{i,i-1} = \frac{2\bar{k}_{i-1,i}}{\ln(\bar{r}_i/\bar{r}_{i-1})}, \quad (\text{II.43})$$

$$h_{n,n} = -\frac{2\bar{k}_{n-1,n}}{\ln(\bar{r}_n/\bar{r}_{n-1})} - \frac{\rho C p_n (r_n^2 - r_{n-1}^2)}{\Delta t} - \frac{2}{\frac{1}{r_n h_f(t + \Delta t)} + \frac{\ln(r_n/\bar{r}_n)}{k_n}} \quad (\text{II.44})$$

(see Appendix B for explicit derivation of $h_{n,n}$). $\bar{T}_F$ is a column vector of unknowns (nodal temperatures at time $t + \Delta t$):

$$\bar{T}_F = \begin{bmatrix} T_1 \\ T_2 \\ \vdots \\ T_i \\ \vdots \\ T_{n-2} \\ T_{n-1} \\ T_n \end{bmatrix}. \quad (\text{II.45})$$

$\bar{B}_F$ is a column vector of knowns:

$$\bar{B}_F = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_{n-3} \\ b_{n-2} \\ b_{n-1} \\ b_n \end{bmatrix} \quad (\text{II.46})$$

For interior nodes within $(0, r_I)$,

$$b_i = \cancel{-\dot{q}_i (r_i^2 - r_{i-1}^2)}^0 - \left[\frac{\rho C p_i (r_i^2 - r_{i-1}^2)}{\Delta t} \right] T_i(t) \quad (\text{II.47})$$

For interior nodes within (r_I, r_H) ,

$$b_i = \cancel{-\dot{q}_i (r_i^2 - r_{i-1}^2)} - \left[\frac{\rho C p_i (r_i^2 - r_{i-1}^2)}{\Delta t} \right] T_i(t) \quad (\text{II.48})$$

For exterior nodes within (r_H, r_S) , except for b_n ,

$$b_i = \cancel{-\dot{q}_i (r_i^2 - r_{i-1}^2)}^0 - \left[\frac{\rho C p_i (r_i^2 - r_{i-1}^2)}{\Delta t} \right] T_i(t) \quad (\text{II.49})$$

For the last node, b_n ,

$$b_n = \cancel{-\dot{q}_n (r_n^2 - r_{n-1}^2)}^0 - \left[\frac{2}{\frac{1}{r_n h_f(t + \Delta t)} + \frac{\ln(r_n/r_n)}{k_n}} \right] T_b(t + \Delta t) - \left[\frac{\rho C p_n (r_n^2 - r_{n-1}^2)}{\Delta t} \right] T_n(t) \quad (\text{II.50})$$

Equation (II.35) can be solved by many techniques. ORINC simply inverts $\bar{H}_F$ to obtain $\bar{H}_F^{-1}$ by the Gauss-Jordan method with full pivoting. Each member of the unknown vector $\bar{T}_F$ is then determined by

$$T_i = \sum_{j=1, n} h_{i,j}^{-1} b_j \quad i = 1, n. \quad (II.51)$$

The inverse conduction problem is then posed. If an internal heat source over (r_I, r_H) is known:

$$\begin{aligned} \dot{q}'''(t) & \quad r_I < r < r_H \text{ and } t \geq 0, \\ \dot{q}'''(t) & = 0 \quad 0 < r < r_I \text{ and } r_H < r < r_S; \end{aligned} \quad (II.52)$$

an internal temperature is known:

$$T(\bar{r}_{n-2}, t) \quad r = \bar{r}_{n-2} \text{ and } t \geq 0. \quad (II.53)$$

with a known steady-state temperature profile of

$$T(r, 0) \quad 0 < r < r_S \text{ and } t = 0; \quad (II.54)$$

solve for the boundary function,

$$\phi(t) \quad t > 0, \quad (II.55)$$

and the temperature distribution,

$$T(r, t) \quad t > 0. \quad (II.56)$$

In essence, the inverse conduction model corresponding to Eq. (II.35) requires the modification of four members of $\bar{B}_F$, one column of $\bar{H}_F$, one row of $\bar{H}_F$, and two members of $\bar{T}_F$. First, inspection of the nth equation of the

forward conduction model shows

$$\begin{aligned}
 & \left[\frac{2\bar{k}_{n-1,n}}{\ln(\bar{r}_n/\bar{r}_{n-1})} \right] T_{n-1}(t + \Delta t) + \left[-\frac{2\bar{k}_{n-1,n}}{\ln(\bar{r}_n/\bar{r}_{n-1})} - \frac{\rho C p_n (r_n^2 - r_{n-1}^2)}{\Delta t} \right. \\
 & \quad \left. - \frac{2}{\frac{1}{r_n h_f} + \frac{\ln(r_n/\bar{r}_n)}{k_n}} \right] T_n(t + \Delta t) = - \left[\frac{2}{\frac{1}{r_n h_f} + \frac{\ln(r_n/\bar{r}_n)}{k_n}} \right] T_b(t + \Delta t) \\
 & \quad - \left[\frac{\rho C p_n (r_n^2 - r_{n-1}^2)}{\Delta t} \right] T_n(t) \quad (II.57)
 \end{aligned}$$

where h_f and T_b are functions of time. Equation (II.57) can be restructured to

$$\begin{aligned}
 & \left[\frac{2\bar{k}_{n-1,n}}{\ln(\bar{r}_n/\bar{r}_{n-1})} \right] T_{n-1}(t + \Delta t) + \left[-\frac{2\bar{k}_{n-1,n}}{\ln(\bar{r}_n/\bar{r}_{n-1})} \right. \\
 & \quad \left. - \frac{\rho C p_n (r_n^2 - r_{n-1}^2)}{\Delta t} \right] T_n(t + \Delta t) \\
 & \quad = \phi(t + \Delta t) - \left[\frac{\rho C p_n (r_n^2 - r_{n-1}^2)}{\Delta t} \right] T_n(t) \quad (II.58)
 \end{aligned}$$

where the boundary condition

$$\phi(t) \quad t > 0 \quad (II.59)$$

replaces Eqs. (II.31) and (II.32). Using the assumption that the heat flow between nodes is constant at any r between the nodes [the basis for Eqs. (II.26) and (II.19)] over the domain (r_H, r_S) , then

$$\begin{aligned}
 \phi &= \left[\frac{2}{\frac{1}{r_n h_f} + \frac{\ln(r_n/\bar{r}_n)}{k_n}} \right] (T_n - T_b) = \left[\frac{2k_n}{\ln(r_n/\bar{r}_n)} \right] (T_n - T_{surf}) \\
 &= 2r_n h_f (T_{surf} - T_b) \quad (II.60)
 \end{aligned}$$

In the inverse conduction problem, ϕ is unknown and Eq. (II.58) must be written as

$$\left[\frac{2\bar{k}_{n-1,n}}{\ln(\bar{r}_n/\bar{r}_{n-1})} \right] T_{n-1}(t + \Delta t) + \left[-\frac{2\bar{k}_{n-1,n}}{\ln(\bar{r}_n/\bar{r}_{n-1})} - \frac{\rho C p_n (r_n^2 - r_{n-1}^2)}{\Delta t} \right] \\ \times T_n(t + \Delta t) - \phi(t + \Delta t) = - \left[\frac{\rho C p_n (r_n^2 - r_{n-1}^2)}{\Delta t} \right] T_n(t) . \quad (\text{II.61})$$

Since $T(\bar{r}_{n-2}, t)$ from Eq. (II.53) is known, there are still n unknowns where ϕ replaces T_{n-2} in $\bar{T}_F$. Also, column $n-2$ of $\bar{H}_F$ must be set equal to zero with $h_{n,n-2}$ set equal to -1 [the coefficient of ϕ in the n th equation (II.61)] and the corresponding members of $\bar{B}_F$ modified. The matrix formulation of the inverse conduction model is

$$\bar{H}_I \bar{T}_I = \bar{B}_I , \quad (\text{II.62})$$

where $\bar{H}_I$ is the tridiagonal coefficient matrix of the system with

$$\bar{H}_I = \begin{bmatrix} h_{1,1} & h_{1,2} & 0 & 0 & \dots & 0 & 0 & 0 & 0 & 0 \\ h_{2,1} & h_{2,2} & h_{2,3} & 0 & \dots & 0 & 0 & 0 & 0 & 0 \\ 0 & h_{3,2} & h_{3,3} & h_{3,4} & \dots & 0 & 0 & 0 & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \dots & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \dots & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \dots & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & \dots & h_{n-3,n-4} & h_{n-3,n-3} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 & h_{n-2,n-3} & 0 & h_{n-2,n-1} & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 & h_{n-1,n-1} & h_{n-1,n} \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & -1 & h_{n,n-1} & h_{n,n} \end{bmatrix} \quad (\text{II.63})$$

and with the coefficient terms for the interior nodes and exterior nodes the same as Eqs. (II.37) to (II.43) except for the following:

$$h_{n-3,n-2} = 0 , \quad (II.64)$$

$$h_{n-2,n-2} = 0 , \quad (II.65)$$

$$h_{n-1,n-2} = 0 , \quad (II.66)$$

$$h_{n,n-2} = -1 , \quad (II.67)$$

$$h_{n,n} = - \frac{2\bar{k}_{n-1,n}}{\ln (\bar{r}_n/\bar{r}_{n-1})} - \frac{\rho C p_n (r_n^2 - r_{n-1}^2)}{\Delta t} . \quad (II.68)$$

$\bar{T}_I$ is a column vector of unknowns where

$$\bar{T}_I = \begin{bmatrix} T_1 \\ T_2 \\ \cdot \\ \cdot \\ \cdot \\ T_f \\ \cdot \\ \cdot \\ \cdot \\ \phi \\ T_{n-1} \\ T_n \end{bmatrix} \quad (II.69)$$

(note that T_{n-2} is replaced by ϕ). $\bar{B}_I$ is a column vector of knowns where

$$\bar{B}_I = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ b_{n-3} \\ b_{n-2} \\ b_{n-1} \\ b_n \end{bmatrix} \quad (II.70)$$

Modifications required for the b 's are

$$b_{n-3} = - \left[\frac{\rho C p_{n-3} (r_{n-3}^2 - r_{n-4}^2)}{\Delta t} \right] T_{n-3}(t) - \left[\frac{2\bar{k}_{n-3,n-2}}{\ln (\bar{r}_{n-2}/\bar{r}_{n-3})} \right] T_{n-2}(t + \Delta t), \quad (II.71)$$

$$b_{n-2} = - \left[\frac{\rho C p_{n-2} (r_{n-2}^2 - r_{n-3}^2)}{\Delta t} \right] T_{n-2}(t) - \left[\frac{2\bar{k}_{n-3,n-2}}{\ln (\bar{r}_{n-2}/\bar{r}_{n-3})} - \frac{\rho C p_{n-2} (r_{n-2}^2 - r_{n-3}^2)}{\Delta t} - \frac{2\bar{k}_{n-2,n-1}}{\ln (\bar{r}_{n-1}/\bar{r}_{n-2})} \right] \times T_{n-2}(t + \Delta t), \quad (II.72)$$

$$b_{n-1} = - \left[\frac{\rho C p_{n-1} (r_{n-1}^2 - r_{n-2}^2)}{\Delta t} \right] T_{n-1}(t) - \left[\frac{2\bar{k}_{n-2,n-1}}{\ln (\bar{r}_{n-1}/\bar{r}_{n-2})} \right] T_{n-2}(t + \Delta t) , \quad (\text{II.73})$$

$$b_n = - \left[\frac{\rho C p_n (r_n^2 - r_{n-1}^2)}{\Delta t} \right] T_n(t) . \quad (\text{II.74})$$

Equation (II.62) is solved similarly to Eq. (II.35),

$$T_i = \sum_{j=1,n} h_{i,j}^{-1} b_j \quad (\text{II.75})$$

$i = 1, n$ $i \neq n-2$, and

$$\phi = \sum_{j=1,n} h_{n-2,j}^{-1} b_j . \quad (\text{II.76})$$

The surface temperature is then calculated from ϕ by

$$T_{\text{surf}}(t + \Delta t) = T_n(t + \Delta t) - \phi(t + \Delta t) / \left(\frac{2k_n}{\ln (\bar{r}_n/\bar{r}_n)} \right) . \quad (\text{II.77})$$

The model development in this section was made for the "general" rod with an internal heat source shown in Fig. II-2. The development of the inverse model specifically for the THTF heaters is given in Appendix B. A description of the THTF heaters is presented in Appendix A.

The boundary condition calculated in Eq. (II.76) is the time-averaged linear surface heat rate divided by π for the time interval Δt ,

$$\phi = \frac{\int_t^{t+\Delta t} \phi \, dt}{\int_t^{t+\Delta t} dt}, \quad (\text{II.78})$$

where ϕ is the instantaneous linear surface heat rate divided by π . The time-averaged surface heat flux (Ψ) is calculated from ϕ by

$$\Psi = \frac{\phi}{(2r_n)}. \quad (\text{II.79})$$

One of the specific objectives of the ORNL-PWR-EDHT separate-effects program is the calculation of the local heat transfer coefficient and the local fluid properties during the blowdown transient; since ORINC cannot do the calculation independently, it is necessary that it be coupled or interfaced with a thermal-hydraulics code which calculates these properties and the local fluid bulk temperature (or local saturation temperature). Consequently, ORINC is presently interfaced²¹ with a RELAP²² model of the THTF core (Fig. II-3)²³ which is driven by a similar model of the THTF loop (Fig. II-4).²³ A 'heat transfer coefficient' can be calculated from ϕ [Eq. (II.76)], T_{surf} [Eq. (II.77)] from ORINC, and T_b (average local fluid bulk temperature) or T_{sat} (local saturation temperature) from RELAP by

$$h_b = \frac{\Psi}{(T_{\text{surf}} - T_b)} \quad (\text{II.80})$$

$$h_{\text{sat}} = \frac{\Psi}{(T_{\text{surf}} - T_{\text{sat}})} \quad (\text{II.81})$$

There is no a priori method at present for deciding which calculation is correct, so both are made. It must be noted that h_b and h_{sat} are calculated from the time-averaged heat flux (Ψ) and the end of the time-step temperatures (T_{surf} , and T_b or T_{sat}).

Fig. II-3. RELAP test section model.

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Fig. II-4. RELAP model for THTF.

CHAPTER III

INVERSE COMPUTER PROGRAM

Code Description

ORINC is an inverse computer program which solves a one-dimensional, transient, lumped-parameter, implicit formulation of the conduction equation at each thermocouple position. The code uses the techniques and equations presented in Section II and, more specifically, those presented in Appendix B for the THTF heaters discussed in Appendix A.

The program is currently operational on the ORNL IBM 360/91 and 360/195 computers. It consists of approximately 3200 lines of coding, including a main driving routine, 26 subroutines and subprograms, and a block data section. The programming language is FORTRAN IV.

A complete listing of ORINC is presented in Appendix C. Table D-1 of Appendix D contains a list of all subroutines, subprograms, and multiple subroutine entry points in ORINC along with a brief description of their functions in the code. A flowchart (with clarifying comments) of the logic in the main driving routine is presented in Fig. D-1 of Appendix D.

Code Verification

The method for testing ORNL's ability to determine the local heat transfer coefficient as a function of calculated local conditions and, in effect, serve as an instrument for verifying ORINC was agreed upon by NRC²⁴ and ORNL,²⁵ and is briefly outlined in the following paragraph.

Upon receipt of RELAP-4, Version 5 from Reactor Safety Research (RSR), the loop and core of the THTF were modeled by the analysis group of the BDHT program. After the models were reviewed by RSR, a heated bundle blow-down case was to be selected from the THTF test matrix¹ and a RELAP4 run performed at ORNL. The results and input decks for the dry run were supplied to RSR. The local fluid conditions and pin radial temperatures (at the internal thermocouple locations) generated by the RELAP4 dry run were used as forcing functions in ORINC for calculation of the sheath surface

temperature, surface flux, and local heat transfer coefficient. The ORINC generated values were then compared with those in the RELAP4 dry run.

Blowdown test 104 was selected from the test matrix for the transient specified by NRC. ORINC runs were made for the 'hot spot' and 'average' nodes²⁶ based on the RELAP4 ORNL-THTF core model results.²⁷ Figures III-1 to III-6²⁸ are overlays of ORINC predictions with RELAP generated values. As shown by these figures, the ORINC dry run results compare favorably with the RELAP4 dry run predictions.

At the time the dry run was conducted, the automatic interfaces and plotting routines for ORINC did not exist; thus, the overlays in Figs. III-1 to III-6 are hand-plotted.

Application of ORINC for THTF Blowdown 104

The fully interfaced version of ORINC has been used to analyze the data from THTF blowdown 104.²⁹ The coefficient data tape contained the final calibration and regression data (Appendix A) for the 100 series tests with gap bias data for test 104. The RELAP-ORINC interface²¹ tape was generated by the best estimate THTF RELAP core model²³ which was driven by the THTF RELAP loop model.²³

Four examples (at thermocouples TE-322AE, TE-318BG, TE-304CH, and TE-301DJ) of ORINC unit 6 output for this test case are presented in Appendix E. Figures III-7 to III-22 are four sets of graphs for these thermocouples. Each set consists of the following: (1) overlay of the ORINC and RELAP4 predicted surface heat fluxes, (2) overlay of the ORINC and RELAP4 predicted surface temperatures, (3) overlay of ORINC and RELAP4 predicted heat transfer coefficients, and (4) the corresponding RELAP4 core volume pressure, bulk averaged temperature, and saturation temperature.

THTF CORE MODEL--TEST 104--FOR 'DRY RUN'

Fig. III-1. Overlay of ORINC and RELAP predicted surface heat fluxes for core hot node (dry run 104).

THTF CORE MODEL--TEST 104--FOR 'DRY RUN'

Fig. III-2. Overlay of ORINC and RELAP predicted surface temperatures for core hot node (dry run 104).

THTF CORE MODEL--TEST 104--FOR 'DRY RUN'

Fig. III-3. Overlay of ORINC and RELAP predicted heat transfer coefficients for core hot node (dry run 104).

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THTF CORE MODEL--TEST 104--FOR 'DRY RUN'

Fig. III-4. Overlay of ORINC and RELAP predicted surface heat fluxes for core average node (dry run 104).

THTF CORE MODEL--TEST 104--FOR 'DRY RUN'

Fig. III-5. Overlay of ORINC and RELAP predicted surface temperatures for core average node (dry run 104).

THIF CORE MODEL--TEST 104--FOR 'DRY RUN'

Fig. III-6. Overlay of ORINC and RELAP predicted heat transfer coefficients for core average node (dry run 104).

Fig. III-7. Overlay of ORINC and RELAP predicted surface heat fluxes (THTF test 104, TE-322AE).

Fig. III-8. Overlay of ORINC and RELAP predicted surface temperatures (THTF test 104, TE-322AE).

THTF BLOW-DOWN TEST NO.104 PRELIMINARY BD104.BE.P1

Fig. III-9. Overlay of ORINC and RELAP predicted heat transfer coefficients (THTF test 104, TE-322AE).

THTF BLOW-DOWN TEST NO.104 PRELIMINARY BD104.BE.P1

Fig. III-10. RELAP predicted core volume pressure, bulk temperature, and saturation temperature (for heat slab relative to TE-322AE).

Fig. III-11. Overlay of ORINC and RELAP predicted surface heat fluxes (THTF test 104, TE-318BG).

Fig. III-12. Overlay of ORINC and RELAP predicted surface temperatures (THTF test 104, TE-318BG).

THTF BLOW-DOWN TEST NO. 104 PRELIMINARY BD104.BE.P1

Fig. III-13. Overlay of ORINC and RELAP predicted heat transfer coefficients (THTF test 104, TE-318BG).

THTF BLOW-DOWN TEST NO. 104 PRELIMINARY BD104.BE.P1

Fig. III-14. RELAP predicted core volume pressure, bulk temperature, and saturation temperature (for heat slab relative to TE-318BG).

Fig. III-15. Overlay of ORINC and RELAP predicted surface heat fluxes (THTF test 104, TE-304CH).

Fig. III-16. Overlay of ORINC and RELAP predicted surface temperatures (THTF test 104, TE-304CH).

THTF BLOW-DOWN TEST NO. 104 PRELIMINARY BD104.BE.P1

Fig. III-17. Overlay of ORINC and RELAP predicted heat transfer coefficients (THTF test 104, TE-304CH).

THTF BLOW-DOWN TEST NO. 104 PRELIMINARY BD104.BE.P1

Fig. III-18. RELAP predicted core volume pressure, bulk temperature, and saturation temperature (for heat slab relative to TE-304CH).

Fig. III-19. Overlay of ORINC and RELAP predicted surface heat fluxes (THTF test 104, TE-301DJ).

Fig. III-20. Overlay of ORINC and RELAP predicted surface temperatures (THTF test 104, TE-301DJ).

THTF BLOW-DOWN TEST NO. 104 PRELIMINARY BD104.BE.P1

Fig. III-21. Overlay of ORINC and RELAP predicted heat transfer coefficients (THTF test 104, TE-301DJ).

THTF BLOW-DOWN TEST NO. 104 PRELIMINARY BD104.BE.P1

Fig. III-22. RELAP predicted core volume pressure, bulk temperature, and saturation temperature (for heat slab relative to TE-301DJ).

CHAPTER IV

CONCLUSIONS

An implicit technique has been developed to determine both the transient surface temperature and the transient surface heat flux of electrically heated rods during a simulated loss-of-coolant accident. A computer code (ORINC) has been developed using this technique; the code will be used in subsequent analysis of THTF-BDHT test data.

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APPENDICES

APPENDIX A

THTF HEATERS

Heater Rod Description¹

The indirect electric heater rods used in THTF bundle 1 are 1.0719 cm diam (0.422 in.) with a stepped, chopped-cosine power profile length of 365.76 cm (12 ft) (Fig. A-1). The overall rod length is 548.64 to 640.08 cm (18 to 21 ft), depending on its location in the bundle. The rod is double-ended, with the sheath and ground-lead extension welded together at the lower end and the power lead insulated from the sheath at the upper end.

The heater rods have a dual-sheath design (see rod cross section in Fig. A-2). The outer sheath is 0.0254-cm-thick (0.010-in.) stainless steel; the inner sheath is 0.0762-cm-thick (0.030-in.) stainless steel and is grooved to accept the 0.0508-cm (0.020-in.) chromel vs alumel thermocouples. The next inner layer is boron nitride, which electrically insulates the heating element from the stainless steel sheaths. The heater element consists of a series of oversleeves swaged over a central base tube to provide the heat-generation zones. The central 'hot zone' consists of only the base Inconel 600 heater tube; this zone has the highest electrical resistance and maximum heat generation rate. Successive oversleeves of Inconel 600 or Cupro Nickel are swaged over the heater element with each succeeding oversleeve extending to the end. As oversleeves are added between the central zone and the ends, the resistance and heat generation rates of that particular zone decrease so that the step-changes approximate the desired chopped-cosine power profile shown in Fig. A-3. The lengths of the steps for different power levels were chosen to match the integrated chopped-cosine power profile (Fig. A-4). Nominal heated zone lengths, power ratios, and local powers for THTF heaters are given in Table A-1. The core of the heater element is filled with MgO, which is both a filler and insulator between the heating element and the central rod thermocouple sheaths.

Fig. A-1. Indirect heater rod assembly. (1 in. = 2.54 cm)

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Fig. A-2. Heater rod cross section. (1 in. = 2.54 cm)

Fig. A-3. Power profile of prototype heater. (1 ft = 30.48 cm)

Fig. A-4. Integrated power profile of stepped, chopped-cosine heater rod compared to the integrated power profile of a smooth chopped-cosine curve. (1 ft = 30.48 cm)

Table A-1. Nominal power profile for the
THTF indirect heater with average power
of 12 kW/ft

(1 in. = 2.54 cm, 1 kW/ft = 3.28084 kW/m)

Length of heated zone from beginning (in.)	Local/average power ratio	Local power rate (kW/ft)
0-18	0.422	5.06
18-31.5	0.597	7.16
31.5-42	1.065	12.78
42-54	1.285	15.42
54-90	1.67	20.0
90-102	1.285	15.42
102-112.5	1.065	12.78
112.5-126	0.597	7.16
126-144	0.422	5.06

The sheath thermocouples are located in axial grooves (two per groove) machined in the inner sheath. After the tips of the thermocouple sheath are spot-welded at the proper location, a stainless steel filler rod is added to the remainder of the groove (Fig. A-5). The heater is then slipped into the 0.0254-cm-thick outer sheath and the whole assembly is swaged down to a 1.0719-cm OD.

BDHT heater 150-5 (originally S/N-5) was cross-sectioned and micro-photographed³⁰ by the Y-12 Development Division Metallurgical Department. A typical cross section (Fig. A-6) shows the peripheral location of sheath thermocouples and heater components. Blow-ups of the inner sheath groove area (Fig. A-7) reveal that the groove has been milled to a depth of 0.0394 cm (0.0155 in.), which is less than the original 0.0508-cm OD of the thermocouple. As a result, during swaging operations the thermocouple is crushed to a somewhat elliptical shape and the edge of the milled groove is pulled away from the outer sheath (Fig. A-7). A review of all photographs of cross sections at thermocouple bead junctions in heater 150-5 results in the composite drawing shown in Fig. A-8.

Fig. A-5. Typical thermocouple junction configuration.

Fig. A-6. Cross section of BDHT heater 150-5.

Fig. A-7. Cross section of sheath thermocouples in BDHT heater
150-5.

Fig. A-8. Segment of heater rod showing mean dimensions in the thermocouple area. (1 in. = 2.54 cm)

Heater Rod Bundle¹

The bundle consists of 49 rods in a 7×7 array spaced on 1.43-cm (0.563-in.) centers which are contained in a 10.16-cm-square (4-in.) shroud box. Low-pressure-drop grid spacers are provided at approximately 30.48-cm (12-in.) intervals along the box (Fig. A-9). The shroud box supports the spacer grids and forms the bundle flow channel. A cross section of the test section with the shroud box and bundle assembly in place is shown in Fig. A-10.

The nominal locations of thermocouples, together with locations of power steps and spacer grids, are summarized in Table A-2. After the assembly of THTF bundle 1, all thermocouples were tested for open circuits; 337 of 348 sheath thermocouples and 75 of 106 center thermocouples were in good condition. The distribution of these thermocouples in bundle 1 is presented on a grid map in Fig. A-11. A schematic illustration showing the locations of thermocouples at different levels is given in Fig. A-12.

Of the available 'good' sheath thermocouples, 50 are monitored by a multichannel temperature monitor (metrascopes) with the thermal responses visually displayed. The rods that are cross-hatched in Fig. A-13 are monitored by the metrascopes. Also, there are 19 thermocouples on level 0 for which the inverse model in ORINC is not applicable. Therefore, of the thermocouples which are scanned by the computer controlled data acquisition system (CCDAS), there are 266 possible positions in THTF bundle 1 for which inverse calculations can be made.

Heater Rod Radial Dimensions

For the inverse model and calculations, it is essential that the internal radial dimensions of the heater rod be as accurate as possible. However, due to the rod manufacturing procedure, these dimensions are not readily available (i.e., as specifications or in any published form). The following description of the manufacturing procedure clarifies the reasons for this problem. The internal thermocouple cluster along with a piano wire stiffener are inserted into the Inconel tube; MgO cores are inserted over the thermocouple cluster. This assembly is then swaged down to a given outer diameter, crushing and compacting the MgO. Successive sleeves

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Fig. A-9. Low-pressure-drop spacer grid assembly. (1 in. = 2.54 cm)

Fig. A-10. Test section using indirect heater rod in 49-rod bundle.
(1 ft = 0.3048 m)

Table A-2. Nominal location of thermocouples in
THTF bundle 1 relative to power zone steps
and grid spacers

(1 in. = 2.54 cm)

Distance (in.) from lower end of heated zone ^a	Grid spacer location	Nominal power		Thermo- couple level
		kW/m	kW/ft	
-3/4 to +3/4 1	X	↑	↑	A
11 1/2 to 12 5/8 13 1/8	X	14.12 ↓	4.30 ↓	B
18 19		↑ 19.95	↑ 5.08	C
23 to 24 1/2 31 1/2	X	↓	↓	
34 7/8 to 36 3/8 36 7/8	X	↑ 35.56	↑ 10.84	D
42 43		↓ ↑	↓ ↑	E
45 1/2 to 47 54	X	42.91 ↓	13.08 ↓	
55		↑	↑	F
58 5/8 to 60 1/8 70 1/2 to 72	X X	↑	↑	
77		55.77 ↓	17.0 ↓	G
82 3/8 to 83 7/8 89	X	↓	↓	H
90 93		↑	↑	I
93 1/2 to 95 101	X	42.91 ↓	13.08 ↓	J
102 105 5/8		↑	↑	K
106 1/8 to 107 5/8 111 1/2	X	35.56 ↓	10.84 ↓	L
112 1/2 118 to 119 1/2	X	↑	↑	
125		19.95 ↓	6.08 ↓	M
126 129 7/8 to 131 3/8	X	↑	↑	
141 1/4 141 3/4 to 143 1/4	X	14.12 ↓	4.30 ↓	N
144 145 1/4		1.21	0.37	O

^aDistances in most cases are nominal and $\pm 1/4$ in.

Fig. A-11. Distribution of thermocouples in THTF test bundle 1 (May 24, 1976).

Fig. A-12. Location of thermocouples in THTF bundle 1. (1 in. = 2.54 cm)

Fig. A-13. THTF test bundle 1 rods monitored by metrascope (shown by cross-hatching).

of Inconel or Cupro Nickel are swaged over the base tube to a uniform outside diameter (further compacting the core and elongating the assembly). The finished heater assembly is placed inside the inner stainless steel sheath, and boron nitride (BN) powder is poured into the annular region and compacted. Another swaging operation is performed and the grooves are milled in the surface. The sheath thermocouples are subsequently tack welded in the grooves and filler rods are added; this assembly is inserted in the outer sheath for the final swaging operation. Obviously, each swaging operation compacts (and elongates) the ceramic insulators and thins (and elongates) the metallic annular regions of the assembly.

The Y-12 Development Division Metallurgical Department measured the internal dimensions³¹ of the cross sections of BDHT heater 150-5. The radial dimensions used by ORINC for THTF bundle 1 inverse calculations are tabulated in Table A-3 (see Fig. A-12 for zone designations).

Heater Rod Component Physical Properties

The inverse model and code requires the following physical properties for each component in the heater rod: density ρ , thermal conductivity k , and specific heat C_p .

An extensive literature search³²⁻⁴³ was conducted to collect the available physical property information for MgO, Inconel-600, Cupro Nickel, BN, and 316 stainless steel. Except for the thermal conductivities of MgO and BN, the optimum polynomial fit in terms of temperature was determined for the heat capacity and thermal conductivity of each component. These least-squares fits are presented in Tables A-4 to A-8.

The difficulty in presenting a single curve for the thermal conductivity of MgO is that it is an extreme function of the packed density (porosity) of the ceramic.³² As stated previously in the description of the rod manufacturing technique, the compaction of the MgO core varies depending on the axial position in the rod. Therefore, the effective MgO thermal conductivity must be determined in situ and is part of the rod calibration procedure.⁴⁴

Table A-3. THTF heater radial dimensions

Zone (refer to Fig. A-12)	MgO outer diam [cm (in.)]	Base Inconel thickness [cm (in.)]	1st Inconel oversleeve thickness [cm (in.)]	2nd Inconel oversleeve thickness [cm (in.)]	1st Cu-Ni oversleeve thickness [cm (in.)]	2nd Cu-Ni oversleeve thickness [cm (in.)]	Boron nitride thickness [cm (in.)]	Inner SS sheath thickness [cm (in.)]	Outer SS sheath thickness [cm (in.)]
I	0.5527 (0.2176)	0.0335 (0.0132)					0.1270 (0.0500)	0.0762 (0.0300)	0.0254 (0.0100)
II	0.5319 (0.2094)	0.0340 (0.0134)	0.0099 (0.0039)				0.1270 (0.0500)	0.0762 (0.0300)	0.0254 (0.0100)
III	0.5126 (0.2018)	0.0348 (0.0137)	0.0099 (0.0039)	0.0089 (0.0035)			0.1270 (0.0500)	0.0762 (0.0300)	0.0254 (0.0100)
IV	0.4831 (0.1902)	0.0356 (0.0140)	0.0099 (0.0039)	0.0089 (0.0035)	0.0140 (0.0055)		0.1270 (0.0500)	0.0762 (0.0300)	0.0254 (0.0100)
V	0.4552 (0.1792)	0.0356 (0.0140)	0.0099 (0.0039)	0.0089 (0.0035)	0.0140 (0.0055)	0.0140 (0.0055)	0.1270 (0.0500)	0.0762 (0.0300)	0.0254 (0.0100)
Zone	MgO outer radius [cm (in.)]	Inconel outer radius [cm (in.)]	Cu-Ni outer radius [cm (in.)]	Boron nitride outer radius [cm (in.)]	Inner sheath outer radius [cm (in.)]	Outer sheath outer radius [cm (in.)]			
I	0.2764 (0.1088)	0.3099 (0.1220)		0.4369 (0.1720)	0.5131 (0.2020)	0.5385 (0.2120)			
II	0.2659 (0.1047)	0.3099 (0.1220)		0.4369 (0.1720)	0.5131 (0.2020)	0.5385 (0.2120)			
III	0.2563 (0.1009)	0.3099 (0.1220)		0.4369 (0.1720)	0.5131 (0.2020)	0.5385 (0.2120)			
IV	0.2416 (0.0951)	0.2959 (0.1165)	0.3099 (0.1220)	0.4369 (0.1720)	0.5131 (0.2020)	0.5355 (0.2120)			
V	0.2276 (0.0896)	0.2819 (0.1110)	0.3099 (0.1220)	0.4369 (0.1720)	0.5131 (0.2020)	0.5355 (0.2120)			

Table A-4. Physical property data for Inconel 600

$$1 \text{ Btu/hr-ft-}^\circ\text{F} = 1.73 \text{ W/m-}^\circ\text{C}$$

$$1 \text{ Btu/lb-}^\circ\text{F} = 1 \text{ cal/g-}^\circ\text{C}$$

$$1 \text{ lb/ft}^3 = 0.01602 \text{ g/cm}^3$$

$$^\circ\text{C} = 5/9 (^\circ\text{F} - 32)$$

$$\text{Density} = 526 \text{ lb/ft}^3$$

$$\text{Melting point} = 2500\text{--}2600^\circ\text{F}$$

Temperature ($^\circ\text{F}$)	Specific heat, C_p ($\text{Btu/lb-}^\circ\text{F}$)	Thermal conductivity, k ($\text{Btu/hr-ft-}^\circ\text{F}$)
0.	0.0977	8.4
50.	0.1011	8.6
100.	0.1041	8.7
150.	0.1068	8.9
200.	0.1092	9.1
250.	0.1113	9.3
300.	0.1132	9.5
350.	0.1148	9.7
400.	0.1163	9.9
450.	0.1176	10.2
500.	0.1188	10.4
550.	0.1199	10.6
600.	0.1209	10.9
650.	0.1218	11.2
700.	0.1228	11.4
750.	0.1237	11.7
800.	0.1247	12.0
850.	0.1257	12.2
900.	0.1270	12.5
950.	0.1283	12.8
1000.	0.1297	13.1
1050.	0.1314	13.4
1100.	0.1332	13.7
1150.	0.1353	14.0
1200.	0.1377	14.3
1250.	0.1404	14.6
1300.	0.1434	14.9
1350.	0.1467	15.2
1400.	0.1503	15.5
1450.	0.1546	15.8
1500.	0.1592	16.1
1550.	0.1643	16.4
1600.	0.1698	16.7
1650.	0.1759	17.0
1700.	0.1826	17.3
1750.	0.1898	17.6
1800.	0.1977	17.8

Best polynomial fit to data for C_p and k :

$$C_p = 9.77430344 \times 10^{-2} + 7.11642706 \times 10^{-5} T - 7.72415660 \times 10^{-8} T^2 + 3.80815379 \times 10^{-11} T^3,$$

$$k = 8.42944336 + 2.88105011 \times 10^{-3} T + 2.42143869 \times 10^{-6} T^2 - 6.19365692 \times 10^{-10} T^3,$$

where k has units of $\text{Btu/hr-ft-}^\circ\text{F}$, C_p has units of $\text{Btu/lb-}^\circ\text{F}$, and T has units of $^\circ\text{F}$.

Table A-5. Physical property data for Cupro Nickel

$$1 \text{ Btu/hr-ft-}^{\circ}\text{F} = 1.73 \text{ W/m-}^{\circ}\text{C}$$

$$1 \text{ Btu/lb-}^{\circ}\text{F} = 1 \text{ cal/g-}^{\circ}\text{C}$$

$$1 \text{ lb/ft}^3 = 0.01602 \text{ g/cm}^3$$

$$^{\circ}\text{C} = 5/9 (^{\circ}\text{F} - 32)$$

$$\text{Density} = 553 \text{ lb/ft}^3$$

$$\text{Melting point} = 2140\text{--}2280^{\circ}\text{F}$$

Temperature ($^{\circ}\text{F}$)	Specific heat, C_p (Btu/lb- $^{\circ}\text{F}$)	Thermal conductivity, k (Btu/hr-ft- $^{\circ}\text{F}$)
0.	0.0950	16.8
50.	0.0965	16.8
100.	0.0978	17.1
150.	0.0991	17.5
200.	0.1004	18.0
250.	0.1016	18.6
300.	0.1027	19.3
350.	0.1039	20.1
400.	0.1049	21.0
450.	0.1060	21.9
500.	0.1070	22.8
550.	0.1080	23.8
600.	0.1090	24.9
650.	0.1100	26.1
700.	0.1110	27.3
750.	0.1119	28.6
800.	0.1129	30.0
850.	0.1139	31.5
900.	0.1149	33.2
950.	0.1159	35.1
1000.	0.1169	37.2
1050.	0.1180	39.5
1100.	0.1191	42.2
1150.	0.1203	45.2
1200.	0.1215	48.6
1250.	0.1227	52.4
1300.	0.1240	56.8
1350.	0.1253	61.7
1400.	0.1268	67.2
1450.	0.1282	73.4
1500.	0.1298	80.4
1550.	0.1314	88.3
1600.	0.1332	97.0
1650.	0.1350	106.8
1700.	0.1369	117.6
1750.	0.1389	129.6
1800.	0.1410	142.9

Best polynomial fit to data for C_p and k .

$$C_p = 9.50193405 \times 10^{-2} + 2.93776393 \times 10^{-5} T - 1.41008059 \times 10^{-8} T^2 + 6.65068001 \times 10^{-12} T^3,$$

$$k = 1.68024902 \times 10^1 - 1.31225586 \times 10^{-1} T + 4.43458557 \times 10^{-5} T^2 - 4.77302819 \times 10^{-8} T^3 + 2.50679477 \times 10^{-11} T^4,$$

where k has units of Btu/hr-ft- $^{\circ}\text{F}$, C_p has units of Btu/lb- $^{\circ}\text{F}$, and T has units of $^{\circ}\text{F}$.

Table A-6. Physical property data for 316 stainless steel

$$1 \text{ Btu/hr-ft-}^\circ\text{F} = 1.73 \text{ W/m-}^\circ\text{C}$$

$$1 \text{ Btu/lb-}^\circ\text{F} = 1 \text{ cal/g-}^\circ\text{C}$$

$$1 \text{ lb/ft}^3 = 0.01602 \text{ g/cm}^3$$

$$^\circ\text{C} = 5/9 (^\circ\text{F} - 32)$$

$$\text{Density} = 496 \text{ lb/ft}^3$$

$$\text{Melting point} = 2500\text{--}2550^\circ\text{F}$$

Temperature ($^\circ\text{F}$)	Specific heat, Cp (Btu/lb- $^\circ\text{F}$)	Thermal conductivity, k (Btu/hr-ft- $^\circ\text{F}$)
0.	0.1042	7.2
50.	0.1072	7.5
100.	0.1099	7.7
150.	0.1124	8.0
200.	0.1148	8.2
250.	0.1170	8.5
300.	0.1190	8.7
350.	0.1209	8.9
400.	0.1227	9.1
450.	0.1243	9.4
500.	0.1259	9.6
550.	0.1274	9.8
600.	0.1288	10.0
650.	0.1301	10.2
700.	0.1313	10.4
750.	0.1325	10.7
800.	0.1337	10.9
850.	0.1348	11.1
900.	0.1359	11.3
950.	0.1369	11.5
1000.	0.1380	11.7
1050.	0.1390	11.9
1100.	0.1400	12.1
1150.	0.1411	12.4
1200.	0.1421	12.6
1250.	0.1431	12.8
1300.	0.1442	13.0
1350.	0.1452	13.2
1400.	0.1463	13.5
1450.	0.1474	13.7
1500.	0.1485	13.9
1550.	0.1496	14.2
1600.	0.1508	14.4
1650.	0.1519	14.7
1700.	0.1531	14.9
1750.	0.1543	15.2
1800.	0.1556	15.4

Best polynomial fit to data for Cp and k:

$$\begin{aligned} \text{Cp} &= 1.04247093 \times 10^{-1} + 6.05583191 \times 10^{-5} T - 4.37721610 \\ &\quad \times 10^{-8} T^2 + 2.01225703 \times 10^{-11} T^3 - 3.16413562 \times 10^{-15} T^4, \\ k &= 7.24584961 + 5.07926941 \times 10^{-3} T - 9.89995897 \times 10^{-7} T^2 \\ &\quad + 3.82840426 \times 10^{-10} T^3, \end{aligned}$$

where k has units of Btu/hr-ft- $^\circ\text{F}$, Cp has units of Btu/lb- $^\circ\text{F}$, and T has units of $^\circ\text{F}$.

Table A-7. Physical property data for magnesium oxide

$$1 \text{ Btu/hr-ft-}^{\circ}\text{F} = 1.73 \text{ W/m-}^{\circ}\text{C}$$

$$1 \text{ Btu/lb-}^{\circ}\text{F} = 1 \text{ cal/g-}^{\circ}\text{C}$$

$$1 \text{ lb/ft}^3 = 0.01602 \text{ g/cm}^3$$

$$^{\circ}\text{C} = 5/9 (^{\circ}\text{F} - 32)$$

$$\text{Density} = 212 \text{ lb/ft}^3$$

Temperature ($^{\circ}\text{F}$)	Specific heat, Cp (Btu/lb- $^{\circ}\text{F}$)
0.	0.2243
50.	0.2302
100.	0.2359
150.	0.2413
200.	0.2463
250.	0.2511
300.	0.2557
350.	0.2599
400.	0.2639
450.	0.2677
500.	0.2712
550.	0.2745
600.	0.2776
650.	0.2805
700.	0.2832
750.	0.2856
800.	0.2879
850.	0.2901
900.	0.2920
950.	0.2938
1000.	0.2955
1050.	0.2970
1100.	0.2984
1150.	0.2997
1200.	0.3009
1250.	0.3020
1300.	0.3030
1350.	0.3039
1400.	0.3047
1450.	0.3055
1500.	0.3062
1550.	0.3069
1600.	0.3075
1650.	0.3081
1700.	0.3087
1750.	0.3093
1800.	0.3098

Best polynomial fit to data for Cp:

$$\begin{aligned} \text{Cp} = & 2.24258423 \times 10^{-1} + 1.22666359 \\ & \times 10^{-4} T - 6.35191100 \times 10^{-8} T^2 \\ & + 1.21040955 \times 10^{-11} T^3, \end{aligned}$$

where Cp has units of Btu/lb- $^{\circ}\text{F}$ and T has units of $^{\circ}\text{F}$.

Table A-8. Physical property data for boron nitride

$$1 \text{ Btu/hr-ft-}^\circ\text{F} = 1.73 \text{ W/m-}^\circ\text{C}$$

$$1 \text{ Btu/lb-}^\circ\text{F} = 1 \text{ cal/g-}^\circ\text{C}$$

$$1 \text{ lb/ft}^3 = 0.01602 \text{ g/cm}^3$$

$$^\circ\text{C} = 5/9 (^\circ\text{F} - 32)$$

$$\text{Density} = 125 \text{ lb/ft}^3$$

Temperature ($^\circ\text{F}$)	Specific heat, C_p (Btu/lb- $^\circ\text{F}$)
0.	0.1678
50.	0.1859
100.	0.2031
150.	0.2195
200.	0.2352
250.	0.2500
300.	0.2641
350.	0.2775
400.	0.2901
450.	0.3021
500.	0.3134
550.	0.3241
600.	0.3342
650.	0.3437
700.	0.3526
750.	0.3610
800.	0.3689
850.	0.3763
900.	0.3832
950.	0.3897
1000.	0.3957
1050.	0.4014
1100.	0.4067
1150.	0.4116
1200.	0.4162
1250.	0.4205
1300.	0.4245
1350.	0.4283
1400.	0.4318
1450.	0.4352
1500.	0.4383
1550.	0.4413
1600.	0.4441
1650.	0.4469
1700.	0.4495
1750.	0.4521
1800.	0.4546

Best polynomial fit to data for C_p :

$$C_p = 1.67812347 \times 10^{-1} + 3.70264053 \times 10^{-4} T - 1.73793524 \times 10^{-7} T^2 + 3.14486215 \times 10^{-11} T^3,$$

where C_p has units of Btu/lb- $^\circ\text{F}$ and T has units of $^\circ\text{F}$.

There are several obstacles in the determination of the BN thermal conductivity: (1) thermal conductivity is a function of the packed density;³⁵ (2) most of the available data has been collected at temperatures in excess of 1089 K (1500°F), which is outside the range of our application;³² and (3) the thermal conductivity is dependent on the direction of the molding (or applied) pressure, i.e., the ratio of the conductivity measured perpendicular to the molding pressure to the conductivity measured parallel to the molding pressure can be as much as 2.³⁷ Therefore, the effective BN thermal conductivity must also be determined in situ as part of the rod calibration procedure.⁴⁴

Heater Rod Calibration⁴⁴

Because of rod-to-rod variance in manufacture, the mechanical and thermal transients involved during a blowdown of the THTF, and changing of the bundle response due to "aging," an extensive thermocouple calibration procedure was developed which supplies heater rod performance information to the inverse heat conduction model.

The heater rod is reduced to its final diameter by swaging, often creating an imperfect fit between the inner and outer sheaths at the thermocouple locations and resulting in a gap between the thermocouple junction and the outer sheath (Figs. A-6 and A-7).³⁰ The thermocouple is welded to the inner sheath, causing the gap between the junction and outer sheath to grow with increasing fluid temperature and to close with increasing heater power. With successive blowdown transients the residual gap increases, apparently due to plastic deformation of the outer sheath.

In order to improve the confidence band on the calculated surface heat flux and temperature, a four-part calibration program, ORTCAL,⁴⁴ and an experimental thermocouple calibration procedure were developed. Before each transient test, a succession of steady-state points at different heater rod power levels and fluid temperatures are taken. These points are accumulated on history tapes which contain all the information gathered for each thermocouple position from the first test to present. These tapes are then processed by the first two parts of ORTCAL.

The first part calculates basic gap information such as width and temperature drop and produces the "aging" history of each location. The second part uses the sheath thermocouple and middle thermocouple indicated temperatures to produce the effective thermal conductivity of the BN insulator. This provides necessary in situ information for the inverse program and gives an indication of the mechanical integrity of the heater.

Power drop tests are performed by the third part of ORTCAL which produces the effective thermal conductivity of the MgO insulator. The results indicate up to 20% porosity in this region.

The fourth part of ORTCAL does regression analysis on the output from part one to determine the expansion coefficients and proper bias points for the stainless steel annuli forming the gap. The mechanical model chosen to utilize this information is one-dimensional, which is consistent with the thermal model used in the inverse calculation.

The combined output from ORTCAL is a coefficient data tape which contains the regression and bias information for each thermocouple position in the THTF bundle. This information is then used by ORINC to simulate the thermo-mechanical response of the heater rod.

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APPENDIX B

INVERSE MODEL FOR THTF HEATERS

The derivation of the inverse model specifically for THTF heaters will be subdivided as follows:

1. Mathematical model of heat transfer inside a continuous substrate where the heat flow between nodes is assumed constant at any radial position between nodes (i.e., for the BN insulator and the inner and outer stainless steel sheaths).
2. Mathematical model of heat transfer inside a continuous substrate where the heat flow between nodes is assumed proportional to r^2 (i.e., for the MgO core and the laminated heater section).
3. Mathematical model of heat transfer at the MgO-to-heater interface.
4. Mathematical model of heat transfer at the Inconel-to-Cupro Nickel interface.
5. Mathematical model of heat transfer at the heater-to-BN interface.
6. Mathematical model of heat transfer at the BN-to-inner stainless steel sheath interface.
7. Mathematical model of heat transfer at the sheath-to-sheath interface.
8. Mathematical model of heat transfer at the outer sheath-to-fluid boundary.
9. Mathematical model of heat transfer from node 1 in the MgO core to the pin center line (or to $r = 0.0$).
10. Mathematical model of the thermal-mechanical behavior of the gap between the inner and outer stainless steel sheaths.

In sections 1 to 8, a slightly different approach from the general model derivation is used; for increased physical understanding, a heat balance is made on a node. The approach is different but the resulting equations are the same.

Note that in 3, 5, and 6, the derived models allow for gaps at the interfaces, which ORINC is coded to accept; at present, these gaps have zero width.

Mathematical Model of Heat Transfer Inside a Continuous
Substrate with Heat Flow Constant (Fig. B-1)

Assumptions:

1. Heat flow between nodes (e.g., $q_{i-1,i}$) is constant at any r between nodes,
2. Nodal mass $(\rho V)_i$ is constant,
3. Heat capacity Cp_i and thermal conductivity k_i are evaluated at the present nodal temperature $T_i(t)$.

A heat balance on the shaded area (node i) in Fig. B-1 yields

$$q_{i-1,i} - q_{i,i+1} + \dot{q}_i = \rho(CpV)_i \partial T_i / \partial t. \quad (B.1)$$

Using assumption 1,

$$q_{i-1,i} = -k_{i-1} 2\pi l \frac{(T@r_{i-1} - T_{i-1})}{\ln(r_{i-1}/\bar{r}_{i-1})} \quad (B.2)$$

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Fig. B-1. Schematic denoting element notation.

and

$$q_{i-1,i} = -k_i 2\pi\ell \frac{(T_i - T_{i-1})}{\ln(\bar{r}_i/r_{i-1})}; \quad (B.3)$$

adding Eqs. (B.2) and (B.3) and with transposition

$$q_{i-1,i} = - \left[\frac{\ln(r_{i-1}/\bar{r}_{i-1})}{2k_{i-1}} + \frac{\ln(\bar{r}_i/r_{i-1})}{2k_i} \right]^{-1} (T_i - T_{i-1})\pi\ell. \quad (B.4)$$

Similarly,

$$q_{i,i+1} = - \left[\frac{\ln(\bar{r}_{i+1}/r_i)}{2k_{i+1}} + \frac{\ln(r_i/\bar{r}_i)}{2k_i} \right]^{-1} (T_{i+1} - T_i)\pi\ell. \quad (B.5)$$

For the heat generation term,

$$\dot{q}_i = \dot{q}_i''' V_i = \dot{q}_i''' \pi\ell(r_i^2 - r_{i-1}^2). \quad (B.6)$$

Expansion of the accumulation term in Eq. (B.1) yields

$$\rho(CpV)_i \frac{\partial T_i}{\partial t} = \rho Cp_i \pi\ell(r_i^2 - r_{i-1}^2) \frac{T_i(t + \Delta t) - T_i(t)}{\Delta t}. \quad (B.7)$$

After substituting Eqs. (B.4), (B.5), (B.6), and (B.7) into (B.1) and dividing out $\pi\ell$, the implicit formulation of the equation is

$$\begin{aligned} & - \left[\frac{2}{\frac{\ln(\bar{r}_i/r_{i-1})}{k_i} + \frac{\ln(r_{i-1}/\bar{r}_{i-1})}{k_{i-1}}} \right] [T_i(t + \Delta t) - T_{i-1}(t + \Delta t)] \\ & + \left[\frac{2}{\frac{\ln(\bar{r}_{i+1}/r_i)}{k_{i+1}} + \frac{\ln(r_i/\bar{r}_i)}{k_i}} \right] [T_{i+1}(t + \Delta t) - T_i(t + \Delta t)] \\ & + \dot{q}_i'''(r_i^2 - r_{i-1}^2) = \left[\frac{\rho Cp_i(r_i^2 - r_{i-1}^2)}{\Delta t} \right] [T_i(t + \Delta t) - T_i(t)]. \quad (B.8) \end{aligned}$$

Rearranging Eq. (B.8) and collecting terms yields

$$\begin{aligned}
 & \left[\frac{2}{\frac{\ln(\bar{r}_i/r_{i-1})}{k_i} + \frac{\ln(r_{i-1}/\bar{r}_{i-1})}{k_{i-1}}} \right] T_{i-1}(t + \Delta t) \\
 & + \left[-\frac{2}{\frac{\ln(\bar{r}_i/r_{i-1})}{k_i} + \frac{\ln(r_{i-1}/\bar{r}_{i-1})}{k_{i-1}}} - \frac{\rho C p_i (r_i^2 - r_{i-1}^2)}{\Delta t} \right. \\
 & \left. - \frac{2}{\frac{\ln(\bar{r}_{i+1}/r_i)}{k_{i+1}} + \frac{\ln(r_i/\bar{r}_i)}{k_i}} \right] T_i(t + \Delta t) + \left[\frac{2}{\frac{\ln(\bar{r}_{i+1}/r_i)}{k_{i+1}} + \frac{\ln(r_i/\bar{r}_i)}{k_i}} \right] \\
 & \times T_{i+1}(t + \Delta t) = -\dot{q}_i (r_i^2 - r_{i-1}^2) - \left[\frac{\rho C p_i (r_i^2 - r_{i-1}^2)}{\Delta t} \right] T_i(t) . \quad (B.9)
 \end{aligned}$$

Mathematical Model of Heat Transfer Inside a Continuous Substrate
with Heat Flow Proportional to r^2 (Fig. B-1)

Assumptions:

1. Heat flow between nodes (e.g., $q_{i-1,1}$) is proportional to r^2 ,
2. Nodal mass $(\rho V)_i$ is constant,
3. Heat capacity $C p_i$ and thermal conductivity k_i are evaluated at the present nodal temperature $T_i(t)$.

A heat balance in the shaded area (node 1) in Fig. B-1 yields

$$q_{i-1,1} - q_{i,1+1} + \dot{q}_i = \rho (C p V)_i \partial T_i / \partial t . \quad (B.10)$$

Using assumption 1

$$q_{i-1,1} = -\frac{\bar{k}_{i-1,1} 4\pi l r_{i-1}^2}{(\bar{r}_i^2 - \bar{r}_{i-1}^2)} (T_i - T_{i-1}) , \quad (B.11)$$

where

$$\bar{k}_{i-1,i} = \frac{k_{i-1} + k_i}{2} . \quad (B.12)$$

Also,

$$\dot{q}_{i,i+1} = - \frac{\bar{k}_{i,i+1} 4\pi\ell r_i^2}{(\bar{r}_{i+1}^2 - \bar{r}_i^2)} (T_{i+1} - T_i) . \quad (B.13)$$

For the heat generation term,

$$\dot{q}_i = \dot{q}_i''' V_i = \dot{q}_i''' \pi\ell (r_i^2 - r_{i-1}^2) . \quad (B.14)$$

Expanding the accumulation term in Eq. (B.10),

$$\rho(CpV)_i \frac{\partial T_i}{\partial t} = \rho Cp_i \pi\ell (r_i^2 - r_{i-1}^2) \frac{T_i(t + \Delta t) - T_i(t)}{\Delta t} . \quad (B.15)$$

The implicit formulation of the equation resulting from the substitution of Eqs. (B.11) to (B.15) into Eq. (B.10) (and dividing out $\pi\ell$) is

$$\begin{aligned} & - \left[\frac{4\bar{k}_{i-1,i} r_{i-1}^2}{(\bar{r}_i^2 - \bar{r}_{i-1}^2)} \right] [T_i(t + \Delta t) - T_{i-1}(t + \Delta t)] \\ & + \left[\frac{4\bar{k}_{i,i+1} r_i^2}{(\bar{r}_{i+1}^2 - \bar{r}_i^2)} \right] [T_{i+1}(t + \Delta t) - T_i(t + \Delta t)] \\ & + \dot{q}_i''' (r_i^2 - r_{i-1}^2) = \left[\frac{\rho Cp_i (r_i^2 - r_{i-1}^2)}{\Delta t} \right] [T_i(t + \Delta t) - T_i(t)] . \quad (B.16) \end{aligned}$$

Rearranging Eq. (B.16) with collection of terms,

$$\begin{aligned}
 & \left[\frac{4\bar{k}_{i-1,i} r_{i-1}^2}{(\bar{r}_i^2 - \bar{r}_{i-1}^2)} \right] T_{i-1}(t + \Delta t) + \frac{4\bar{k}_{i-1,i} r_{i-1}^2}{(\bar{r}_i^2 - \bar{r}_{i-1}^2)} - \frac{\rho C p_i (r_i^2 - r_{i-1}^2)}{\Delta t} \\
 & - \frac{4\bar{k}_{i,i+1} r_i^2}{(\bar{r}_{i+1}^2 - \bar{r}_i^2)} \left[T_i(t + \Delta t) + \left[\frac{4\bar{k}_{i,i+1} r_i^2}{(\bar{r}_{i+1}^2 - \bar{r}_i^2)} \right] T_{i+1}(t + \Delta t) \right. \\
 & \left. = -\bar{q}_i (\bar{r}_i^2 - \bar{r}_{i-1}^2) - \left[\frac{\rho C p_i (r_i^2 - r_{i-1}^2)}{\Delta t} \right] T_i(t) \right. \quad (B.17)
 \end{aligned}$$

Equation (B.17) can be further simplified for the MgO core by employing the definitions of r_i and $\bar{r}_i$

$$r_{i-1+j} = (r_{i-1}^2 + j \Delta r^2)^{1/2} \quad (B.18)$$

where $j = 0, n$ and

$$\bar{r}_{i-1+j} = (r_{i-1+j}^2 - 0.5 \Delta r^2)^{1/2} \quad (B.19)$$

where $j = 1, n'$ and

$$\Delta r^2 = \frac{r_{i-1+n}^2 - r_{i-1}^2}{n} \quad (B.20)$$

where n = number of nodes. Applying the above equations to the radial domain of $(0, r_{MgO})$ for MgO,

$$\Delta r_{MgO}^2 = r_{MgO}^2 / N_{MgO} \quad (B.21)$$

where N_{MgO} = number of nodes in MgO,

$$r_j^2 = j \Delta r_{MgO}^2 \quad (B.22)$$

where $j = 0, N_{MgO}$ and

$$\bar{r}_j^2 = r_j^2 - 0.5 \Delta r_{MgO}^2 \quad (B.23)$$

where $j = 1, \text{NMGO}$; substituting Eq. (B.22) into (B.23) yields

$$\bar{r}_j^2 = j \Delta r_{\text{MgO}}^2 - 0.5 \Delta r_{\text{MgO}}^2 = (j - 0.5) \Delta r_{\text{MgO}}^2. \quad (\text{B.24})$$

Substituting Eqs. (B.22) and (B.24) into Eq. (B.17) and with $\dot{q}''' = 0$,

$$\begin{aligned} & \left[\frac{4\bar{k}_{i-1,i} (i-1) \Delta r_{\text{MgO}}^2}{(i-0.5-i+1+0.5)\Delta r_{\text{MgO}}^2} \right] T_{i-1}(t + \Delta t) \\ & + \left[\frac{4\bar{k}_{i-1,i} (i-1) \Delta r_{\text{MgO}}^2}{(i-0.5-i+1+0.5)\Delta r_{\text{MgO}}^2} - \frac{\rho C p_i (i-i+1) \Delta r_{\text{MgO}}^2}{\Delta t} \right. \\ & \quad \left. - \frac{4\bar{k}_{i,i+1} (i) \Delta r_{\text{MgO}}^2}{(i+1-0.5-i+0.5)\Delta r_{\text{MgO}}^2} \right] T_i(t + \Delta t) \\ & + \left[\frac{4\bar{k}_{i,i+1} (i) \Delta r_{\text{MgO}}^2}{(i+1-0.5-i+0.5)\Delta r_{\text{MgO}}^2} \right] T_{i+1}(t + \Delta t) \\ & = -\dot{q}_i''' (i-i+1) \Delta r_{\text{MgO}}^2 - \left[\frac{\rho C p_i (i-i+1) \Delta r_{\text{MgO}}^2}{\Delta t} \right] T_i(t). \quad (\text{B.25}) \end{aligned}$$

Equation (B.25) reduces to

$$\begin{aligned} & \left[4\bar{k}_{i-1,i} (i-1) \right] T_{i-1}(t + \Delta t) + \left[-4\bar{k}_{i-1,i} (i-1) - \frac{\rho C p_i \Delta r_{\text{MgO}}^2}{\Delta t} \right. \\ & \quad \left. - 4\bar{k}_{i,i+1} (i) \right] T_i(t + \Delta t) + \left[4\bar{k}_{i,i+1} (i) \right] T_{i+1}(t + \Delta t) \\ & = - \left[\frac{\rho C p_i \Delta r_{\text{MgO}}^2}{\Delta t} \right] T_i(t). \quad (\text{B.26}) \end{aligned}$$

Equation (B.26) is applicable only for the MgO core, whereas Eq. (B.17) can be applied to the Cupro Nickel, Inconel, and MgO regions.

Mathematical Model of Heat Transfer at the
MgO-to-Heater Interface (Fig. B-2)

Assumptions:

1. Heat flow between nodes is proportional to r^2 ,
2. Nodal mass $(\rho V)_1$ is constant, heat capacity Cp_1 and thermal conductivity k_1 are evaluated at the present nodal temperature $T_1(t)$,
3. A gap exists at the MgO-to-heater interface and heat can be transferred via conduction, convection, and radiation across the gap.

A heat balance on node NMGO in Fig. B-2 yields

$$q_{NMGO-1, NMGO} - q_{NMGO, NM} + \dot{q}_{NMGO}^0 = \rho(CpV)_{NMGO} (\partial T_{NMGO} / \partial t) \quad (B.27)$$

Applying Eqs. (B.11), (B.12), and (B.24)

$$\begin{aligned} q_{NMGO-1, NMGO} &= - \frac{\bar{k}_{NMGO-1, NMGO} 4\pi l r_{NMGO-1}^2}{(r_{NMGO}^2 - r_{NMGO-1}^2)} (T_{NMGO} - T_{NMGO-1}) \\ &= - \frac{\bar{k}_{NMGO-1, NMGO} 4\pi l (NMGO - 1) \Delta r_{MgO}^2}{(NMGO - 0.5 - NMGO + 1 + 0.5) \Delta r_{MgO}^2} (T_{NMGO} - T_{NMGO-1}) \end{aligned}$$

Therefore,

$$q_{NMGO-1, NMGO} = - \bar{k}_{NMGO-1, NMGO} 4\pi l (NMGO - 1) (T_{NMGO} - T_{NMGO-1}) \quad (B.28)$$

Also, for $q_{NMGO, NM}$

$$\begin{aligned} q_{NMGO, NM} &= - \frac{k_{NMGO} 4\pi l r_{NMGO}^2}{(r_{NMGO}^2 - r_{NMGO}^2)} (T_{MgO_{surf}} - T_{NMGO}) \\ &= - \frac{k_{NMGO} 4\pi l (NMGO) \Delta r_{MgO}^2}{(NMGO - NMGO + 0.5) \Delta r_{MgO}^2} (T_{MgO_{surf}} - T_{NMGO}) \\ &= - NMGO 8\pi l (NMGO) (T_{MgO_{surf}} - T_{NMGO}) ; \quad (B.29) \end{aligned}$$

and considering a gap between the MgO and heater and that heat can be

Fig. B-2. Notation relative to the derivation of the heat transfer model at the MgO-heater interface.

transferred via conduction, convection, and radiation across the gap; via conduction

$$q_{\text{NMGO}, \text{NM}} = - \frac{k_{\text{gap}} 2\pi l}{\ln(r_{\text{NMGO}} + \Delta r_{\text{gap1}} / r_{\text{NMGO}})} (T_{\text{Heat surf}} - T_{\text{MgO surf}}), \quad (\text{B.30})$$

via convection

$$q_{\text{NMGO}, \text{NM}} = -2\pi r_{\text{NMGO}} h_{\text{gap1}} (T_{\text{Heat surf}} - T_{\text{MgO surf}}), \quad (\text{B.31})$$

via radiation

$$q_{\text{NMGO}, \text{NM}} = -2\pi r_{\text{NMGO}} h_{r1} (T_{\text{Heat surf}} - T_{\text{MgO surf}}), \quad (\text{B.32})$$

where

$$h_{r1} = \sigma (T_{\text{Heat surf}}^2 + T_{\text{MgO surf}}^2) (T_{\text{Heat surf}} + T_{\text{MgO surf}}) \quad (\text{B.33})$$

and h_{r1} is evaluated at present time. Also,

$$\begin{aligned} q_{\text{NMGO}, \text{NM}} &= - \frac{k_{\text{NM}} 4\pi l r_{\text{NMGO}}^2}{(r_{\text{NM}}^2 - r_{\text{NMGO}}^2)} (T_{\text{NM}} - T_{\text{Heat surf}}) \\ &= - \frac{k_{\text{NM}} 8\pi l r_{\text{NMGO}}^2}{\Delta r_{\text{heater}}^2} (T_{\text{NM}} - T_{\text{Heat surf}}). \end{aligned} \quad (\text{B.34})$$

Adding Eqs. (B.29), (B.30), (B.31), (B.32), and (B.34) with transposition,

$$\begin{aligned} q_{\text{NMGO}, \text{NM}} &= -\pi l \left[\frac{\Delta r_{\text{heater}}^2}{8k_{\text{NM}} r_{\text{NMGO}}^2} \right. \\ &\quad + \frac{1}{\frac{2k_{\text{gap1}}}{\ln(r_{\text{NMGO}} + \Delta r_{\text{gap1}} / r_{\text{NMGO}})} + 2r_{\text{NMGO}} h_{\text{gap1}} + 2r_{\text{NMGO}} h_{r1} + \frac{1}{8k_{\text{NMGO}}(\text{NMGO})}} \left. \right]^{-1} (T_{\text{NM}} - T_{\text{NMGO}}). \end{aligned} \quad (\text{B.35})$$

Substituting Eqs. (B.28) and (B.35) into (B.27) with expansion of the accumulation term and elimination of πl ,

$$\begin{aligned}
 & - \left[\bar{k}_{\text{NMGO}-1, \text{NMGO}}^{4(\text{NMGO}-1)} \right] [T_{\text{NMGO}}(t + \Delta t) - T_{\text{NMGO}-1}(t + \Delta t)] \\
 & + \left[\frac{\Delta r_{\text{heater}}^2}{8k_{\text{NM}} r_{\text{NMGO}}^2} + \frac{1}{\frac{2k_{\text{gap1}}}{\ln(r_{\text{NMGO}} + \Delta r_{\text{gap1}}/r_{\text{NMGO}})} + 2r_{\text{NMGO}} h_{\text{gap1}} + 2r_{\text{NMGO}} h_{r1}} \right. \\
 & \left. + \frac{1}{8k_{\text{NMGO}}(\text{NMGO})} \right]^{-1} [T_{\text{NM}}(t + \Delta t) - T_{\text{NMGO}}(t + \Delta t)] = \left[\frac{\rho_{\text{H}_2\text{O}} C_p \text{NMGO} \Delta r_{\text{H}_2\text{O}}^2}{\Delta t} \right] [T_{\text{NMGO}}(t + \Delta t) - T_{\text{NMGO}}(t)] . \quad (\text{B.36})
 \end{aligned}$$

Rearranging Eq. (B.36) and collecting terms gives the following equation for node NMGO (the last node in the MgO core):

$$\begin{aligned}
 & \left[\bar{k}_{\text{NMGO}-1, \text{NMGO}}^{4(\text{NMGO}-1)} \right] T_{\text{NMGO}-1}(t + \Delta t) + \left[-\bar{k}_{\text{NMGO}-1, \text{NMGO}}^{4(\text{NMGO}-1)} - \frac{\rho_{\text{H}_2\text{O}} C_p \text{NMGO} \Delta r_{\text{H}_2\text{O}}^2}{\Delta t} \right. \\
 & \left. \frac{2}{\frac{\Delta r_{\text{heater}}^2}{4k_{\text{NM}} r_{\text{NMGO}}^2} + \frac{1}{\frac{k_{\text{gap1}}}{\ln(r_{\text{NMGO}} + \Delta r_{\text{gap1}}/r_{\text{NMGO}})} + r_{\text{NMGO}} h_{\text{gap1}} + r_{\text{NMGO}} h_{r1}} + \frac{1}{4k_{\text{NMGO}}(\text{NMGO})}} \right] T_{\text{NMGO}}(t + \Delta t) \\
 & + \left[\frac{\Delta r_{\text{heater}}^2}{4k_{\text{NM}} r_{\text{NMGO}}^2} + \frac{1}{\frac{k_{\text{gap1}}}{\ln(r_{\text{NMGO}} + \Delta r_{\text{gap1}}/r_{\text{NMGO}})} + r_{\text{NMGO}} h_{\text{gap1}} + r_{\text{NMGO}} h_{r1}} + \frac{1}{4k_{\text{NMGO}}(\text{NMGO})} \right] T_{\text{NM}}(t + \Delta t) \\
 & = \left[\frac{\rho_{\text{H}_2\text{O}} C_p \text{NMGO} \Delta r_{\text{H}_2\text{O}}^2}{\Delta t} \right] T_{\text{NMGO}}(t) . \quad (\text{B.37})
 \end{aligned}$$

A development similar to Eq. (B.37) could be made for node NM in the heater, but since it is analogous, only the final formulation will be presented:

$$\begin{aligned}
 & \left[\frac{\Delta r_{\text{heater}}^2}{4k_{\text{NM}} r_{\text{NMGO}}^2} + \frac{1}{\frac{k_{\text{gap1}}}{\ln(r_{\text{NMGO}} + \Delta r_{\text{gap1}}/r_{\text{NMGO}})} + r_{\text{NMGO}} h_{\text{gap1}} + r_{\text{NMGO}} h_{r1}} + \frac{1}{4k_{\text{NMGO}}(\text{NMGO})} \right] T_{\text{NMGO}}(t + \Delta t) \\
 & + \left[\frac{\Delta r_{\text{heater}}^2}{4k_{\text{NM}} r_{\text{NMGO}}^2} + \frac{1}{\frac{k_{\text{gap1}}}{\ln(r_{\text{NMGO}} + \Delta r_{\text{gap1}}/r_{\text{NMGO}})} + r_{\text{NMGO}} h_{\text{gap1}} + r_{\text{NMGO}} h_{r1}} + \frac{1}{4k_{\text{NMGO}}(\text{NMGO})} \right. \\
 & \left. - \frac{\rho_{\text{heater}} C_p \text{NM} \Delta r_{\text{heater}}^2}{\Delta t} - \frac{4k_{\text{NM}, \text{NM}+1} r_{\text{NM}}^2}{\Delta r_{\text{heater}}^2} \right] T_{\text{NM}}(t + \Delta t) + \left[\frac{4k_{\text{NM}, \text{NM}+1} r_{\text{NM}}^2}{\Delta r_{\text{heater}}^2} \right] T_{\text{NM}+1}(t + \Delta t) \\
 & = \left[\frac{\rho_{\text{heater}} C_p \text{NM} \Delta r_{\text{heater}}^2}{\Delta t} - \frac{4k_{\text{NM}, \text{NM}+1} r_{\text{NM}}^2}{\Delta r_{\text{heater}}^2} \right] T_{\text{NM}}(t) . \quad (\text{B.38})
 \end{aligned}$$

Mathematical Model of Heat Transfer at the Inconel-
to-Cupro Nickel Interface (Fig. B-3)

Assumptions:

1. Heat flow between nodes is proportional to r^2 ,
2. Nodal mass $(\rho V)_1$ is constant, heat capacity Cp_1 and thermal conductivity k_1 are evaluated at the present nodal temperature $T_1(t)$,
3. A gap does not exist at the interface.

A heat balance on node NOD2 in Fig. B-3 yields

$$q_{\text{NOD2-1,NOD2}} - q_{\text{NOD2,NH}} + \dot{q}_{\text{NOD2}} = \rho(CpV)_{\text{NOD2}} \frac{\partial T_{\text{NOD2}}}{\partial t} \quad (\text{B.39})$$

Applying Eq. (B.11),

$$q_{\text{NOD2-1,NOD2}} = - \frac{\bar{k}_{\text{NOD2-1,NOD2}} 4\pi \ell r_{\text{NOD2-1}}^2}{(\bar{r}_{\text{NOD2}}^2 - \bar{r}_{\text{NOD2-1}}^2)} (T_{\text{NOD2}} - T_{\text{NOD2-1}}) \quad (\text{B.40})$$

and

$$q_{\text{NOD2,NH}} = - \left[\frac{(r_{\text{NOD2}}^2 - \bar{r}_{\text{NOD2}}^2)}{k_{\text{NOD2}} 4\pi \ell r_{\text{NOD2}}^2} + \frac{(\bar{r}_{\text{NH}}^2 - r_{\text{NOD2}}^2)}{k_{\text{NH}} 4\pi \ell r_{\text{NOD2}}^2} \right]^{-1} (T_{\text{NH}} - T_{\text{NOD2}}) \quad (\text{B.41})$$

Equation (B.41) can be simplified since

$$r_{\text{NOD2}}^2 - \bar{r}_{\text{NOD2}}^2 = \frac{\Delta r_{\text{heater}}^2}{2} \quad (\text{B.42})$$

and

$$\bar{r}_{\text{NH}}^2 - r_{\text{NOD2}}^2 = \frac{\Delta r_{\text{Cu}}^2}{2} \quad (\text{B.43})$$

Thus,

$$q_{\text{NOD2,NH}} = -\pi \ell \left[\frac{\Delta r_{\text{heater}}^2}{8k_{\text{NOD2}} r_{\text{NOD2}}^2} + \frac{\Delta r_{\text{Cu}}^2}{8k_{\text{NH}} r_{\text{NOD2}}^2} \right]^{-1} (T_{\text{NH}} - T_{\text{NOD2}}) \quad (\text{B.44})$$

Fig. B-3. Notation relative to the derivation of the heat transfer model at the Inconel to Cupro Nickel interface).

Substituting Eqs. (B.40) and (B.44) into (B.39) with expansion of the heat generation term and accumulation term and elimination of πl yields

$$\begin{aligned}
 & \left[\frac{\bar{k}_{\text{NOD2-1, NOD2}} 4r_{\text{NOD2-1}}^2}{(r_{\text{NOD2}}^2 - r_{\text{NOD2-1}}^2)} \right] [T_{\text{NOD2}}(t + \Delta t) - T_{\text{NOD2-1}}(t + \Delta t)] \\
 & + \left[\frac{2}{\frac{\Delta r_{\text{heater}}^2}{4k_{\text{NOD2}} r_{\text{NOD2}}^2} + \frac{\Delta r_{\text{Cu}}^2}{4k_{\text{NH}} r_{\text{NOD2}}^2}} \right] [T_{\text{NH}}(t + \Delta t) - T_{\text{NOD2}}(t + \Delta t)] \\
 & + \dot{q}_{\text{NOD2}} \Delta r_{\text{heater}}^2 = \left[\frac{\rho_{\text{heater}} C_p \text{NOD2} \Delta r_{\text{heater}}^2}{\Delta t} \right] \\
 & \times [T_{\text{NOD2}}(t + \Delta t) - T_{\text{NOD2}}(t)] . \quad (\text{B.45})
 \end{aligned}$$

Rearranging Eq. (B.45) and collecting terms gives the following equation for the last node (NOD2) in the Inconel layer:

$$\begin{aligned}
 & \left[\frac{\bar{k}_{\text{NOD2-1, NOD2}} 4r_{\text{NOD2-1}}^2}{\Delta r_{\text{heater}}^2} \right] T_{\text{NOD2-1}}(t + \Delta t) + \left[-\frac{\bar{k}_{\text{NOD2-1, NOD2}} 4r_{\text{NOD2-1}}^2}{\Delta r_{\text{heater}}^2} \right. \\
 & \left. - \frac{\rho_{\text{heater}} C_p \text{NOD2} \Delta r_{\text{heater}}^2}{\Delta t} - \frac{2}{\frac{\Delta r_{\text{heater}}^2}{4k_{\text{NOD2}} r_{\text{NOD2}}^2} + \frac{\Delta r_{\text{Cu}}^2}{4k_{\text{NH}} r_{\text{NOD2}}^2}} \right] T_{\text{NOD2}}(t + \Delta t) \\
 & + \left[\frac{2}{\frac{\Delta r_{\text{heater}}^2}{4k_{\text{NOD2}} r_{\text{NOD2}}^2} + \frac{\Delta r_{\text{Cu}}^2}{4k_{\text{NH}} r_{\text{NOD2}}^2}} \right] T_{\text{NH}}(t + \Delta t) = \dot{q}_{\text{NOD2}} \Delta r_{\text{heater}}^2 \\
 & - \left[\frac{\rho_{\text{heater}} C_p \text{NOD2} \Delta r_{\text{heater}}^2}{\Delta t} \right] T_{\text{NOD2}}(t) . \quad (\text{B.46})
 \end{aligned}$$

Similarly, for node NH in the Cupro Nickel layer

$$\begin{aligned}
 & \left[\frac{2}{\frac{\Delta r_{\text{heater}}^2}{4k_{\text{NOD2}} r_{\text{NOD2}}^2} + \frac{\Delta r_{\text{Cu}}^2}{4k_{\text{NH}} r_{\text{NOD2}}^2}} \right] T_{\text{NOD2}}(t + \Delta t) \\
 & + \left[-\frac{2}{\frac{\Delta r_{\text{heater}}^2}{4k_{\text{NOD2}} r_{\text{NOD2}}^2} + \frac{\Delta r_{\text{Cu}}^2}{4k_{\text{NH}} r_{\text{NOD2}}^2}} - \frac{\rho_{\text{Cu}} C_{\text{pNH}} \Delta r_{\text{Cu}}^2}{\Delta t} - \frac{\bar{k}_{\text{NH,NH+1}} 4r_{\text{NH}}^2}{\Delta r_{\text{Cu}}^2} \right] \\
 & \times T_{\text{NH}}(t + \Delta t) + \left[\frac{\bar{k}_{\text{NH,NH+1}} 4r_{\text{NH}}^2}{\Delta r_{\text{Cu}}^2} \right] T_{\text{NH+1}}(t + \Delta t) \\
 & = -\dot{q}_{\text{NH}} \Delta r_{\text{Cu}}^2 - \left[\frac{\rho_{\text{Cu}} C_{\text{pNH}} \Delta r_{\text{Cu}}^2}{\Delta t} \right] T_{\text{NH}}(t) . \quad (\text{B.47})
 \end{aligned}$$

Mathematical Model of Heat Transfer at the
Heater-to-BN Interface (Fig. B-4)

Assumptions:

1. Heat flow between nodes within the heater element is proportional to r^2 ,
2. Heat flow between nodes within the BN is constant at any r between nodes,
3. Nodal mass $(\rho V)_i$ is constant,
4. Heat capacity $C_{\text{p}i}$ and thermal conductivity k_i are evaluated at the present nodal temperature $T_i(t)$,
5. A gap exists at the heater-to-BN interface and heat can be transferred via conduction, convection, and radiation across the gap.

A heat balance on NOD3 in Fig. B-4 yields

$$q_{\text{NOD3-1,NOD3}} - q_{\text{NOD3,NC}} + \dot{q}_{\text{NOD3}} = \rho_{\text{NOD3}} (C_{\text{pV}})_{\text{NOD3}} \frac{\partial T_{\text{NOD3}}}{\partial t} . \quad (\text{B.48})$$

Fig. B-4. Notation relative to the derivation of the heat transfer model at the heater (either Cupro Nickel or Inconel) to boron nitride interface.

Applying Eq. (B.11),

$$q_{NOD3-1, NOD3} = \frac{\bar{k}_{NOD3-1, NOD3} r_{NOD3-1}^2}{(r_{NOD3}^2 - r_{NOD3-1}^2)} (T_{NOD3} - T_{NOD3-1}) \quad (B.49)$$

A development similar to the one for Eq. (B.35) yields

$$q_{NOD3, NC} = \frac{2}{\left[\frac{\ln(r_{NC}/r_{NOD3})}{k_{NC}} + \frac{1}{\frac{k_{RAP2}}{\ln(r_{NOD3} + \Delta r_{RAP2}/r_{NOD3})} + r_{NOD3} h_{RAP2} + r_{NOD3} h_{r2}} + \frac{(r_{NOD3}^2 - r_{NOD3-1}^2)}{2k_{NOD3} r_{NOD3}^2} \right]} (T_{NC} - T_{NOD3}) \quad (B.50)$$

Substituting Eqs. (B.49) and (B.50) into (B.48) with expansion of the heat generation term and accumulation term and elimination of πl gives

$$\begin{aligned} & \left[\frac{\bar{k}_{NOD3-1, NOD3} r_{NOD3-1}^2}{(r_{NOD3}^2 - r_{NOD3-1}^2)} \right] [T_{NOD3}(t + \Delta t) - T_{NOD3-1}(t + \Delta t)] \\ & + \left[\frac{2}{\left[\frac{\ln(r_{NC}/r_{NOD3})}{k_{NC}} + \frac{1}{\frac{k_{RAP2}}{\ln(r_{NOD3} + \Delta r_{RAP2}/r_{NOD3})} + r_{NOD3} h_{RAP2} + r_{NOD3} h_{r2}} + \frac{(r_{NOD3}^2 - r_{NOD3-1}^2)}{2k_{NOD3} r_{NOD3}^2} \right]} \right] \\ & \cdot [T_{NC}(t + \Delta t) - T_{NOD3}(t + \Delta t)] + \frac{\rho_{NOD3} C_p NOD3 (r_{NOD3}^2 - r_{NOD3-1}^2)}{\Delta t} \\ & = [T_{NOD3}(t + \Delta t) - T_{NOD3}(t)] \quad (B.51) \end{aligned}$$

Rearranging Eq. (B.51) and collecting terms gives the following implicit formulation of the equation for the last node (NOD3) in the heater (either Inconel or Cupro Nickel):

$$\begin{aligned} & \left[\frac{\bar{k}_{NOD3-1, NOD3} r_{NOD3-1}^2}{(r_{NOD3}^2 - r_{NOD3-1}^2)} \right] T_{NOD3-1}(t + \Delta t) + \left[\frac{\bar{k}_{NOD3-1, NOD3} r_{NOD3-1}^2}{(r_{NOD3}^2 - r_{NOD3-1}^2)} \frac{\rho_{NOD3} C_p NOD3 (r_{NOD3}^2 - r_{NOD3-1}^2)}{\Delta t} \right. \\ & \left. + \frac{2}{\left[\frac{\ln(r_{NC}/r_{NOD3})}{k_{NC}} + \frac{1}{\frac{k_{RAP2}}{\ln(r_{NOD3} + \Delta r_{RAP2}/r_{NOD3})} + r_{NOD3} h_{RAP2} + r_{NOD3} h_{r2}} + \frac{(r_{NOD3}^2 - r_{NOD3-1}^2)}{2k_{NOD3} r_{NOD3}^2} \right]} \right] \\ & \cdot T_{NOD3}(t + \Delta t) + \left[\frac{2}{\left[\frac{\ln(r_{NC}/r_{NOD3})}{k_{NC}} + \frac{1}{\frac{k_{RAP2}}{\ln(r_{NOD3} + \Delta r_{RAP2}/r_{NOD3})} + r_{NOD3} h_{RAP2} + r_{NOD3} h_{r2}} + \frac{(r_{NOD3}^2 - r_{NOD3-1}^2)}{2k_{NOD3} r_{NOD3}^2} \right]} \right] \\ & \cdot T_{NC}(t + \Delta t) = \left[\frac{\rho_{NOD3} C_p NOD3 (r_{NOD3}^2 - r_{NOD3-1}^2)}{\Delta t} \right] T_{NOD3}(t) \quad (B.52) \end{aligned}$$

Similarly, for node NC in the BN layer

$$\begin{aligned}
 & \left[\frac{\ln(\bar{r}_{NC}/\bar{r}_{NOD3})}{k_{NC}} + \frac{2}{\frac{k_{gap2}}{\ln(r_{NOD3} + \Delta r_{gap2}/r_{NOD3})} + r_{NOD3} h_{gap2} + r_{NOD3} h_{r2}} + \frac{(r_{NOD3}^2 - \bar{r}_{NOD3}^2)}{2k_{NOD3} r_{NOD3}} \right] T_{NOD3}(t + \Delta t) \\
 & + \left[\frac{\ln(\bar{r}_{NC}/\bar{r}_{NOD3})}{k_{NC}} + \frac{2}{\frac{k_{gap2}}{\ln(r_{NOD3} + \Delta r_{gap2}/r_{NOD3})} + r_{NOD3} h_{gap2} + r_{NOD3} h_{r2}} + \frac{(r_{NOD3}^2 - \bar{r}_{NOD3}^2)}{2k_{NOD3} r_{NOD3}} \right] \\
 & - \frac{\rho_{BN} C_p \Delta r_{BN}^2}{\Delta t} \left[\frac{\ln(\bar{r}_{NC}/\bar{r}_{NC})}{k_{NC}} + \frac{\ln(\bar{r}_{NC+1}/\bar{r}_{NC})}{k_{NC+1}} \right] T_{NC}(t + \Delta t) + \left[\frac{2}{\frac{k_{NC}}{\ln(\bar{r}_{NC}/\bar{r}_{NC})} + \frac{k_{NC+1}}{\ln(\bar{r}_{NC+1}/\bar{r}_{NC})}} \right] \\
 & \times T_{NC+1}(t + \Delta t) = - \left[\frac{\rho_{BN} C_p \Delta r_{BN}^2}{\Delta t} \right] T_{NC}(t) \quad (B.53)
 \end{aligned}$$

Mathematical Model of Heat Transfer at the BN-to-Inner Stainless Steel Sheath Interface (Fig. B-5)

Assumptions:

1. Heat flow between nodes is constant at any r between nodes,
2. Nodal mass $(\rho V)_i$ is constant, heat capacity Cp_i and thermal conductivity k_i are evaluated at the present nodal temperature $T_i(t)$,
3. A gap exists at the BN-to-sheath interface and heat can be transferred via conduction, convection, and radiation across the gap.

A heat balance on node NOD4 in Fig. B-5 gives

$$q_{NOD4-1, NOD4} - q_{NOD4, NB} + \dot{q}_{NOD4}^0 = \rho_{BN} (CpV)_{NOD4} \frac{\partial T_{NOD4}}{\partial t} \quad (B.54)$$

Since Eq. (B.4) is applicable for $q_{NOD4-1, NOD4}$,

$$q_{NOD4-1, NOD4} = \left[\frac{\ln(r_{NOD4-1}/\bar{r}_{NOD4-1})}{2k_{NOD4-1}} + \frac{\ln(\bar{r}_{NOD4}/\bar{r}_{NOD4-1})}{2k_{NOD4}} \right]^{-1} (T_{NOD4} - T_{NOD4-1}) \pi l \quad (B.55)$$

Fig. B-5. Notation relative to the derivation of the heat transfer model at the boron nitride to inner stainless steel sheath interface.

Using the same technique required to develop Eq. (B.35) yields

$$q_{NOD4, BN} = -\pi l \left[\frac{\ln(r_{NOD4}/\bar{r}_{NOD4})}{k_{NOD4}} + \frac{1}{\frac{k_{gap,1}}{\ln(r_{NOD4} + \Delta r_{gap,1}/r_{NOD4})} + r_{NOD4} h_{gap,1} + r_{NOD4} h_r} + \frac{\ln(\bar{r}_{NB}/r_{NOD4})}{k_{NB}} \right] \quad (B.56)$$

$$= (T_{NB} - T_{NOD4})$$

Substituting Eqs. (B.55) and (B.56) into (B.54) with expansion of the accumulation term and elimination of πl gives

$$\begin{aligned} & - \left[\frac{\ln(r_{NOD4-1}/\bar{r}_{NOD4-1})}{k_{NOD4-1}} + \frac{\ln(\bar{r}_{NOD4}/r_{NOD4-1})}{k_{NOD4}} \right] [T_{NOD4}(t + \Delta t) - T_{NOD4-1}(t + \Delta t)] \\ & + \left[\frac{\ln(r_{NOD4}/\bar{r}_{NOD4})}{k_{NOD4}} + \frac{1}{\frac{k_{gap,1}}{\ln(r_{NOD4} + \Delta r_{gap,1}/r_{NOD4})} + r_{NOD4} h_{gap,1} + r_{NOD4} h_r} + \frac{\ln(\bar{r}_{NB}/r_{NOD4})}{k_{NB}} \right] \\ & \times [T_{NB}(t + \Delta t) - T_{NOD4}(t + \Delta t)] = \frac{\rho_{BN} C_{p,NOD4} \Delta r_{BN}^2}{\Delta t} [T_{NOD4}(t + \Delta t) - T_{NOD4}(t)] \quad (B.57) \end{aligned}$$

Rearranging (B.57) and collecting terms gives the implicit formulation for the last node (NOD4) in the BN annular region:

$$\begin{aligned} & \left[\frac{\ln(r_{NOD4-1}/\bar{r}_{NOD4-1})}{k_{NOD4-1}} + \frac{\ln(\bar{r}_{NOD4}/r_{NOD4-1})}{k_{NOD4}} \right] T_{NOD4-1}(t + \Delta t) \\ & + \left[- \frac{\ln(r_{NOD4-1}/\bar{r}_{NOD4-1})}{k_{NOD4-1}} + \frac{\ln(\bar{r}_{NOD4}/r_{NOD4-1})}{k_{NOD4}} - \frac{\rho_{BN} C_{p,NOD4} \Delta r_{BN}^2}{\Delta t} \right] \\ & - \left[\frac{\ln(r_{NOD4}/\bar{r}_{NOD4})}{k_{NOD4}} + \frac{1}{\frac{k_{gap,1}}{\ln(r_{NOD4} + \Delta r_{gap,1}/r_{NOD4})} + r_{NOD4} h_{gap,1} + r_{NOD4} h_r} + \frac{\ln(\bar{r}_{NB}/r_{NOD4})}{k_{NB}} \right] \\ & = T_{NOD4}(t + \Delta t) + \left[\frac{\ln(r_{NOD4}/\bar{r}_{NOD4})}{k_{NOD4}} + \frac{1}{\frac{k_{gap,1}}{\ln(r_{NOD4} + \Delta r_{gap,1}/r_{NOD4})} + r_{NOD4} h_{gap,1} + r_{NOD4} h_r} + \frac{\ln(\bar{r}_{NB}/r_{NOD4})}{k_{NB}} \right] \\ & \times T_{NB}(t + \Delta t) = - \frac{\rho_{BN} C_{p,NOD4} \Delta r_{BN}^2}{\Delta t} T_{NOD4}(t) \quad (B.58) \end{aligned}$$

Similarly, for node NB in the inner stainless steel sheath,

$$\begin{aligned}
 & \left[\frac{\ln(r_{\text{NOD4}}/\bar{r}_{\text{NOD4}})}{k_{\text{NOD4}}} + \frac{1}{\frac{k_{\text{gap}}}{\ln(r_{\text{NOD4}} + \Delta r_{\text{gap}}/r_{\text{NOD4}})} + r_{\text{NOD4}} h_{\text{gap}} + r_{\text{NOD4}} h_r} + \frac{\ln(\bar{r}_{\text{NB}}/r_{\text{NOD4}})}{k_{\text{NB}}} \right] \\
 & \times T_{\text{NOD4}}(t + \Delta t) + \left[\frac{\ln(r_{\text{NOD4}}/\bar{r}_{\text{NOD4}})}{k_{\text{NOD4}}} + \frac{1}{\frac{k_{\text{gap}}}{\ln(r_{\text{NOD4}} + \Delta r_{\text{gap}}/r_{\text{NOD4}})} + r_{\text{NOD4}} h_{\text{gap}} + r_{\text{NOD4}} h_r} + \frac{\ln(\bar{r}_{\text{NB}}/r_{\text{NOD4}})}{k_{\text{NB}}} \right] \\
 & - \frac{\rho_{\text{SS}} C_p \text{NB} \Delta r_{\text{SS}}^2}{\Delta t} \left[\frac{\ln(r_{\text{NB}}/\bar{r}_{\text{NB}})}{k_{\text{NB}}} + \frac{\ln(\bar{r}_{\text{NB}+1}/r_{\text{NB}})}{k_{\text{NB}+1}} \right] T_{\text{NB}}(t + \Delta t) + \left[\frac{\ln(r_{\text{NB}}/\bar{r}_{\text{NB}})}{k_{\text{NB}}} + \frac{\ln(\bar{r}_{\text{NB}+1}/r_{\text{NB}})}{k_{\text{NB}+1}} \right] T_{\text{NB}+1}(t + \Delta t) \\
 & - \left[\frac{\rho_{\text{SS}} C_p \text{NB} \Delta r_{\text{SS}}^2}{\Delta t} \right] T_{\text{NB}}(t) \quad (\text{B.59})
 \end{aligned}$$

Mathematical Model of Heat Transfer at the Sheath-to-Sheath Interface (Fig. B-6)

Assumptions:

1. Heat flow between nodes is constant for any r between nodes,
2. Nodal mass $(\rho V)_i$ is constant, heat capacity C_{p_i} and thermal conductivity k_i are evaluated at the present nodal temperature $T_i(t)$,
3. A gap exists at the sheath-to-sheath interface and heat can be transferred via conduction, convection, and radiation across the gap,
4. The last node (NOD5) temperature (T_{NOD5}) in the inner sheath is known as a function of time (i.e., the known thermocouple response is placed in the last node of the inner sheath),
5. The gap size is evaluated at the present nodal temperatures [$T_{\text{NOD5}}(t)$ and $T_{\text{NS}}(t)$] via the thermo-mechanical model developed in the last section of Appendix B.

A heat balance on NOD5 in Fig. B-6 yields

$$q_{\text{NOD5-1,NOD5}} - q_{\text{NOD5,NS}} + \dot{Q}_{\text{NOD5}} = \rho_{\text{SS}} (C_p V)_{\text{NOD5}} (\partial T_{\text{NOD5}} / \partial t) \quad (\text{B.60})$$

Applying Eq. (B.4),

$$q_{\text{NOD5-1,NOD5}} = \left[\frac{\ln(r_{\text{NOD5-1}}/\bar{r}_{\text{NOD5-1}})}{k_{\text{NOD5-1}}} + \frac{\ln(\bar{r}_{\text{NOD5}}/r_{\text{NOD5-1}})}{k_{\text{NOD5}}} \right] (T_{\text{NOD5}} - T_{\text{NOD5-1}}) \quad (\text{B.61})$$

Fig. B-6. Notation relative to the derivation of the heat transfer model at the inner stainless steel sheath to the outer stainless steel sheath interface.

An equation similar to (B.56) applies for $q_{\text{NOD5,NS}}$

$$q_{\text{NOD5,NS}} = \left[\frac{\ln(r_{\text{NOD5}}/r_{\text{NOD5}})}{k_{\text{NOD5}}} + \frac{1}{\ln(r_{\text{NOD5}}/r_{\text{gap}}/r_{\text{NOD5}}) + r_{\text{NOD5}}h_{\text{gap}} + r_{\text{NOD5}}h_{\text{r}}} + \frac{\ln(r_{\text{NS}}/r_{\text{NOD5}})}{k_{\text{NS}}} \right] (T_{\text{SS}} - T_{\text{NOD5}}) \quad (\text{B.62})$$

Substituting Eqs. (B.61) and (B.62) into Eq. (B.60) with expansion of the accumulation term and elimination of πl gives

$$\left[\frac{\ln(r_{\text{NOD5-1}}/r_{\text{NOD5-1}})}{k_{\text{NOD5-1}}} + \frac{\ln(r_{\text{NOD5}}/r_{\text{NOD5-1}})}{k_{\text{NOD5}}} \right] [T_{\text{NOD5}}(t + \Delta t) - T_{\text{NOD5-1}}(t + \Delta t)] + \left[\frac{\ln(r_{\text{NOD5}}/r_{\text{NOD5}})}{k_{\text{NOD5}}} + \frac{1}{\ln(r_{\text{NOD5}}/r_{\text{gap}}/r_{\text{NOD5}}) + r_{\text{NOD5}}h_{\text{gap}} + r_{\text{NOD5}}h_{\text{r}}} + \frac{\ln(r_{\text{NS}}/r_{\text{NOD5}})}{k_{\text{NS}}} \right] [T_{\text{NS}}(t + \Delta t) - T_{\text{NOD5}}(t + \Delta t)] + [T_{\text{NS}}(t + \Delta t) - T_{\text{NOD5}}(t + \Delta t)] \left[\frac{\partial_{\text{SS}}^{\text{CP}} \text{NOD5} \cdot r_{\text{SS1}}^2}{\Delta t} \right] [T_{\text{NOD5}}(t + \Delta t) - T_{\text{NOD5}}(t)] \quad (\text{B.63})$$

Rearranging Eq. (B.63) and collecting terms gives the implicit formulation of the equation for the last node (NOD5) in the inner sheath:

$$\left[\frac{\ln(r_{\text{NOD5-1}}/r_{\text{NOD5-1}})}{k_{\text{NOD5-1}}} + \frac{\ln(r_{\text{NOD5}}/r_{\text{NOD5-1}})}{k_{\text{NOD5}}} \right] T_{\text{NOD5-1}}(t + \Delta t) + \left[\frac{\ln(r_{\text{NOD5}}/r_{\text{NOD5}})}{k_{\text{NOD5}}} + \frac{1}{\ln(r_{\text{NOD5}}/r_{\text{gap}}/r_{\text{NOD5}}) + r_{\text{NOD5}}h_{\text{gap}} + r_{\text{NOD5}}h_{\text{r}}} + \frac{\ln(r_{\text{NS}}/r_{\text{NOD5}})}{k_{\text{NS}}} \right] T_{\text{NS}}(t + \Delta t) + \left[\frac{\ln(r_{\text{NOD5-1}}/r_{\text{NOD5-1}})}{k_{\text{NOD5-1}}} + \frac{\ln(r_{\text{NOD5}}/r_{\text{NOD5-1}})}{k_{\text{NOD5}}} \right] T_{\text{NOD5}}(t + \Delta t) + \left[\frac{\ln(r_{\text{NOD5}}/r_{\text{NOD5}})}{k_{\text{NOD5}}} + \frac{1}{\ln(r_{\text{NOD5}}/r_{\text{gap}}/r_{\text{NOD5}}) + r_{\text{NOD5}}h_{\text{gap}} + r_{\text{NOD5}}h_{\text{r}}} + \frac{\ln(r_{\text{NS}}/r_{\text{NOD5}})}{k_{\text{NS}}} \right] T_{\text{NOD5}}(t + \Delta t) + \left[\frac{\partial_{\text{SS}}^{\text{CP}} \text{NOD5} \cdot r_{\text{SS1}}^2}{\Delta t} \right] T_{\text{NOD5}}(t) \quad (\text{B.64})$$

Similarly, for node NS in the outer stainless steel sheath

$$\begin{aligned}
 & \left[\frac{\ln(r_{\text{NOD5}}/r_{\text{NOD5}})}{k_{\text{NOD5}}} + \frac{1}{\ln(r_{\text{NOD5}} + \Delta r_{\text{gap}}/r_{\text{NOD5}}) + r_{\text{NOD5}} h_{\text{gap}} + r_{\text{NOD5}} h_r} + \frac{\ln(r_{\text{NS}}/r_{\text{NOD5}})}{k_{\text{NS}}} \right. \\
 & \left. - \frac{\rho_{\text{SS}} C_p \text{NS} \Delta r_{\text{SS}}^2}{\Delta t} \frac{\ln(r_{\text{NS}}/r_{\text{NS}})}{k_{\text{NS}}} + \frac{\ln(r_{\text{NS}+1}/r_{\text{NS}})}{k_{\text{NS}+1}} \right] T_{\text{NS}}(t + \Delta t) + \left[\frac{\ln(r_{\text{NS}}/r_{\text{NS}})}{k_{\text{NS}}} + \frac{\ln(r_{\text{NS}+1}/r_{\text{NS}})}{k_{\text{NS}+1}} \right] \\
 & T_{\text{NS}+1}(t + \Delta t) = \left[\frac{\ln(r_{\text{NOD5}}/r_{\text{NOD5}})}{k_{\text{NOD5}}} + \frac{1}{\ln(r_{\text{NOD5}} + \Delta r_{\text{gap}}/r_{\text{NOD5}}) + r_{\text{NOD5}} h_{\text{gap}} + r_{\text{NOD5}} h_r} + \frac{\ln(r_{\text{NS}}/r_{\text{NOD5}})}{k_{\text{NS}}} \right] \\
 & T_{\text{NOD5}}(t + \Delta t) - \left[\frac{\rho_{\text{SS}} C_p \text{NS} \Delta r_{\text{SS}}^2}{\Delta t} \right] T_{\text{NS}}(t) \quad (\text{B.65})
 \end{aligned}$$

Also, for NOD5-1 in the inner sheath,

$$\begin{aligned}
 & \left[\frac{\ln(r_{\text{NOD5-2}}/r_{\text{NOD5-2}})}{k_{\text{NOD5-2}}} + \frac{\ln(r_{\text{NOD5-1}}/r_{\text{NOD5-2}})}{k_{\text{NOD5-1}}} \right] T_{\text{NOD5-2}}(t + \Delta t) \\
 & + \left[\frac{\ln(r_{\text{NOD5-2}}/r_{\text{NOD5-2}})}{k_{\text{NOD5-2}}} + \frac{\ln(r_{\text{NOD5-1}}/r_{\text{NOD5-2}})}{k_{\text{NOD5-1}}} - \frac{\rho_{\text{SS}} C_p \text{NOD5-1} \Delta r_{\text{SS}}^2}{\Delta t} \frac{\ln(r_{\text{NOD5-1}}/r_{\text{NOD5-1}})}{k_{\text{NOD5-1}}} + \frac{\ln(r_{\text{NOD5}}/r_{\text{NOD5-1}})}{k_{\text{NOD5}}} \right] \\
 & T_{\text{NOD5-1}}(t + \Delta t) = \left[\frac{\ln(r_{\text{NOD5-1}}/r_{\text{NOD5-1}})}{k_{\text{NOD5-1}}} + \frac{\ln(r_{\text{NOD5}}/r_{\text{NOD5-1}})}{k_{\text{NOD5}}} \right] T_{\text{NOD5}}(t + \Delta t) - \left[\frac{\rho_{\text{SS}} C_p \text{NOD5-1} \Delta r_{\text{SS}}^2}{\Delta t} \right] T_{\text{NOD5-1}}(t) \quad (\text{B.66})
 \end{aligned}$$

Mathematical Model of Heat Transfer at the Outer Sheath-to-Fluid Boundary (Fig. B-7)

Assumptions:

1. Heat flow between nodes is constant at any r between nodes,
2. Nodal mass $(\rho V)_i$ is constant, heat capacity C_{p_i} and thermal conductivity k_i are evaluated at the present nodal temperature $T_i(t)$.

A heat balance on NOD6 in Fig. B-7 gives

$$\rho_{\text{NOD6-1}} V_{\text{NOD6-1}} \frac{dT_{\text{NOD6-1}}}{dt} + \rho_{\text{NOD6}} V_{\text{NOD6}} \frac{dT_{\text{NOD6}}}{dt} = \rho_{\text{SS}} C_p V_{\text{NOD6}} \frac{dT_{\text{NOD6}}}{dt} \quad (\text{B.67})$$

Fig. B-7. Notation relative to the derivation of the heat transfer model at the heater surface.

Applying Eq. (B.4),

$$q_{\text{NODE 6-1, NODE 6}} = - \left[\frac{2}{\frac{\ln(r_{\text{NODE 6-1}}/\bar{r}_{\text{NODE 6-1}})}{k_{\text{NODE 6-1}}} + \frac{\ln(\bar{r}_{\text{NODE 6}}/r_{\text{NODE 6-1}})}{k_{\text{NODE 6}}}} \right] \times (T_{\text{NODE 6}} - T_{\text{NODE 6-1}}) \pi l. \quad (\text{B.68})$$

Substituting Eq. (B.68) into (B.67) with expansion of the accumulation term and elimination of πl yields

$$- \left[\frac{2}{\frac{\ln(r_{\text{NODE 6-1}}/\bar{r}_{\text{NODE 6-1}})}{k_{\text{NODE 6-1}}} + \frac{\ln(\bar{r}_{\text{NODE 6}}/r_{\text{NODE 6-1}})}{k_{\text{NODE 6}}}} \right] \times [T_{\text{NODE 6}}(t + \Delta t) - T_{\text{NODE 6-1}}(t + \Delta t)] - \Phi(t + \Delta t) = \left[\frac{\rho_{\text{SS}} C_p \text{NODE 6} \Delta r_{\text{SS2}}^2}{\Delta t} \right] [T_{\text{NODE 6}}(t + \Delta t) - T_{\text{NODE 6}}(t)]. \quad (\text{B.69})$$

Rearranging Eq. (B.69) and collecting terms gives the implicit formulation of the equation for the last node (NOD6) in the outer sheath:

$$\left[\frac{2}{\frac{\ln(r_{\text{NOD6-1}}/\bar{r}_{\text{NOD6-1}})}{k_{\text{NOD6-1}}} + \frac{\ln(\bar{r}_{\text{NOD6}}/r_{\text{NOD6-1}})}{k_{\text{NOD6}}}} \right] T_{\text{NOD6-1}}(t + \Delta t) + \left[-\frac{2}{\frac{\ln(r_{\text{NOD6-1}}/\bar{r}_{\text{NOD6-1}})}{k_{\text{NOD6-1}}} + \frac{\ln(\bar{r}_{\text{NOD6}}/r_{\text{NOD6-1}})}{k_{\text{NOD6}}}} - \frac{\rho_{\text{SS}} C_p \text{NOD6} \Delta r_{\text{SS2}}^2}{\Delta t} \right] T_{\text{NOD6}}(t + \Delta t) - \phi(t + \Delta t) = - \left[\frac{\rho_{\text{SS}} C_p \text{NOD6} \Delta r_{\text{SS2}}^2}{\Delta t} \right] T_{\text{NOD6}}(t) \quad (\text{B.70})$$

Since

$$\phi = - \left[\frac{2}{\frac{\ln(r_{\text{NOD6}}/\bar{r}_{\text{NOD6}})}{k_{\text{NOD6}}}} \right] (T_{\text{surf}} - T_{\text{NOD6}}) \quad (\text{B.71})$$

the surface temperature can be calculated from

$$T_{\text{surf}}(t + \Delta t) = T_{\text{NOD6}}(t + \Delta t) - \frac{\phi(t + \Delta t)}{\left[\frac{2k_{\text{NOD6}}}{\ln(r_{\text{NOD6}}/\bar{r}_{\text{NOD6}})} \right]} \quad (\text{B.72})$$

Mathematical Model of Heat Transfer from Node 1 in the MgO Core to the Heater Center Line (i.e., to $r = 0.0$, Fig. B-8)

Consider the fundamental differential equation for the conduction of heat in a solid with an internal heat source:

$$\nabla \cdot (k \nabla T) + \dot{q}''' = \rho C_p \frac{\partial T}{\partial t} \quad (\text{B.73})$$

Volume integration of Eq. (B.73) yields

$$\int_V (\nabla \cdot (k \nabla T)) dV + \int_V \dot{q}''' dV = \int_V \rho C_p \frac{\partial T}{\partial t} dV \quad (\text{B.74})$$

Fig. B-8. Notation relative to the derivation of the heat transfer model in the MgO core to the heater center line.

Since, for the MgO core,

$$\int_V \dot{q} \, dV = 0$$

B.75)

and with the application of the divergence theorem to the left side of

Eq. (B.74), it reduces to

$$\int_A k \bar{\nabla} T \cdot \bar{n} dA = \int_V \rho C_p \frac{\partial T}{\partial t} dv . \quad (B.76)$$

Expanding the gradient of T in cylindrical coordinates,

$$\int_A k \left(\frac{\partial T}{\partial r} \bar{r} + \frac{1}{r} \frac{\partial T}{\partial \theta} \bar{\theta} + \frac{\partial T}{\partial z} \bar{z} \right) \cdot \bar{n} dA = \int_V \rho C_p \frac{\partial T}{\partial t} dv . \quad (B.77)$$

Assuming there is no azimuthal temperature dependence and no axial conduction (i.e., $\partial T / \partial \theta = \partial T / \partial z = 0$), Eq. (B.77) reduces to

$$\int_A k \frac{\partial T}{\partial r} (\bar{r} \cdot \bar{n}) dA = \int_V \rho C_p \frac{\partial T}{\partial t} dv . \quad (B.78)$$

With the assumption that $k (\partial T / \partial r)$ is a function of r and t only and that

$$\left. \frac{\partial T}{\partial r} \right|_{r=0} = 0 , \quad (B.79)$$

then

$$-2\pi k \ell \left| r \frac{\partial T}{\partial r} \right|_r = \int_V \rho C_p \frac{\partial T}{\partial t} dv \quad (B.80)$$

for the radial interval $(0, r)$. Also, assuming k is constant on the interval $(0, r)$, expanding the right side of Eq. (B.80), and integrating over the domain $(0, r)$ yields

$$-2\pi k \ell r \left. \frac{\partial T}{\partial r} \right|_r = \int_0^r 2\pi r \ell \rho C_p \frac{\partial T}{\partial t} dr . \quad (B.81)$$

Assuming that $\partial T / \partial t$ can be expressed as an average, then

$$-2\pi k \ell r \left. \frac{\partial T}{\partial r} \right|_r = \pi r^2 \ell \rho C_p \frac{\partial \bar{T}}{\partial t} . \quad (B.82)$$

The simplification of Eq. (B.82) gives

$$-\frac{2k}{r\rho C_p} \frac{\partial T}{\partial r} \bigg|_r = \frac{\partial \bar{T}}{\partial t} . \quad (\text{B.83})$$

Assigning $\partial \bar{T} / \partial t$ at $r = \bar{r}_1$

$$\frac{\partial \bar{T}}{\partial t} = -\frac{2k}{\rho C_p \bar{r}_1} \frac{\partial T}{\partial r} \bigg|_{\bar{r}_1} . \quad (\text{B.84})$$

Assuming that Eq. (B.84) is a wave propagation formulation with characteristic velocity $\bar{v}$,

$$\frac{\partial \bar{T}}{\partial t} = -\bar{v} \frac{\partial T}{\partial r} \bigg|_{\bar{r}_1} . \quad (\text{B.85})$$

Also, assuming that $\bar{v}$ is constant in the MgO domain of $(0, r)$, then the time lag of $\partial T / \partial t$ arriving at $r = 0$ is

$$\frac{\partial T}{\partial t} \bigg|_{r=0} (t) = \frac{\partial T}{\partial t} \bigg|_{r=\bar{r}_1} \left(t - \frac{\bar{r}_1}{\bar{v}} \right) , \quad (\text{B.86})$$

or

$$\frac{\partial T}{\partial t} \bigg|_{r=0} (t) = \frac{\partial T}{\partial t} \bigg|_{r=\bar{r}_1} \left(t - \frac{\rho C_p \bar{r}_1^2}{2k} \right) . \quad (\text{B.87})$$

This formulation is known as the Hedrick Wave Theory of Heat Propagation.⁴⁵

Mathematical Model of the Thermal-Mechanical Behavior of the Gap
Between the Inner and Outer Stainless Steel Sheaths (Fig. B-9)

Consider the definition for the coefficient of linear expansion

$$\alpha \equiv \frac{1}{L} \left(\frac{\partial L}{\partial T} \right)_p , \quad (\text{B.88})$$

Fig. B-9. Notation relative to the derivation of the mathematical model of the thermomechanical behavior of the gap between the inner and outer stainless steel sheaths.

which for solids is approximated by

$$\alpha \doteq \frac{1}{L} \frac{dL}{dT} . \quad (\text{B.89})$$

Assuming α is a function of T only and that it can be approximated by a polynomial in terms of T , then

$$\alpha(T) \doteq C_1 + C_2 T + C_3 T^2 . \quad (\text{B.90})$$

Substituting Eq. (B.90) into (B.89) and separating variables gives

$$\{C_1 + C_2 T + C_3 T^2\} dT = \frac{dL}{L} . \quad (\text{B.91})$$

Upon integration,

$$\ln L = C_1 T + \frac{C_2}{2} T^2 + \frac{C_3}{3} T^3 + \text{constant} . \quad (\text{B.92})$$

For the initial conditions of

$$L = L_0 \text{ at } T = T_0 , \quad (\text{B.93})$$

and referring to Eq. (B.92),

$$\text{Constant} = \ln L_0 - C_1 T_0 - (C_2/2) T_0^2 - (C_3/3) T_0^3 . \quad (\text{B.94})$$

Substituting Eq. (B.94) into (B.92) and simplifying yields

$$\ln \frac{L}{L_0} = C_1 (T - T_0) + \frac{C_2}{2} (T^2 - T_0^2) + \frac{C_3}{3} (T^3 - T_0^3) . \quad (\text{B.95})$$

Exponentiation of Eq. (B.95) gives

$$\frac{L}{L_0} = \exp [C_1 (T - T_0) + \frac{C_2}{2} (T^2 - T_0^2) + \frac{C_3}{3} (T^3 - T_0^3)] . \quad (\text{B.96})$$

Subtracting 1 from both sides of Eq. (B.96) and multiplying through by L_0 gives

$$L - L_0 = L_0 \left\{ \exp [C_1 (T - T_0) + \frac{C_2}{2} (T^2 - T_0^2) + \frac{C_3}{3} (T^3 - T_0^3)] - 1 \right\} . \quad (\text{B.97})$$

Therefore, for a change in temperature, the resulting change in L (ΔL) can be determined by Eq. (B.97).

The linear gap model used in ORINC is

$$\Delta \text{gap} = \Delta \text{gap}_0 + \bar{\Delta r}_{\text{NS}} - \bar{\Delta r}_{\text{NOD5}} . \quad (\text{B.98})$$

Expanding $\bar{\Delta r}_{\text{NS}}$ and $\bar{\Delta r}_{\text{NOD5}}$ by Eq. (B.97),

$$\begin{aligned} \bar{\Delta r}_{\text{NS}} = \bar{r}_{\text{NS}} \left(\exp [C_1 (T_{\text{NS}} - T_{\text{NS}}|_0) + \frac{C_2}{2} (T_{\text{NS}}^2 - T_{\text{NS}}|_0^2) \right. \\ \left. + \frac{C_3}{3} (T_{\text{NS}}^3 - T_{\text{NS}}|_0^3)] - 1 \right) , \end{aligned} \quad (\text{B.99})$$

and

$$\begin{aligned} \bar{\Delta r}_{\text{NOD5}} = \bar{r}_{\text{NOD5}} \left(\exp [C_1 (T_{\text{NOD5}} - T_{\text{NOD5}}|_0) + \frac{C_2}{2} (T_{\text{NOD5}}^2 - T_{\text{NOD5}}|_0^2) \right. \\ \left. + \frac{C_3}{3} (T_{\text{NOD5}}^3 - T_{\text{NOD5}}|_0^3)] - 1 \right) . \end{aligned} \quad (\text{B.100})$$

Therefore, Eq. (B.98) becomes

$$\begin{aligned} \Delta \text{gap} = \Delta \text{gap}_0 + \bar{r}_{\text{NS}} \left(\exp [C_1 (T_{\text{NS}} - T_{\text{NS}}|_0) + \frac{C_2}{2} (T_{\text{NS}}^2 - T_{\text{NS}}|_0^2) \right. \\ \left. + \frac{C_3}{3} (T_{\text{NS}}^3 - T_{\text{NS}}|_0^3)] - 1 \right) - \bar{r}_{\text{NOD5}} \left(\exp [C_1 (T_{\text{NOD5}} - T_{\text{NOD5}}|_0) \right. \\ \left. + \frac{C_2}{2} (T_{\text{NOD5}}^2 - T_{\text{NOD5}}|_0^2) + \frac{C_3}{3} (T_{\text{NOD5}}^3 - T_{\text{NOD5}}|_0^3)] - 1 \right) . \end{aligned} \quad (\text{B.101})$$

In the above equation, Δgap_0 is the bias gap and $T_{\text{NS}}|_0$ and $T_{\text{NOD5}}|_0$ are the bias nodal temperatures.

APPENDIX C

ORINC LISTING

This section contains a complete listing of the ORNL Inverse Code (ORINC) that is operational on the ORNL IBM 360/91 and 360/195 computers effective April 1, 1977.

The programming language is FORTRAN IV. The program consists of approximately 3200 lines of coding with a main driving routine, 26 sub-routines and subprograms, and a block data section containing information pertinent to the computer data acquisition system, the THTF bundle 1, and the RELAP model of the core.

```

ITCL=ITCNUM-300000 -1600*1000-15GV*100
IF(ITCL.EQ.15)GO TO 200
DO 10 I=1,4
10 DELGAP(I)=0.0
C-----SEARCH ITC FILE FOR ITCNUM AND ASSIGN VALUES TO REQUIRED
C-----ARRAYS FOR ITCNUM
DO 20 I=1,348
JC=I
IF(ITCNUM.EQ.NTCS(I))GO TO 28
20 CONTINUE
C-----SET-UP COEFFICIENT ARRAYS FROM COT
C-----AXIAL PEAKING FACTOR
28 PFA=PFAX(JC)
KBN COEFFICIENTS
DO 30 I=1,4
30 CBNA(I)=CBNO(JC,I)
KNGO COEFFICIENTS
DO 40 I=1,5
40 CMGA(I)=CMGC(JC,I)
PR3=PRSS(JC)
KOD2=KOD(JC)
C-----GAP PARAMETERS
DO 50 I=1,3
50 GP1(I)=GPCF(JC,I)
GPB=GAPO(JC)
TNSB=TNS(JC)
TNSB=TNSD(JC)
FEEB=FEEBEE(JC)
TMAX=TMAX(JC)
IODE=KOD(JC)
C-----OUTPUT COEFFICIENT ARRAYS FOR ITCNUM
CALL COT
C-----SET-UP RADII,NOODING ETC.
NCU=0
DO 60 I=1,7
60 RHEAT(I)=RHT(ITCL,I)
IF(ITCL.LT.4.OR.ITCL.GT.12)NCU=2
CALL RADII
PFR(1)=PFR(ITCL,1)
PFR(2)=PFR(ITCL,2)
C-----OUTPUT INFORMATION ON FIN NOODING, PIN RADIAL DIMENSIONS.
C-----AND PEAKING FACTORS
CALL OUTPUT
C-----LOAD BLOW-DCWA INPUT ARRAYS
C-----TCSS,QAUGG,TCPP,TIMEE)
CALL INBD
C-----LOAD RELAP INTERFACE INPUT ARRAYS
C-----TIMR,TBR,TSAT,PRESSUR,QUALR,AMFR,HBR,SFLUXR,TSURR,MODER,
C-----TRPEND,AND JRF)
CALL INREL
C-----STEADY STATE TEMPERATURE PROFILE AND FILM COEFFICIENT DETERMINATION
PI=3.14159265
QAVG=QAUGG(1)
TCSS=TCSS(1)
TBR=TBR(1)
MFR=MFR(1)/3600.0
TSAT=TSAT(1)
QTOT=PFA*QAVG
QDPI=QTOT/PI
C-----DETERMINE GAP AT STEADY STATE
ESP=0.0001
TI=TNSB
TNS=TCSS
TNS=TNS
IF(GPB.LE.0.0001)GO TO 68
CALL FALSE(TI,10.0,GAP,TZERO,50,1,ESP,MOUT)
GO TO 69
66 GPCAL=0.0
TZERO=TNSB
65 DELGAP(4)=GPCAL
DELRO(1)=GPCAL*12000.0
TNS=TZERO
C-----DETERMINE STEADY STATE TEMPERATURE PROFILE
CALL STEADY(CBNA,TSAT,MFR,KO)
SFLUX(1)=QTOT/(2.0*PI*R(NOD6))*350,0
TSUR(1)=TSURF(9)
C-----INITIAL PIN INTERNAL ENERGY CONTENT
CALL ENTHAL(MINIT)
C-----ZERO HEAT AND B MATRICES
DO 70 I=1,40
B(I)=0.0
DO 70 J=1,40
HEAT(I,J)=0.0
70 CONTINUE
C-----TRANSIENT CALCULATIONS
C-----INITIALIZE SCRAM MATRICES
TIM(1)=TIMEE(1)

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TIME(1)=TIMEE(1)
DO 80 I=1,NOD6
  TSAVE(1,1)=T(1)
  TC(1,1)=T(1)
  MC(1)=MF*3600.0
  QO(1)=QTOT
  TBO(1)=TB
  FEO(1)=PRESUR(1)
  TSATO(1)=TSAT
  MSATO(1)=SFLUX(1)/(TSURO(1)-TSATO(1))
  AMFO(1)=AMFR(1)
  QALLO(1)=QUALR(1)
  RMO(1)=HBR(1)
  RSFXO(1)=SFLXR(1)
  RTSURO(1)=TSURR(1)
  MCDEO(1)=MODER(1)
  TCM(1)=T(1)
C-----ZERO DTOT MATRIX
DO 90 I=1,30
  SO DTOT(I)=0.0
C-----CALL PROP AND THEN DETERMINE TIME DELAY
CALL PROP
DELAY=DMGO*MC(1)+RBOAR(1)*2/(2.0*K(1))
ISTAR=FIX(DELAY/0.05)
DELD=DELAY/0.05-FLGAT(ISTAR)
C-----TRANSIENT COUNTER INITIALIZATION
AND FIRST CALLS TO OUTTAP AND MNFLX1
LG=1
JO=1
KC=1
CALL OUTTAP(KO)
IF(ICS7.EQ.1) CALL MNFLX1 (KO,LO)
NO=2
LINES=18
CALL OUTSS(KO,QAVG)
C-----TRANSIENT INPUT
SLMCP=0.0
SLMO=0.0
SLMFLX=0.0
SE LC=LO+1
C-----TRANSIENT CALCULATIONS AND OUTPUT
TIM(2)=TIMEE(LO)
QTOT=FFA+QAVG*(LC)
DEL.=TIM(2)-TIM(1)
SLMO=SUMO+QTOT*DELT
TB=TBR(LO)
TC=TCSS(LO)
TSAT=TSATR(LO)
JO=JO+1
CALL TRANS
DO 100 I=1,NOD6
  TSAVE(1,2)=T(1)
  TC(1,2)=T(1)
  TCM(LO)=TCM(LO-1)+DELT*(DTOT(ISTAR) +DELD*(DTOT(ISTAR+1)
    -DTOT(ISTAR)))
  DO 120 JA=1,29
    JB=31-JA
    DTOT(JB)=DTOT(JB-1)
    DTOT(1)=(TSAVE(1,2)-TSAVE(1,1))/DELT
    TIME(JO)=TIM(2)
    TIM(1)=TIM(2)
    QO(JO)=QTOT
    TBO(JO)=TB
    SLMFLX=SLMFLX+MF*DELT
    CALL ENERGY(TSAVE,DELU)
    SLMCP=SLMCP+DELU
    DO 130 I=1,NOD6
      TSAVE(1,1)=TSAVE(1,2)
      SFLUX(JO)=MF*3600.0
      TSURO(JO)=T(NOD6)-2.0*R(NOD6)*MF/ZZ
      MC(JO)=SFLUX(JO)/(TSURO(JO)-TB)
      FEO(JO)=PRESUR(LC)
      AMFO(JO)=AMFR(LO)
      QALLO(JO)=QUALR(LO)
      RMO(JO)=HBR(LC)
      RSFXO(JO)=SFLXR(LO)
      RTSURO(JO)=TSURR(LO)
      MCDEO(JO)=MODER(LO)
      TSATO(JO)=TSAT
      MSATO(JO)=SFLUX(JO)/(TSURO(JO)-TSATO(JO))
      DELRO(JO)=DELGAP(4)*12000.0
      CALL OUTTAP(KC)
      IF(ICS7.EQ.1) CALL MNFLX1(KO,LO)
      IF((LO.GE.JRP.CR-LO.GE.IRP).OR.LO.GE.601) GO TO 138
      IF(JO-12)98,138,138
    138 LINES=LINES+NOD6+20
      IF(LINES-68)148,158,158
    148 NO=1
      CALL OUTTNS
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      IF((L.O.GE.JRP,OR.L.O.GE.IRP).OR.L.O.GE.601) GO TO 168
      GO TO 98
155  AC=2
      CALL OUTTNS
      JO=0
      LINES=NOD6+20
      IF((L.O.GE.JRP,OR.L.O.GE.IRP).OR.L.O.GE.601) GO TO 168
      GO TO 98
156  CONTINUE
C-----FINAL PIN INTERNAL ENERGY CONTENT AND OUTPUT
      CALL EWTAL(*FINAL)
      EGNLFT=SUMCP+SLNQ
      DELH=HINIT-HFINAL
      EGNRT=2.0*PI*(R(NOD6)*SUMFLX
      ERROR1=ABS(EGNLFT-EGNRT)/EGNLFT*100.0
      ERROR2=ABS(DELH+SUMQ-EGNRT)/(DELH+SLNQ)*100.0
      CALL OUTFNL
C-----PLOT TCM VERSUS TCMF
      IF(TCMN(1)-10.0)188,188,178
178  NOP=JRP
      IF(NOP.GE.IRF) NOP=IRP
      SX=0.0
      EX=TRPEND
      ANTELX=0.05
      CALL MAXMIN(TCP,TCMF,EY,SY,NOP)
      ITYPE=2
      NLM=JRP
      IF(NLM.GE.IRF) NLM=IRF
      IORD=1
      DO 180 I=1,NOP
180  XXX(I)=TIMEE(I)
      WRITE(NOUT,187)
187  FORMAT(1H1,T11,'OVERLAY OF MIDDLE T/C RESPONSE (ASTERISES) VERSUS
      IOPINC PREDICTED RESPONSE (X-S)')
      CALL PLOT(NOP,TIMEE,TCMF,SX,EX,ANTELX,SY,EY,ITYPE,N,CC,NUM,
      1      XXX,TCM,IORD)
C-----DENOTE END OF RECORD FOR THIS T/C
157  VAR(1)=-100.0
      KB=NOD6+18
      DO 190 I=2,KB
190  VAR(I)=0.0
      WRITE(9)(VAR(I),I=1,KB)
200  CONTINUE
      END FILE 9
C*****FINAL CALL TO MNFLX2: TO COMPUTE MEAN FLUXES
C      AND TO OUTPUT TO RELAP PLOTTAPE
      IF(IC57.EQ.1) CALL MNFLX2
C*****RETRIEVE CASE INFORMATION FROM DISK (FILE 1)
C*****AND WRITE TO SECOND FILE OF NTAPE=9
      END FILE 1
      REWIND 1
202  READ(1,207,END=218) INN
207  FORMAT(20A4)
      WRITE(9,207)INN
      GO TO 208
218  END FILE 9
      ?TOP 1002
      END

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C*****OR110340
C*****OR110341
C*****OR110342
C*****OR110343
C*****OR110344
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C*****OR110346
C*****OR110347
C      OAK RIDGE INVERSE CODE      VERSION 1.0      4-1-77
      COMMON /NODES/NMGO,NMT,ACU,NBN,N3S1,N5S2,NOD2,NOD3,NOD4,NOD5,NOD6,
      1      AN,NH,NC,NB,N5,NEN,NOUT,R(40),RBAR(40),RHEAT(7),
      2      DLRMG0,DLRMT R,DLRCU,DLRBN,DLRSS1,DLRSS2
C*****OR110348
C*****OR110349
C*****OR110350
C*****OR110351
C*****OR110352
C*****OR110353
C*****OR110354
C*****OR110355
      NMGO= NUMBER OF AGGIES IN THE MGO CORE (.GE.2)
      NMT = NUMBER OF NODES IN THE INCONEL-600 HEATER LAYER (.GE.1)
      NCU = NUMBER OF NODES IN THE CUPRO-NICKEL HEATER LAYER (.GE.0)

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C*****OR1104C2
C*****OR1104C5
C*****OR110410
C*****OR110411
C*****OR110412
C*****OR110414
SUBROUTINE STEADY(CBNO,TSAT,HFR,KD)OR110415
C OAK RIDGE INVERSE CODE VERSION 1.0 4-1-77OR111416
REAL K(40),KCAP(4),TS(40),HT(40),HKGAP(4),TF(2,40),TSF(2),HSF(2)OR111417
1 ,CBNO(4)OR111418
COMMON /NODES/AMGO,AMT,KCU,NBN,NSS1,NSS2,NOD2,NOD3,NOD4,NOD5,NOD6,OR111419
2 AM,NM,NC,NS,NE,NM,NMT,R(40),RBAR(40),RHEAT(7),OR111420
1 DLRNGC,DLNTR,DLRNC,DLRBN,DLRSS1,DLRSS2,OR111421
COMMON /SAVE/ T(40),HKGAP(4),DEL,HT,HEAT(40,40),AMGO,AMTR,ACU,OR111422
1 AM,ASS1,ASS2,RESIST(4),TSURF(9),TI,QTOT,Q(40),ZZOR111423
2 ,B(40),DELGAP(4),PFA,PPR(2),TCS,TBOR111424
DATA HKCAP/40.0/OR111425
C THERMAL CONDUCTIVITY FUNCTIONS FOR PIN COMPONENTSOR111426
HKGAP(A)=(0.013+0.0000216*A)/3600.0OR111427
AMTR(A)=(8.42944336+A*(2.88125311E-03+A*(2.42143869E-06OR111428
1 -6.15365892E-10*A)))/3600.0OR111429
ANCLIN(A)=(16.8024902-A*(1.31225586E-03-A*(4.43484557E-05-A*(OR111430
1 4.77302819E-08-2.50679477E-11*A)))/3600.0OR111431
ARDN(A)=(0A+A*IDB+A*(OC+ODP*A))/3600.0OR111432
AKSS(A)=(7.24584961+A*(5.67926941E-03-A*(9.89998897E-07OR111433
1 -3.8280424E-10*A)))/3600.0OR111434

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      IF(KD.LT.2)GO TO 29
      CALL TSMEN(TT,T,TSF,TSURF(9),NSF,HF,KD)
C  DETERMINATION OF TEMPERATURE PROFILE IN INNER S.S.SHEATH
110 J=0
      DO 110 I=NB,NCDS
110 T(I)=TCS
      TSURF(6)=TCS
110 DO 120 I=NB,NCDS
120 K(I)=AKSS(T(I))
      HT(NOD4)=ALCG(RBAR(NB)/R(NOD4))/K(NB)
      IF(NSSI.LT.2)GC TO 138
      DO 130 I=NB,NCDS
      IF(I.EQ.NOD5)GO TO 138
120 HT(I)=ALOG(R(I)/RBAR(I))/K(I)+ALOG(RBAR(I+1)/R(I+1)/K(I+1))
138 TS(NOD5)=TCS
      IF(NSSI.LT.2)GO TO 148
      DO 140 I=1,NOD5
      N1=NOD5-I
      N2=N1+1
      TS(N1)=QDPI/(2.0/HT(N1))+TS(N2)
      IF(N1.EQ.NB)GO TO 148
140 CONTINUE
140 TSUR=QDPI/(2.0/HT(NOD4))+TS(NB)
      ERROR=ABS(TSLR-TSURF(6))
      TSURF(6)=TSUR
      DO 150 I=NB,NCDS
      ERROR=ERROR+ABS(TS(I)-T(I))
150 T(I)=TS(I)
      IF(ERROR.LT.0.0020)GC TO 168
      J=J+1
      IF(J-10)110,110,150
150 WRITE(NOUT,167)
167 FORMAT(1H, '***WARNING--STEADY--TEMPERATURE PROFILE DETERMINATION
      IN INNER S.S.SHEATH DID NOT CONVERGE. CALCULATIONS TERMINATED')
      STOP
168 CONTINUE
C-----CALCULATION OF BN OUTSIDE SURFACE TEMPERATURE
      IF(DELGAP(3).EQ.0.0)GC TO 188
      KGAP(3)=AKGAP(TSURF(6))
      TSURF(5)=TSURF(6)+QDPI/(2.0*(KGAP(3)/ALOG((R(NOD4)+DELGAP(3))/
      R(NOD4))+R(NOD4)*HCGAP(3)))
      DO 170 I=1,10
      KGAP(3)=AKGAP(TSURF(5)+TSURF(6))/2.0)
      RTS=TSURF(5)+459.67
      RT6=TSURF(6)+459.67
      HR3=STEPAN*(RT5**2+RT6**2)*(RT5+RT6)
      TSUR=TSURF(6)+QDPI/(2.0*(KGAP(3)/ALOG((R(NOD4)+DELGAP(3))/
      R(NOD4))+R(NOD4)*HCGAP(3)+R(NOD4)*HR3))
      ERROR=ABS(TSLR-TSURF(5))/TSJR
      TSURF(5)=TSUR
      IF(ERROR.LT.0.0001)GO TO 198
170 CONTINUE
      IF(ERROR.GT.0.001)WRITE(NOUT,177)
177 FORMAT(1H, '***WARNING--STEADY--DETERMINATION OF SURFACE TEMPERATURE
      IE (GAP 3) FOR HR CALCULATION DID NOT CONVERGE (I.E., WITHIN ERROR
      2ITERION)')
      GO TO 198
188 TSURF(5)=TSURF(6)
180 RTS=TSURF(5)+459.67
      RT6=TSURF(6)+459.67
      HRCAP(3)=STEPAN*(RT5**2+RT6**2)*(RT5+RT6)
C  DETERMINATION OF TEMPERATURE PROFILE IN BN ANNULAR LAYER
      J=0
      DO 200 I=NC,NCDA
200 T(I)=TSURF(5)
      TSURF(4)=TSURF(5)
200 DO 210 I=NC,NCDA
210 K(I)=AKBN(T(I))
      HT(NOD3)=ALCG(RBAR(NC)/R(NOD3))/K(NC)
      IF(NBN.LT.2)GC TO 228
      DO 220 I=NC,NCDA
      IF(I.EQ.NOD4)GC TO 228
220 HT(I)=ALOG(R(I)/RBAR(I))/K(I)+ALOG(RBAR(I+1)/R(I+1)/K(I+1))
220 HT(NOD4)=ALCG(R(NOD4)/RBAR(NOD4))/K(NOD4)
      TS(NOD4)=QDPI/(2.0/HT(NOD4))+TSJRF(5)
      IF(NBN.LT.2)GC TO 238
      DO 230 I=1,NOD4
      N1=NOD4-I
      N2=N1+1
      TS(N1)=QDPI/(2.0/HT(N1))+TS(N2)
      IF(N1.EQ.NC)GC TO 238
220 CONTINUE
230 TSUR=QDPI/(2.0/HT(NOD3))+TS(N.)
      ERROR=ABS(TSLR-TSURF(4))
      TSURF(4)=TSUR
      DO 240 I=NC,NCDA
      ERROR=ERROR+ABS(TS(I)-T(I))
240 T(I)=TS(I)
      IF(ERROR.LT.0.0050)GO TO 258
      J=J+1
      IF(J-10)208,208,248
240 WRITE(NOUT,257)

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257 FORMAT(1H1,'***WARNING--STEADY--TEMPERATURE PROFILE DETERMINATION IOR110615
1A BN DID NOT CONVERGE. CALCULATIONS TERMINATED')
STOP OR110620
258 CONTINUE OR110621
C-----CALCULATION OF HEATER ELEMENT OUTSIDE SURFACE TEMPERATURE OR110622
IF(DELGAP(2).EQ.0.0)GO TO 278 OR110623
KGAP(2)=AKGAP(TSURF(4)) OR110624
TSURF(3)=TSURF(4)+QDPI/(2.0*(KGAP(2)/ALOG(R(NOD3)+DELGAP(2)))/ OR110625
R(NOD3))+R(NOD3)*HCGAP(2)) OR110626
DO 260 I=1,10 OR110627
KGAP(2)=AKGAP((TSURF(3)+TSURF(4))/2.0) OR110628
RT3=TSURF(3)+459.67 OR110629
RT4=TSURF(4)+459.67 OR110630
HR2=STEFAN*(RT3**2+RT4**2)*(RT3+RT4) OR110631
TSUR=TSURF(4)+QDPI/(2.0*(KGAP(2)/ALOG((R(NOD3)+DELGAP(2))/ OR110632
R(NOD3))+R(NOD3)*HCGAP(2)+R(NOD3)*HR2)) OR110633
ERROR=ABS(TSUR-TSURF(3))/TSUR OR110634
TSURF(3)=TSUR OR110635
IF(ERROR.LT.0.0001)GO TO 288 OR110636
260 CONTINUE OR110637
IF(ERROR.GT.0.001)WRITE(NOUT,257) OR110638
267 FORMAT(1H1,'***WARNING--STEADY--DETERMINATION OF SURFACE TEMPERATURE OR110639
1E (GAP 2) FOR HR CALCULATION DID NOT CONVERGE (I.E., WITHIN ERROR COR110640
2RITERION)') OR110641
GO TO 288 OR110642
278 TSURF(3)=TSURF(4) OR110643
288 RT3=TSURF(3)+459.67 OR110644
RT4=TSURF(4)+459.67 OR110645
HRCAP(2)=STEFAN*(RT3**2+RT4**2)*(RT3+RT4) OR110646
C DETERMINATION OF TEMPERATURE PROFILE IN HEATER ELEMENT OR110647
JCU=0 OR110648
JIN=0 OR110649
IF(NCU)298,258,368 OR110650
C-----INCONEL-600 HEATER ELEMENT SECTION OR110651
258 QINCON=PFR(1)*QDPI OR110652
QIN=QINCON/FLCAT(NHT) OR110653
IF(NCL.EQ.0)TI=TSURF(3) OR110654
DO 300 I=NP,NOD2 OR110655
300 T(I)=TI OR110656
302 DC 310 I=NM,NCD2 OR110657
310 K(I)=AKHTR(T(I)) OR110658
IF(NHT.LT.2)GO TO 328 OR110659
302 DC 320 I=NM,NCD2 OR110660
IF(I.EQ.NOD2)GO TO 328 OR110661
320 HT(I)=DLRHTR/R(I)/R(I)/2.0/((K(I)+K(I+1))/2.0) OR110662
328 HT(NOD2)=DLRHTR/R(NCD2)/R(NOD2)/4.0/K(NOD2) OR110663
TS(NOD2)=QINCON/(2.0/HT(NOD2))+TI OR110664
IF(NHT.LT.2)GO TO 338 OR110665
QSUM=QINCON OR110666
DC 330 I=1,NOD2 OR110667
QSUM=QSUM-QIN OR110668
N1=NOD2-I OR110669
N2=N1+1 OR110670
TS(N1)=QSUM/(2.0/HT(N1))+TS(N2) OR110671
IF(N1.EQ.NM)GO TO 338 OR110672
330 CONTINUE OR110673
338 ERROR=0.0 OR110674
DO 340 I=NP,NOD2 OR110675
ERROR=ERROR+ABS(TS(I)-T(I)) OR110676
340 T(I)=TS(I) OR110677
IF(ERROR.LT.0.0020)GO TO 358 OR110678
JIN=JIN+1 OR110679
IF(JIN-10)308,308,348 OR110680
348 WRITE(NOUT,357) OR110681
357 FORMAT(1H1,'***WARNING--STEADY--TEMPERATURE PROFILE DETERMINATION IOR110682
1A INCONEL HEATER ELEMENT DID NOT CONVERGE. CALCULATIONS TERMINATED OR110683
2') OR110684
STOP OR110685
358 CONTINUE OR110686
TSURF(2)=T(NM) OR110687
TSURF(1)=T(NM) OR110688
DO 360 I=1,NMGC OR110689
360 T(I)=TSURF(1) OR110690
RT2=TSURF(2)+459.67 OR110691
RT1=TSURF(1)+459.67 OR110692
HRCAP(1)=STEFAN*(RT2**2+RT1**2)*(RT2+RT1) OR110693
C OR110694
C STEADY STATE TEMPERATURE PROFILE DETERMINATION COMPLETED OR110695
C OR110696
RETURN OR110697
C-----CLPRO-NICKEL HEATER ELEMENT SECTION OR110698
368 QCLNI=PFR(2)*QDPI OR110699
QCL=QCLNI/FLCAT(ACU) OR110700
DO 370 I=NM,NCD3 OR110701
270 T(I)=TSURF(3) OR110702
TI=TSURF(3) OR110703
378 DO 380 I=NM,ACD3 OR110704
380 K(I)=AKCUN(T(I)) OR110705
HT(NOD2)=DLRCU/R(NOD2)/R(NOD2)/4.0/K(NM) OR110706
IF(NCL.LT.2)GO TO 398 OR110707
DC 390 I=NM,NCD3 OR110708
IF(I.EQ.NOD3)GO TO 398 OR110709

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35C HT(I)=DLRCL/R(I)/R(I)/2.0/((K(I)+K(I+1))/2.0)
35E HT(NOD3)=GLRCL/R(NOD3)/R(NOD3)/4.0/K(NOD3)
      QSUM=QDPI
      TS(NOD3)=QSUM/(2.0/HT(NOD3))+TSJRF(3)
      IF(NCL.LT.2)GO TO 408
      DO 400 I=1,NOD3
      QSUM=QSUM-QCL
      N1=NOD3-I
      N2=N1+1
      TS(N1)=QSUM/(2.0/HT(N1))+TS(N2)
      IF(N1.EQ.N1)GC TC 408
47C CONTINUE
47E QSUM=QSUM-QCU
      TSLR=QSUM/(2.0/HT(NOD2))+TS(NM)
      ERROR=ABS(TSLR-TI)
      TI=TSLR
      DO 410 I=NM,NOD3
      ERROR=ERROR+ABS(TS(I)-T(I))
41C T(I)=TS(I)
      IF(ERROR.LT.0.0020)GO TC 295
      JCU=JCU+1
      IF(JCU-10)378,378,418
41E WRITE(NOUT,427)
427 FORMAT(1H1,'***WARNING--STEADY--TEMPERATURE PROFILE DETERMINATION
      IN CU-NI HEATER ELEMENT DID NOT CONVERGE. CALCULATIONS TERMINATED')
C
C      END OF STEADY
C
C      STOP
C      END

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ORI1C711
ORI1C712
ORI1C713
ORI1C714
ORI1C715
ORI1C716
ORI1C717
ORI1C718
ORI1C719
ORI1C720
ORI1C721
ORI1C722
ORI1C723
ORI1C724
ORI1C725
ORI1C726
ORI1C727
ORI1C728
ORI1C729
ORI1C730
ORI1C731
ORI1C732
ORI1C733
ORI1C734
ORI1C735
ORI1C736
ORI1C737
ORI1C738
ORI1C739
ORI1C740

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      SUBROUTINE TSMIN(TT,T,TSF,TSURF,HSF,MF,KO)
C   CAK RIDGE INVERSE CODE   VERSION 1.0   4-1-77
      DIMENSION TT(2,40),T(40),TSF(2),HSF(2)
      COMMON /NODES/MGO,NMT,NOJ,NBN,NSS1,NSS2,NOD2,NOD3,NOD4,NOD5,NOD6,
      1      AF,NH,NC,NB,NS,NIN,NOU,R(40),RBAR(40),RHEAT(7),
      2      CLANGC,DLRHTA,DLRCL,DLRBN,DLRSS1,DLRSS2
      IF(HSF(2))18,18,8
      E IF(TSF(1).LT.TSF(2))GC TO 18
      DO 10 I = NS,ACD6
      T(I) = TT(2,I)
      TSURF=TSF(2)
      MF = HSF(2)
      KD=2
      RETURN
      18 DO 20 I = NS, ACD6
      20 T(I) = TT(1,I)
      TSURF=TSF(1)
      MF = HSF(1)
      KD=1
      RETURN
      END

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ORI1C741
ORI1C742
ORI1C743
ORI1C744
ORI1C745
ORI1C746
ORI1C747
ORI1C748
ORI1C749
ORI1C750
ORI1C751
ORI1C752
ORI1C753
ORI1C754
ORI1C755
ORI1C756
ORI1C757
ORI1C758
ORI1C759
ORI1C760
ORI1C761

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C*****ORI10762
C*****ORI10763
C*****ORI10764
C*****SUBROUTINE TRANS*****ORI10765
C*****ORI10766
C*****ORI10767
C*****ORI10768
C*****ORI10769
C*****ORI10770
C*****ORI10771
C*****ORI10772
C   CAK RIDGE INVERSE CODE   VERSION 1.0   4-1-77
      REAL K,KGAP
      LOGICAL SING
      SUBROUTINE TRANS IS THE TRANSIENT DRIVING ROUTINE

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ORI10762
ORI10763
ORI10764
ORI10765
ORI10766
ORI10767
ORI10768
ORI10769
ORI10770
ORI10771
ORI10772
ORI10773
ORI10774
ORI10775

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DIMENSION A(40,40),AB(40),X(40)
COMMON /NODES/AMGO,NHT,NCU,NBN,NSS1,NSS2,NOD2,NOD3,NOD4,NOD5,NOD6,
1 AB,NH1,NC,NB,NS,NIN,NOUT,R(40),RBAR(40),RHEAT(7),
2 CLAMGO,DLRHT,R,DLRCJ,DLRBN,DLRSS1,D,RSS2
COMMON /PROP1/DMGO,DHTE,DCUNI,DBN,DS5,C(40),K(40),CBND(4),CMGO(5),
1 KGAP(4),KCD2,PRS
COMMON /SAVE/ T(40),HFGAP(4),DELG,HF,HEAT(40,40),AMGO,AMTR,ACU,
1 ABN,ASS1,ASS2,RESIST(4),TSURF(9),TI,QTOT,Q(40),ZZ
2 B(40),DELGAP(4),PFA,PFR(2),TCS,TB
STEFAN=0.1714E-08/3600.0
PI=3.14159265
OR11C776
OR11C777
OR11C778
OR11C779
OR11C780
OR11C781
OR11C782
OR11C783
OR11C784
OR11C785
OR11C786
OR11C787
OR11C788
OR11C789
OR11C790
OR11C791
OR11C792
OR11C793
OR11C794
OR11C795
OR11C796
OR11C797
OR11C798
OR11C799
OR11C800
OR11C801
OR11C802
OR11C803
OR11C804
OR11C805
OR11C806
OR11C807
OR11C808
OR11C809
OR11C810
OR11C811
OR11C812
OR11C813
OR11C814
OR11C815
OR11C816
OR11C817
OR11C818
OR11C819
OR11C820
OR11C821
OR11C822
OR11C823
OR11C824
OR11C825
OR11C826
OR11C827
OR11C828
OR11C829
OR11C830
OR11C831
OR11C832
OR11C833
OR11C834
OR11C835
OR11C836
OR11C837
OR11C838
OR11C839
OR11C840
OR11C841
OR11C842
OR11C843
OR11C844
OR11C845
OR11C846
OR11C847
OR11C848
OR11C849
OR11C850
OR11C851
OR11C852
OR11C853
OR11C854
OR11C855
OR11C856
OR11C857
OR11C858
OR11C859

C
C CALCULATE RADIAL HEAT GENERATION FOR EACH NODE
QINCON=(PFR(1)*QTOT)/FLCAT(NHT)/PI
CCLNI=0.0
IF(NCU.GT.0) DCUNI=(PFR(2)*QTOT)/FLOAT(NCU)/PI
C
C-----MGO CCRE
DO 10 I=1,NMGO
10 Q(I)=0.0
C
C-----HEATER SECTION (INCCNCL-600 LAYER)
DO 20 I=AN,ACD2
20 Q(I)=QINCON
C
C-----HEATER SECTION (CUPRC-NICKEL LAYER, IF ANY)
IF(NCU)38,38,28
28 DO 30 I=NH,ACD3
30 Q(I)=QINCON
C
C-----BCRON NITRIDE SECTION, AND STAINLESS STEEL SHEATHS
38 DO 40 I=NC,NOD6
40 Q(I)=0.0
C
C CALCULATE GAP RADIATION HEAT TRANSFER COEFFICIENTS
DO 50 I=1,4
50 HRGAP(I)=0.0
IF(DELGAP(1).NE.0.0) HFGAP(1)=STEFAN*((T(NMGO)+459.67)**2+(T(NH1)+
459.67)**2)*((T(NMGO)+459.67)+(T(NH1)+459.67))
IF(DELGAP(2).NE.0.0) HRGAP(2)=STEFAN*((T(NOD3)+459.67)**2+(T(NC)+
459.67)**2)*((T(NOD3)+459.67)+(T(NC)+459.67))
IF(DELGAP(3).NE.0.0) HFGAP(3)=STEFAN*((T(NOD4)+459.67)**2+(T(NB)+
459.67)**2)*((T(NOD4)+459.67)+(T(NB)+459.67))
IF(DELGAP(4).NE.0.0) HFGAP(4)=STEFAN*((T(NOD5)+459.67)**2+(T(NS)+
459.67)**2)*((T(NOD5)+459.67)+(T(NS)+459.67))
C
C SET-UP HEAT MATRIX AND CONSTANT B VECTOR
CALL FROP
CALL GAPTRN
CALL HEATR
CALL BVCTR
C
C SOLVE THE SYSTEM OF EQUATIONS
ZZ=2.0/(ALGG(R(NOD6)/REAR(NOD6))/K(NOD6))
HEAT(NOD6,NOD6)=-HEAT(NOD6,NOD6-1)-ASS2*C(NOD6)
B(NOD6)=-ASS2*C(NOD6)+T(NOD6)-Q(NOD6)
DO 60 I=1,40
AB(I)=B(I)
DO 60 J=1,40
A(I,J)=HEAT(I,J)
A(I,NOD5)=0.0
60 CONTINUE
A(NOD5,NOD5)=-1.0
AB(NOD5-1)=AB(NOD5-1)-HEAT(NOD5-1,NOD5)*TCS
AB(NOD5+1)=AB(NOD5+1)-HEAT(NOD5+1,NOD5)*TCS
AB(NOD5)=AB(NOD5)-HEAT(NOD5,NOD5)*TCS
CALL SOLVE(A,40,40,NOD6,AB,X,SING)
IF(.NOT.SING)GO TO 88
WRITE(NOUT,67)
67 FORMAT(1H1,22HTHE MATRIX IS SINGULAR)
68 WRITE(NOUT,69)IJ,DEV
69 FORMAT(1H1,3H1J=,I3,10X,4HDEV=,1PE17.9)
STOP
C
C OUTPUT T VECTOR
88 DO 90 I=1,NOD6
90 T(I)=X(I)
T(NOD5)=TCS
HF=X(NOD5)/(2.0*R(NOD6))
C
C TRANSIENT CALCULATIONS FOR THIS TIME STEP ARE COMPLETED
RETURN
END

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C*****OR11C86C
C*****OR11C861
C*****OR11C862
C*****OR11C863
C*****OR11C864
C*****OR11C865
C*****OR11C866
C SUBROUTINE KEATR OR11C867
C CAK RIDGE INVERSE CODE VERSION 1.0 4-1-77 OR11C868
REAL K,KGAP,HCGAP(4) OR11C869
COMMON /NODES/NMGO,INT,NCU,NBN,NSS1,NSS2,NOD2,NOD3,NOD4,NOD5,NOD6,OR11C870
1 AM,NH,AC,AB,NS,MIN,NOUT,R(40),RBAR(40),RHEAT(7), OR11C871
2 DLANGC,DLRMT,DLRCU,DLRBN,DLRSS1,DLRSS2 OR11C872
COMMON/PROPI/DNGO,DHTR,DCUNI,DBN,DSS,C(40),K(40),CBND(4),CHGO(5), OR11C873
1 KGAP(4),KOD2,PRS OR11C874
COMMON /SAVE/ T(40),HFGAP(4),DELT,MF,HEAT(40,40),ANGC,AMTR,ACU, OR11C875
1 ABN,ASS1,ASS2,RESIST(4),TSURF(9),TI,OTDT,Q(40),ZZ OR11C876
2 R(40),DELGAP(4),PFA,PFR(2),TCS,TB OR11C877
DATA HCGAP/4*0.0/ OR11C878
C OR11C879
C SET-UP MATRIX ARRAY OR11C880
C ***FOR THE NGO CORE AND CORE-HEATER BOUNDARY OR11C881
HEAT(1,2)=4.0*(K(1)+K(2))/2.0 OR11C882
ANGC=DNGO*DLRNGO/DELT OR11C883
HEAT(1,1)=HEAT(1,2)-ANGC*C(1) OR11C884
HEAT(2,1)=HEAT(1,2) OR11C885
IF(NMGO.LT.3)GC TO 8 OR11C886
DO 70 I=1,NMGO OR11C887
HEAT(I, I)=4.0*FLOAT(I-1)*(K(I-1)+K(I))/2.0 OR11C888
7C HEAT(I,I-1)=HEAT(I-1,I) OR11C889
8 IF(DELGAP(1).EQ.0.0)GO TO 28 OR11C890
IF((KGAP(1)+HCGAP(1)).EQ.0.0.AND.HRGAP(1).EQ.0.0)GO TO 18 OR11C891
RESIST(1)=1.0/(KGAP(1)/ALOG((R(NMGO)+DELGAP(1))/R(NMGO))+ OR11C892
R(NMGO)*HCGAP(1)+R(NMGO)*HRGAP(1)) OR11C893
GO TO 38 OR11C894
18 WRITE(NOUT,7) OR11C895
7. FORMAT('H1.***WARNING--HEATR--INFINITE RESISTANCE AT NGO-HTR INTER OR11C896
FACE') OR11C897
STOP OR11C898
28 RESIST(1)=0.0 OR11C899
38 HEAT(NMGO,NH)=2.0/(DLRMT/R(NMGO)/R(NMGO)/4.0/K(NH)+RESIST(1)+ OR11C900
1 DLNGO/R(NMGO)/R(NMGO)/4.0/K(NMGO)) OR11C901
HEAT(NH,NMGO)=HEAT(NMGO,NH) OR11C902
DO 80 I=2,NMGO OR11C903
2C HEAT(I,I)=HEAT(I,I-1)-HEAT(I,I+1)-ANGC*C(I) OR11C904
C ***FOR THE HEATER AND HEATER-BNG BOUNDARY OR11C905
IF(NCU)81,81,82 OR11C906
C INCONEL-HEATER WITH NO-CUPRO-NICKEL-OVERSLEEVES OR11C907
81 AMTR=DHTR*DLRMT/DELT OR11C908
IF(NHT.LT.2)GC TO 48 OR11C909
J=NM+1 OR11C910
DO 90 I=J,NOD2 OR11C911
HEAT(I-1,I)=4.0*(K(I)+K(I-1))/2.0*R(I-1)*R(I-1)/DLRMT OR11C912
5C HEAT(I,I-1)=HEAT(I-1,I) OR11C913
48 IF(DELGAP(2).EQ.0.0)GO TO 68 OR11C914
IF((KGAP(2)+HCGAP(2)).EQ.0.0.AND.HRGAP(2).EQ.0.0)GO TO 58 OR11C915
RESIST(2)=1.0/(KGAP(2)/ALOG((R(NOD2)+DELGAP(2))/R(NOD2))+ OR11C916
R(NOD2)*HCGAP(2)+R(NOD2)*HRGAP(2)) OR11C917
GO TO 78 OR11C918
58 WRITE(NOUT,17) OR11C919
17. FORMAT('H1.***WARNING--HEATR--INFINITE RESISTANCE AT HTR-BN INTER OR11C920
FACE') OR11C921
STOP OR11C922
68 RESIST(2)=0.0 OR11C923
78 HEAT(NOD2,NH)=2.0/(DLRMT/R(NOD2)/R(NOD2)/4.0/K(NOD2)+RESIST(2)+ OR11C924
1 ALOG(RBAR(NH)/R(NOD2))/K(NH)) OR11C925
HEAT(NH,NOD2)=HEAT(NOD2,NH) OR11C926
DO 100 I=NH,NOD2 OR11C927
10C HEAT(I,I)=HEAT(I,I-1)-HEAT(I,I+1)-AMTR*C(I) OR11C928
GO TO 1002 OR11C929
C INCONEL HEATER WITH CUPRO-NICKEL OVERSLEEVES OR11C930
82 AMTR=DHTR*DLRMT/DELT OR11C931
ACU=DCUNI*DLRCU/DELT OR11C932
IF(NHT.LT.2)GO TO 430 OR11C933
J=NM+1 OR11C934
DO 900 I=J,NOD2 OR11C935
HEAT(I-1,I)=4.0*(K(I)+K(I-1))/2.0*R(I-1)*R(I-1)/DLRMT OR11C936
5C HEAT(I,I-1)=HEAT(I-1,I) OR11C937
480 HEAT(NOD2,NH)=2.0/(DLRMT/R(NOD2)/R(NOD2)/4.0/K(NOD2)+ OR11C938
1 DLRCU/R(NOD2)/R(NOD2)/4.0/K(NH)) OR11C939
HEAT(NH,NOD2)=HEAT(NOD2,NH) OR11C940
DO 1000 I=NH,NOD2 OR11C941
10C0 HEAT(I,I)=HEAT(I,I-1)-HEAT(I,I+1)-AMTR*C(I) OR11C942
IF(NCL.LT.2)GO TO 481 OR11C943
J=NM+1 OR11C944
DO 901 I=J,NOD3 OR11C945
HEAT(I-1,I)=4.0*(K(I)+K(I-1))/2.0*R(I-1)*R(I-1)/DLRCU OR11C946
5C1 HEAT(I,I-1)=HEAT(I-1,I) OR11C947
481 IF(DELGAP(2).EQ.0.0)GC TO 680 OR11C948
IF((KGAP(2)+HCGAP(2)).EQ.0.0.AND.HRGAP(2).EQ.0.0)GO TO 580 OR11C949
RESIST(2)=1.0/(KGAP(2)/ALOG((R(NOD3)+DELGAP(2))/R(NOD3))+ OR11C950
R(NOD3)*HCGAP(2)+R(NOD3)*HRGAP(2)) OR11C951

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GO TO 780
5EC WRITE(NOUT,17)
STOP
6EC RESIST(2)=0.0
780 HEAT(NOD3,NC)=2.0/(DLRCU/R(NOD3)/R(NOD3)/4.0/K(NOD3)+RESIST(2)+
  1 ALOG(RBAR(NC)/R(NOD3))/K(NC))
  HEAT(NC,NOD3)=HEAT(NOD3,NC)
  DO 1001 I=NH,NOD3
1001 HEAT(I,I)=-HEAT(I,I-1)-HEAT(I,I+1)-ACU*C(I)
C ***FOR THE BN LAYER AND BN-SSI BOUNDARY
1002 ABN=0BN*DLRBN/DELT
  IF(NBN.LT.2)GO TO 88
  J=NC+1
  DO 110 I=J,NCD4
  HEAT(I-1,I)=2.0/(ALOG(R(I-1)/RBAR(I-1))/K(I-1)+ALOG(RBAR(I)/
  1 R(I-1))/K(I))
110 HEAT(I,I-1)=HEAT(I-1,I)
  88 IF(DELGAP(3).EQ.0.0)GO TO 128
  IF((KCAP(3)+HCGAP(3)).EQ.0.0.AND.HRGAP(3).EQ.0.0)GO TO 90
  RESIST(3)=1.0/(KGAP(3)/ALOG((R(NOD4)+DELGAP(3))/R(NOD4))+
  1 R(NOD4)*HCGAP(3)+R(NOD4)*HRGAP(3))
  GO TO 118
5E WRITE(NOUT,27)
27 FORMAT(1H1,'**WARNING--HEATR--INFINITE RESISTANCE AT BN-SSI INTER
  1ACE')
STOP
10E RESIST(3)=0.0
118 HEAT(NOD4,NB)=2.0/(ALOG(R(NOD4)/RBAR(NOD4))/K(NOD4)+RESIST(3)+
  1 ALOG(RBAR(NB)/R(NOD4))/K(NB))
  HEAT(NB,NOD4)=HEAT(NOD4,NB)
  DO 120 I=NC,NOD4
120 HEAT(I,I)=-HEAT(I,I-1)-HEAT(I,I+1)-ABN*C(I)
C ***FOR THE SS-SHEATH (INNER) AND SHEATH-TO-SHEATH BOUNDARY
  ASS1=DSS*DLRSS1/DELT
  IF(NSSI.LT.2)GO TO 128
  J=NB+1
  DO 130 I=J,NOD5
  HEAT(I-1,I)=2.0/(ALOG(R(I-1)/RBAR(I-1))/K(I-1)+ALOG(RBAR(I)/
  1 R(I-1))/K(I))
130 HEAT(I,I-1)=HEAT(I-1,I)
128 IF(DELGAP(4).LE.8.0E-09)GO TO 149
  IF((KCAP(4)+HCGAP(4)).EQ.0.0.AND.HRGAP(4).EQ.0.0)GO TO 138
  RESIST(4)=ALOG((R(NOD5)+DELGAP(4))/R(NOD5))/
  1 (KGAP(4)+R(NOD5)*HCGAP(4)+R(NOD5)*HRGAP(4))+
  2 ALOG((R(NOD5)+DELGAP(4))/R(NOD5))
  GO TO 158
138 WRITE(NOUT,37)
37 FORMAT(1H1,'**WARNING--HEATR--INFINITE RESISTANCE AT SHEATH-TO-SHEATH
  1ATH INTERFACE')
STOP
148 RESIST(4)=0.0
158 HEAT(NOD5,NS)=2.0/(ALOG(R(NOD5)/RBAR(NOD5))/K(NOD5)+RESIST(4)+
  1 ALOG(RBAR(NS)/R(NOD5))/K(NS))
  HEAT(NS,NOD5)=HEAT(NOD5,NS)
  DO 140 I=NB,NOD5
140 HEAT(I,I)=-HEAT(I,I-1)-HEAT(I,I+1)-ASS1*C(I)
C ***FOR THE S.S-SHEATH (OUTER) AND SHEATH-TO-WATER BOUNDARY
  ASS2=DSS*DLRSS2/DELT
  IF(NSS2.LT.2)GO TO 168
  J=NS+1
  DO 150 I=J,NOD6
  HEAT(I-1,I)=2.0/(ALOG(R(I-1)/RBAR(I-1))/K(I-1)+ALOG(RBAR(I)/
  1 R(I-1))/K(I))
150 HEAT(I,I-1)=HEAT(I-1,I)
  DO 160 I=NS,NOD6
  IF(I.EQ.NOD6)GO TO 168
160 HEAT(I,I)=-HEAT(I,I-1)-HEAT(I,I+1)-ASS2*C(I)
168 CONTINUE
C
C HEAT MATRIX COMPLETED
C
  RETURN
  END

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OR110952
OR110953
OR110954
OR110955
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OR110965
OR110966
OR110967
OR110968
OR110969
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OR110978
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OR111016
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OR111018
OR111019
OR111020
OR111021
OR111022
OR111023
OR111024

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C*****ORII11025
C*****ORII11026
C*****ORII11027
C*****SUBROUTINE BVECTR*****ORII11026
C*****ORII11025
C*****ORII11030
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C*****ORII11080

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C*****ORII1080
C*****ORII1081
C*****SUBROUTINE PROP*****ORII1082
C*****ORII1083
C*****ORII1084
C*****ORII1085
C      DETERMINATION OF PIN COMPONENT PHYSICAL PROPERTIES (I.E.:SPECIFIC
C      HEAT-C,AND THERMAL CONDUCTIVITY-K ) AS FUNCTIONS OF TEMPERATURE:
C      WHERE:
C      K HAS UNITS OF BTU/(SEC*FT**2/FT*F)
C      C HAS UNITS OF BTU/(LB*F)
C      T HAS UNITS OF DEGREES F
C      DENSITIES HAVE UNITS OF LB/FT**3
C*****ORII1086
C*****ORII1087
C*****ORII1088
C*****ORII1089
C*****ORII1090
C*****ORII1091
C*****ORII1092
C*****ORII1093
C      SUBROUTINE PRCP
C      OAK RIDGE INVERSE CODE      VERSION 1.0      4-1-77
C      REAL K,KCAP
C      COMMON /NODES/NRG0,NHT,NCU,NBN,NBS1,NBS2,NOD2,NOD3,NOD4,NOD5,NOD6,
1      NP,NH,NC,NB,NS,NT,N,OUT,R(40),RBAR(40),RHEAT(7),
2      DLNMC,DLNMR,DLACU,DLARN,DLRSS1,DLRSS2
C      COMMON/PROP/DMFC,OMTN,OCUNT,OSN,DS,C(40),K(40),CBNO(4),CMGO(5),
1      KCAP(4),NOD2,PRS
C*****ORII1094
C*****ORII1095
C*****ORII1096
C*****ORII1097
C*****ORII1098
C*****ORII1099
C*****ORII1100
C*****ORII1101

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COMMON /SAVE/ T(40),HKGAP(4),DELT,NF,HEAT(40,40),AM20,AMTR,ACU,
1  ABA,ASS1,ASS2,RES13T(4),TSUMF(9),TI,OTOT,Q(40),ZZ
2  B(40),DELGAP(4),PFA,CPR(2),TCS,TB
CPGOD(A)=0.224258423+A*(1.22646359E-04-A*(6.351911E-08
1  -1.21040955E-11*A))
AKKGD(A)=CA+A*(CE-A*(CC+A*(CD+A*CE)))
CHTR(A)=0.097743034+A*(7.11642206E-05-A*(7.7241566E-08
1  -3.8081537E-11*A))
AMTR(A)=0.42944336+A*(2.88105011E-03+A*(2.42143869E-06
1  -6.19365892E-10*A))
CCUN(A)=0.0950193405+A*(2.93776393E-05-A*(1.41008059E-08
1  -6.65068001E-12*A))
AKCUN(A)=16.8024902-A*(1.31225586E-03-A*(4.43458557E-05-A*(
1  4.77302819E-08-2.50679477E-11*A)))
CBNA(A)=0.167812347+A*(3.70264053E-04-A*(1.73793524E-07
1  -3.14486215E-11*A))
AKBN(A)=DA+A*(DB+A*(DC+DD*A))
CSS(A)=0.104247093+A*(6.05533191E-05-A*(4.3772161E-08-A*(
1  2.01225703E-11-3.16413542E-15*A)))
AKSS(A)=7.24584961+A*(5.07926941E-03-A*(9.89995897E-07
1  -3.82840426E-10*A))
KRGAP(A)=0.013+0.0000216*A
AKCONT(A)=33.2194824-A*(5.2362442E-02-A*(3.97711992E-05-A*(
1  1.46937964E-08-2.15005791E-12*A)))

C
C DENSITY DATA
DNGO=212.0
DHTR=526.0
DCUN=553.0
DBN=125.0
DSS=496.0

C
C SET CONSTANTS FOR AKNGC AND AKBN
CA=CMGO(1)
CB=CMGO(2)
CC=CMGO(3)
CD=CMGO(4)
CE=CMGO(5)
DA=CBNO(1)
DB=CBNO(2)
DC=CBNO(3)
DD=CBNO(4)

C
C THERMAL CONDUCTIVITY AND SPECIFIC HEAT DATA
C****MAGNESIUM OXIDE CORE
IF(KOD2-2)8.8,14
8 DO 10 I=1,NMGO
C(I)=CMGO(T(I))
10 K(I)=AKNGO(T(I))/3600.0
KCAP(1)=KRGAP((T(NMGO)+T(NM))/2.0)/3600.0
GO TO 18
14 DO 16 I=1,NMGC
C(I)=CMGO(T(I))
AX=3.891*PRS
GAMMA=AKGAP(T(I))/AKCCAT(T(I))-1.0
FAC=(1.0+AX**0.85599*GAMMA)/(1.0+AX**0.85599*GAMMA-AX*GAMMA)
16 K(I)=FAC*AKCCAT(T(I))/3600.0
KCAP(1)=KRGAP((T(NMGO)+T(NM))/2.0)/3600.0

C
C****HEATER (INCONEL-600 LAYERS)
1E DO 20 I=NM,NGO2
C(I)=CHTR(T(I))
20 K(I)=AMTR(T(I))/3600.0

C
C****HEATER (CUPRC-NICKEL LAYERS, IF ANY)
IF(NCU)38,38,28
2E DO 30 I=NM,NGO3
C(I)=CCUN(T(I))
30 K(I)=AKCUN(T(I))/3600.0
3E KCAP(2)=KRGAP((T(NGO3)+T(NC))/2.0)/3600.0

C
C****CHROM NITRIDE ANNULAR LAYER
DO 40 I=NC,NGO4
C(I)=CBN(T(I))
40 K(I)=AKBN(T(I))/3600.0
KCAP(3)=KRGAP((T(NGO4)+T(NB))/2.0)/3600.0

C
C****FIRST S.S. SHEATH
DO 50 I=NB,NGO5
C(I)=CSS(T(I))
50 K(I)=AKSS(T(I))/3600.0
KCAP(4)=KRGAP((T(NGO5)+T(NS))/2.0)/3600.0

C
C****SECOND S.S. SHEATH
DO 60 I=NS,NGO6
C(I)=CSS(T(I))
60 K(I)=AKSS(T(I))/3600.0

C
RETURN
END

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[illegible]

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C*****ORII1264
C*****ORII1265
C*****ORII1266
C*****INTERNAL ENERGY CALCULATIONS*****ORII1267
C*****ORII1268
C*****ORII1269
C*****ORII1270
C*****ORII1271
C      DETERMINATION OF PIN INTERNAL ENERGY CONTENT
C      WHERE:
C      PIN ENERGY = SUM OF RHO*CP*PI*DELTA*DIFFERENCE IN T
C      (SUBROUTINE ENERGY(TSAVE,DELTA))
C      OAK RIDGE INVERSE CODE      VERSION 1.0      4-1-77
C      REAL K,TSAVE(40,2)
C      COMMON /NODES/AMGO,AMT,ACU,AMN,NSS1,NSS2,NOD2,NOD3,NOD4,NOD5,NOD6,
1      AM,AM,NC,AB,NS,NIN,NOJT,R(40),RBAR(40),RHEAT(7),
2      DLRNGO,DLRHT,DLRCJ,DLRBN,DLRSS1,DLRSS2
C
C*****COMPONENT CP STATEMENT FUNCTIONS
CNGO(A)=0.224258423+A*(1.22666359E-04-A*(6.351911E-08
1      -1.21040955E-11*A))
CHTR(A)=0.0977430344+A*(7.11642206E-05-A*(7.7241566E-08
1      -3.8081537E-11*A))
CCUN(A)=0.0950193405+A*(2.93776393E-05-A*(1.41008059E-08
1      -6.65068001E-12*A))
CBN(A)=0.167812347+A*(3.70264)53E-04-A*(1.73793524E-07
1      -3.14486215E-11*A))
CSS(A)=0.104247093+A*(6.05583191E-05-A*(4.3772161E-08-A*(
1      2.01225703E-11-3.16413562E-15*A)))
C
C*****COMPONENT DENSITIES
DMGO=212.0
DHTR=526.0
DCUN=653.0
DBN=125.0
DIS=496.0
C
C*****MAGNESIUM OXIDE CORE
SLN=0.0
DO 10 I=1,NMGC
10 SLN=SUM+DLRMGC*DMGO+CNGO(TSAVE(I,1))*(TSAVE(I,1)-TSAVE(I,2))
C
C*****HEATER (INCONEL-600 LAYER)
DO 20 I=NM,NOD2
20 SLN=SUM+DLRHT*DHTR+CHTR(TSAVE(I,1))*(TSAVE(I,1)-TSAVE(I,2))
C
C*****HEATER (CUPRO-NICKEL LAYER, IF ANY)
IF(NCU)38,38,28
28 DO 30 I=NM,NOD3
30 SLN=SUM+DLACL*DCUN+CCUN(TSAVE(I,1))*(TSAVE(I,1)-TSAVE(I,2))
C
C*****BROWN NITRIDE ANNULAR LAYER
38 DO 40 I=NC,NOD4
40 SLN=SUM+DLRBN*DBN+CBN(TSAVE(I,1))*(TSAVE(I,1)-TSAVE(I,2))
C
C*****FIRST S.S. SHEATH
DO 50 I=NB,NOD5
50 SLN=SUM+DLRSS1*DISS+CSS(TSAVE(I,1))*(TSAVE(I,1)-TSAVE(I,2))
C
C*****SECOND S.S. SHEATH
DO 60 I=NS,NOD6
60 SLN=SUM+DLRSS2*DISS+CSS(TSAVE(I,1))*(TSAVE(I,1)-TSAVE(I,2))
C
      DELU=J.14159265*SLN
      RETURN
      END

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C      FUNCTION USED TO DETERMINE SHEATH GAP AND NS TEMPERATURE FOR S.S. STAINLESS STEEL
C      FUNCTION GAF(T)
C      OAK RIDGE INVERSE CODE      VERSION 1.0      4-1-77
C      COMMON /NODES/AMGO,AMT,ACU,AMN,NSS1,NSS2,NOD2,NOD3,NOD4,NOD5,NOD6,
1      AM,AM,NC,AB,NS,NIN,NOJT,R(40),RBAR(40),RHEAT(7),
2      DLRNGC,DLRHT,DLRCJ,DLRBN,DLRSS1,DLRSS2
C      COMMON /GAPCAL/GFB,GPI(3),TNB,TNDB,TNDS,TNS,GDPI,YCAL,FEED,
1      TMAX,ICDE
C
C      STATEMENT FUNCTIONS
AKGAP(A)=(0.013+0.0000216*A)/3600.0

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      AKSS(A)=(7.24584961+A*(5.079269+1E-03-A*(9.09995897E-07
1      -3.8284426E-10*A)))/3600.0
C
      ND5=RBAR(NOD5)*1.0E+07
      R2=RBAR(NS)*1.0E+07
      GP=GPB/1.2E-03
      IF(GPB.EQ.0.0)GO TO 6
      IF(IODE-2)4,4,6
4      A1=T-TNSB
      A2=TND5-TNDSB
      B1=T+2-TNSB+2
      B2=TND5+2-TNDSB+2
      C1=T+3-TNSB+3
      C2=TND5+3-TNDSB+3
      F1=(GP1(1)*A1+GP1(2)*B1+GP1(3)*C1)*1.0E-07
      F2=(GP1(1)*A2+GP1(2)*B2+GP1(3)*C2)*1.0E-07
      F3=EXP(F1)
      FDS=EXP(F2)
      YCAL=GP+RS*(F3-1.0)-ND5*(FDS-1.0)
      IF(YCAL.LE.0.0)YCAL=0.0
      GO TO 8
E      YCAL=GP
C      YCAL=YCAL*1.0E-07
      TSURF7=TND5-GDF1/(2.0/(ALOG(R(NOD5)/RBAR(NOD5))/AKSS(TND5)))
      IF(YCAL.LE.0.0)GO TC 18
      TSURF8=TSURF7-GDF1/2.0*ALOG((R(NOD5)+YCAL)/R(NOD5))/
1      AKGAP(TSURF7)
      STEFAN=0.1714E-08/3600.0
      DO 19 I=1,10
      RT7=TSURF7+459.67
      RT8=TSURF8+459.67
      HR4=STEFAN*(RT7**2+RT8**2)*(RT7+RT8)
      TSUR=TSURF7-GDF1/2.0*ALOG((R(NOD5)+YCAL)/R(NOD5))/
1      (AKGAP(TSURF7+TSURF8)/2.0)+R(NOD5)*HR4
2      ALG((R(NOD5)+YCAL)/R(NOD5))
      ERROR=ABS(TSUR-TSURF8)/TSUR
      TSURF8=TSUR
      IF(ERROR.LT.0.00015)GO TO 28
1C CONTINUE
      WRITE(6,17)
17 FORMAT(1H1,'***WARNING--GAP--DETERMINATION OF SURFACE TEMPERATURE
      IDIO NOT CONVERGE.'//.T20.'JOB TERMINATED.')
      STOP
1E TSURF8=TSURF7
28 TNS=TSURF8-GDF1/(2.0/(ALOG(RBAR(NS)/R(NOD5) )/AKSS(TSURF8)))
      DO 30 I=1,20
      TC =TSURF8-GDF1/(2.0/(ALOG(RBAR(NS)/R(NOD5) )/AKSS(TNS)))
      ERROR=ABS(TC-TNS)/TC
      TNS=TC
      IF(ERROR.LT.0.00015)GO TO 38
30 CONTINUE
      WRITE(6,37)
37 FORMAT(1H1,'***WARNING--GAP--DETERMINATION OF NS TEMPERATURE IDIO
1 NOT CONVERGE.'//.T20.'JOB TERMINATED.')
      STOP
3E GAP=TNS-T
      RETURN
      END

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OR111344
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OR111400

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      SUBROUTINE GAPTNS
C      OAK RIDGE INVERSE CODE      VERSION 1.0      4-1-77
C
      COMMON /NODES/AMGO,AMT,NCU,NBN,NSS1,NSS2,MOD2,MOD3,MOD4,NOD5,NOD6,
1      NM,NC,NS,NS,NIN,NOUT,R(40),RBAR(40),RHEAT(7),
2      DLAMGO,DLAMTR,DLRCJ,DLRBN,DLRSS1,DLRSS2
      COMMON /SAVE/
1      ABN,ASS1,ASS2,RES(3T(4),TSURF(9),T1,QTOT,Q(40),ZZ
2      ,B(40),DELGAP(4),PFA,PFR(2),TCS,TB
      COMMON /GAPCAL/GFB,GP1(3),TNSB,TNDSB,TNS,GDF1,GPCAL,FEED,
1      TRAX,ICDE
C
      F1(X,Y)=X-Y
      F2(X,Y)=X+X-Y+Y
      F3(X,Y)=X+33-Y+33
C
      IF(GPB.LE.0.00015)GO TC 77
      IF(IODE.EQ.3)GO TO 78
      R05=RBAR(NOD5)*1.7E+07

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OR111402
OR111403
OR111404
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OR111418
OR111419
OR111420

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      RS=RBAR(NS)*1.0E+07
      GP=GPB/1.2E-03
C-----OLTER S.S. SHEATH
      IF(T(NS)-TMAX)18,18,28
18  FOX=(GP1(1)*F1(T(NS),TNSB)+GP1(2)*F2(T(NS),TNSB)+
1   GP1(3)*F3(T(NS),TNSB))*1.0E-07
      FSO=EXP(FOX)
      GO TO 38
28  FOX=(GP1(1)*F1(TMAX,TNSB)+GP1(2)*F2(TMAX,TNSB)+
1   GP1(3)*F3(TMAX,TNSB))*1.0E-07
      DFOX=(GP1(1)+2.0*GP1(2)*TMAX+3.0*GP1(3)*TMAX*TMAX)*EXP(FOX)
1   *1.0E-07
      FSC=EXP(FOX)+DFOX*(T(NS)-TMAX)
38  CONTINUE
C-----INNER S.S. SHEATH
      IF(T(NDS5)-TMAX)48,48,58
48  FI=(GP1(1)*F1(T(NDS5),TND5B)+GP1(2)*F2(T(NDS5),TND5B)+
1   GP1(3)*F3(T(NDS5),TND5B))*1.0E-07
      FSI=EXP(FI)
      GO TO 68
58  FCX=(GP1(1)*F1(TMAX,TND5B)+GP1(2)*F2(TMAX,TND5B)+
1   GP1(3)*F3(TMAX,TND5B))*1.0E-07
      DFCX=(GP1(1)+2.0*GP1(2)*TMAX+3.0*GP1(3)*TMAX*TMAX)*EXP(FCX)
1   *1.0E-07
      FSI=EXP(FCX)+DFCX*(T(NDS5)-TMAX)
68  CONTINUE
C-----NEB GAP BETWEEN SHEATHS
      YCAL=GP+RS*(FSC-1.0)-GDS*(FSI-1.0)
      IF(YCAL.LE.0.0)YCAL=0.0
      YCAL=YCAL*1.0E-07
      GO TO 88
77  GPB=0.0
78  YCAL=GPB/1.2E-03*1.0E-07
88  DELGAP(4)=YCAL
      RETURN
      END

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ORI11421
 ORI11422
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      SUBROUTINE MNFLXG
C OAK RIDGE INVERSE CODE          VERSION 1.0          4-1-77
      LOGICAL SLAB
      COMMON /CCDAS/ITCS(348),ICHTCS(348),ISUBCH(348),ITCM(106),
1   ICHTCM(106),ICHEIE(49),ICHEEE(49),ICHBW1,ICHBW2,
2   IRVOL(15,3),NTRY1(348),NTRY2(106),NTRY3(49),
3   NTRY4(49),NBW1,NBW2,IC(1000),
4   NTC(348),NCHTCS(348),NK,IRSLR(15,3),NSLAB
      COMMON /OUT/
1   TC(40,12),TIME(12),MO(12),QO(12),TBO(12),SFLUX(12),
2   TSURO(12),DELH,SJMCP,SUMO,EQWRT,ERROR1,ERROR2,
3   FSO(12),TSATO(12),HSATO(12),AMPO(12),QUALO(12),
4   RHBO(12),RSFXO(12),RTSURO(12),MODEQ(12),NO,JO
      COMMON /INPLT/ITCMN,KICK,MED(17),IS(6),TCSS(601),TCMN(601),
1   QAVGG(601),TIMEE(601),TIMR(601),TBR(601),TSATR(601),
2   PRESUR(601),QUALR(601),AMPR(601),HBR(601),
3   SFLXR(601),TSURR(601),MODER(601),TRPEND,JRP
4   IKF,ICS7
      COMMON /FLSH/ SLAB(50),PFAA(15)
      DIMENSION FLXMN(50,601),TCMNN(50,601),TSFMM(50,601),NSUM(50)
C*****ZERO NSUM AND FLXMN ARRAYS
      DO 10 I=1,50
        NSUM(I)=0
      DO 10 J=1,601
        TCMNN(I,J)=0.0
        TSFMM(I,J)=0.0
        FLXMN(I,J)=0.0
10  CONTINUE
      RETURN
C*****SLABMATION CALL
      ENTRY MNFLX1(KC,LO)
      GO TO (18,28),KC
18  NSUM(NSLAB)=NSUM(NSLAB)+1
28  FLXMN(NSLAB,LC)=FLXMN(NSLAB,LO)+SFLUX(JO)
      TCMNN(NSLAB,LC)=TCMNN(NSLAB,LO)+TO(1,JO)
      TSFMM(NSLAB,LC)=TSFMM(NSLAB,LO)+TSURO(JO)
      RETURN
C

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ORI11460
 ORI11461
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```

C*****COMPLTATION OF MEANS
ENTRY MFLX2
DO 40 I=1,50
  IF(NSLM(I)).EQ.0.OR.(.ACT.SLAB(I)) GO TO 40
  ASUM= FLOAT(ASLM(I))
  DO 30 J=1,601
    TCMN(I,J)= TCMN(I,J)/ASUM
    TSFNN(I,J)= TSFNN(I,J)/ASUM
  30 FLXNN(I,J)= FLXNN(I,J)/ASUM
40 CONTINUE
C-----CHECK FOR SLABS WHICH HAVE NSUM(NSLAB)=0, AND LOAD
C CENTRAL SUBCHANNEL SLAB MEAN FLUX(NSLAB,-) VALUES
C IN THE ZEROED MEAN FLUX ARRAY:
DO 120 I=1,50
  IF(NSUM(I).NE.0) GO TO 120
  IF(.NOT.SLAB(I)) GO TO 120
C SEARCH IRSLB ARRAY FOR LEVEL
DO 60 J=1,15
  JBAR= J
  DO 60 K=1,3
    KBAR= K
    IF(I.EQ.IRSLB(J,K)) GO TO 50
  60 CONTINUE
  STOP 1111
C CHECK CENTRAL SUBCHANNEL SLAB
  22 CONTINUE
  KI= 1
  IF(NSUM(IRSLE(JBAR,1)).EQ.0) GO TO 60
  65 DO 80 K=1,601
    TCMN(I,K)= TCMN(IRSLE(JBAR,KI),K)
    TSFNN(I,K)= TSFNN(IRSLE(JBAR,KI),K)
  60 FLXNN(I,K)= FLXNN(IRSLE(JBAR,KI),K)
  60 TO 120
  22 KI=2
  IF(NSUM(IRSLE(JBAR,2)).NE.0) GO TO 59
  KI=3
  IF(NSUM(IRSLE(JBAR,3)).NE.0) GO TO 59
  IF(JBAR-7) 78,78,98
  72 JJ= JBAR
  80 JJ= JJ+1
  IF(NSUM(IRSLE(JJ,1)).EQ.0) GO TO 80
  DO 90 K=1,601
  90 FLXNN(I,K)= FLXNN(IRSLE(JJ,1),K) + PFAA(JBAR)/PFAA(JJ)
  GO TO 120
  52 JJ= JBAR
  100 JJ= JJ+1
  IF(NSUM(IRSLE(JJ,1)).EQ.0) GO TO 100
  DO 110 K=1,601
  110 FLXNN(I,K)= FLXNN(IRSLE(JJ,1),K) + PFAA(JBAR)/PFAA(JJ)
  120 CONTINUE
  WRITE(6,127) (IRSLE(I,1),I=1,3)
  127 FORMAT(1H1,T7,'***OUTPUT OF MEAN FLUX ROUTINE***',
    1 //,T34,'(CENTRAL)',T69,'(NALL)',T99,'(CORNER)',/,
    2 T7,'RELAP SLAB NO.',T37,I3,T69,I3,T101,I3,/,
    3 T13,'TIME',T27,'FLUX',T43,'TSURF',T59,'FLUX',T75,'TSURF',
    4 T91,'FLUX',T107,'TSURF',/)
  KRP=JRP
  IF(KRP.GE.1RP) KRP=IRF
  DO 130 I=1,KRP
  130 WRITE(6,137) TIMEE(I),FLXNN(IRSLE(I,1),I),TSFNN(IRSLE(I,1),I),
    1 FLXNN(IRSLE(I,2),I),TSFNN(IRSLE(I,2),I),
    2 FLXNN(IRSLE(I,3),I),TSFNN(IRSLE(I,3),I)
  130 CONTINUE
  137 FORMAT(1H1,F6.2,GX,E13.6,5X,F7.1,7X,E13.6,5X,F7.1,7X,E13.6,5X,
    1 F7.1)
  DO 150 J=2,14
  IF(IRSLE(J,1).EQ.IRSLE(J-1,1)) GO TO 150
  WRITE(6,127) (IRSLE(J,I),I=1,3)
  DO 140 I=1,KRP
  140 WRITE(6,137) TIMEE(I),(FLXNN(IRSLE(J,K),I),
    1 TSFNN(IRSLE(J,K),I),K=1,3)
  140 CONTINUE
  150 CONTINUE
C GET THE NUMBER OF SLABS IN THE RELAP MODEL
C THEN WRITE 51 RECORDS TO UNIT 13 THAT HAS THE FLUXES SAVED FOR LATER
C CALL TO RPRNIN
  CALL INPSLB(1SLAB)
  WRITE (13) 1SLAB,TIMEE
  DO 200 I=1,50
  200 WRITE(13) (FLXNN(I,J),TCMNN(I,J),TSFNN(I,J),J=1,601)
  200 CONTINUE
  RETURN
END

```

```

ORI115CC
ORI11501
ORI115C2
ORI115C3
ORI11504
ORI11508
ORI115C6
ORI115C7
ORI115C8
ORI115C5
ORI1151C
ORI11511
ORI11512
ORI11513
ORI11514
ORI11518
ORI1151C
ORI11517
ORI1151E
ORI11515
ORI1152C
ORI11521
ORI11522
ORI11523
ORI11524
ORI11528
ORI1152C
ORI11527
ORI1152E
ORI11525
ORI11530
ORI11531
ORI11532
ORI11533
ORI11534
ORI1153E
ORI1153C
ORI11537
ORI1153E
ORI11536
ORI11540
ORI11541
ORI11542
ORI11543
ORI11544
ORI11545
ORI1154C
ORI11547
ORI1154E
ORI11546
ORI11550
ORI11551
ORI11552
ORI11553
ORI11554
ORI1155E
ORI1155C
ORI11557
ORI1155E
ORI11556
ORI11560
ORI11561
ORI11562
ORI11563
ORI11564
ORI11565
ORI1156C
ORI11567
ORI11568
ORI1156C
ORI1157C
ORI11571
ORI11572
ORI11573
ORI11574
ORI11576
ORI1157E
ORI11577
ORI11578
ORI11575
ORI1158C
ORI11581
ORI11582

```

```

      SUBROUTINE SOLVE(A,NA,NA,N,B,X,SING)
C   OAK RIDGE INVERSE CODE      VERSION 1.0      4-1-77
      LOGICAL SING
      DIMENSION A(NA,NA),B(N),X(N)
      CALL INVERT(A,NA,NA,SING)
      IF(SING)RETURN
      DO 10 I=1,N
        X(I)=0.0
      DO 10 J=1,N
1C  X(I)=X(I)+A(I,J)*B(J)
      RETURN
      END

```

ORI11587
 ORI11588
 ORI11589
 ORI11590
 ORI11591
 ORI11592
 ORI11593
 ORI11594

```

      SUBROUTINE INVERT(A,ORDER,DIM A,SING)
C   OAK RIDGE INVERSE CODE      VERSION 1.0      4-1-77
C   INVERT INVERTS A MATRIX IN ITS OWN SPACE USING THE GAUSS-JORDAN
C   METHOD AS ARRANGED BY H. RUTISHAUSER WITH FULL PIVOTING.
C   ARGUMENTS
C   A      IS THE MATRIX TO BE INVERTED. A IS SINGLE PRECISION.
C           THE INVERSE OF A IS RETURNED IN A.
C   ORDER  IS AN INTEGER VARIABLE. THE ORDER OF THE MATRIX TO BE
C           INVERTED.
C   DIM A  IS AN INTEGER VARIABLE CONTAINING THE FIRST DIMENSION
C           OF THE VARIABLE A IN THE CALLING PROGRAM. DIM A MAY BE
C           GREATER THAN ORDER.
C   SING   IS A LOGICAL VARIABLE. WHEN THE ROUTINE RETURNS
C           SING IS .FALSE. IF THE MATRIX WAS NON-SINGULAR AND
C           .TRUE. IF THE MATRIX WAS SINGULAR. IF SING IS .TRUE.
C           THE MATRIX A CONTAINS GARBAGE.
C
      INTEGER ORDER,DIM A
      REAL A(DIM A,1),B(100),C(100)
      N=ORDER
      LOGICAL SING
      INTEGER IP(100),IQ(100)
      DO 1 K=1,N
C   DETERMINATION OF PIVOT ELEMENT
        PIVOT=0.
        DO 100 I=K,N
          DO 100 J=K,N
1C1  IF(ABS(A(I,J))-ABS(PIVOT))100,100,101
          PIVOT=A(I,J)
          IP(K)=I
          IQ(K)=J
1C  CONTINUE
        IF(PIVOT)102,900,102
102  IPK=IP(K)
        IQK=IQ(K)
C   EXCHANGE OF THE PIVOTAL ROW WITH THE KTH ROW
        IF(IPK-K)200,299,200
20C  DO 201 J=1,N
          Z=A(IPK,J)
          A(IPK,J)=A(K,J)
201  A(K,J)=Z
299  CONTINUE
C   EXCHANGE OF THE PIVOTAL COLUMN WITH THE KTH COLUMN
        IF(IQK-K)300,399,300
30C  DO 301 I=1,N
          Z=A(I,IQK)
          A(I,IQK)=A(I,K)
301  A(I,K)=Z
399  CONTINUE
C   JORDAN ELIMINATION STEP
        DO 400 J=1,N
          IF(J-K)403,402,403
402  B(J)=1./PIVOT
          C(J)=1.
          GOTO 404
403  B(J)=A(K,J)/PIVOT
          C(J)=A(J,K)
404  A(K,J)=0.
4CC  A(J,K)=0.
        DO 405 I=1,N
          DO 405 J=1,N

```

ORI11595
 ORI11596
 ORI11597
 ORI11598
 ORI11599
 ORI11600
 ORI11601
 ORI11602
 ORI11603
 ORI11604
 ORI11605
 ORI11606
 ORI11607
 ORI11608
 ORI11609
 ORI11610
 ORI11611
 ORI11612
 ORI11613
 ORI11614
 ORI11615
 ORI11616
 ORI11617
 ORI11618
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 ORI11641
 ORI11642
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 ORI11650
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 ORI11654
 ORI11655
 ORI11656
 ORI11657
 ORI11658
 ORI11659
 ORI11660
 ORI11661

```

4CE A(I,J)=A(I,J)+C(I)*E(J)
1 CONTINUE
C REORDERING THE MATRIX
K=N
DC 500 KDU=1,N
IPK=IP(K)
IQK=IQ(K)
IF(IPK-K)501,502,501
501 DC 503 I=1,N
Z=A(I,IPK)
A(I,IPK)=A(I,K)
502 A(I,K)=Z
502 IF(IQK-K)504,500,504
504 DC 506 J=1,N
Z=A(IQK,J)
A(IQK,J)=A(K,J)
506 A(K,J)=Z
506 K=K-1
SING = .FALSE.
RETURN
500 SING = .TRUE.
RETURN
END

```

```

SUBROUTINE FALSE(XI,XINC,F,XZERO,NTRIES,[ERR,ESP,NOUT])
CAK RIDGE INVERSE CCDE          VERSION 1.0          4-1-77

      )INC=X INCREMENT(I.E., INTERVAL ON THE X-AXIS BY WHICH X IS INCREMENTED UNTIL A ROOT OF F(X) IS BRACKETED
      Y1=INITIAL VALUE OF X
      F=F(X)=FUNCTION SUBPROGRAM SUPPLIED BY USER (EXTERNAL-ED IN USER MAIN)
      XZERO=ROOT OF F(X), WHERE F(XZERO)=0.0
      NTRIES=NUMBER OF TIMES X IS INCREMENTED IN SEARCH FOR CROSSOVER POINT IN F(X)
      ESP=RELATIVE ERROR CRITERION
      IERR=INDEX FOR PRINT OUT OF ERROR MESSAGE
      NOUT=OUTPUT DEVICE NUMBER

      DELX = XINC
      Y1 = F(X1)
      )IM = X1
      YIM = Y1
      X2 = X1 + DELX
      Y2 = F(X2)
      )M = X1
      IF (Y1 .EQ. 0.0 .AND. Y2 .EQ. 0.0 ) GO TO 8
      IF ((Y1 .GT. 0.0 .AND. Y2 .LT. 0.0 ) .OR.
1      (Y1 .LT. 0.0 .AND. Y2 .GT. 0.0 )) GO TO 8
      IF (ABS(Y2) .LT. ABS(Y1)) GO TO 58
      DELX = - DELX
EE DC 10 I=1,NTRIES
      )M = X1
      X2 = X1 + DELX
      Y2 = F(X2)
      IF (Y2 .EQ. 0.0 ) GO TO 8
      IF ((Y1 .GT. 0.0 .AND. Y2 .LT. 0.0 ) .OR.
1      (Y1 .LT. 0.0 .AND. Y2 .GT. 0.0 )) GO TO 8
      )I = X2
      YI = Y2
1C CONTINUE
      WRITE (NOUT,7) NTRIES
7 FORMAT(1H1,'***WARNING--FALSE--UNABLE TO FIND CROSSOVER POINT IN',
110,' TRIES FOR')
      GO TO (208),IERR
E DC 20 J=1,25
      )A = (X1*Y2 - X2*Y1)/(Y2 - Y1)
      IF (ABS((XM - XA)/XA) .LT. ESP) GO TO 28
      )M = XA
      YM = F(XM)
      IF ((Y1 .GT. 0.0 .AND. YN .GT. 0.0 ) .OR.
1      (Y1 .LT. 0.0 .AND. YN .LT. 0.0 )) GO TO 38
      Y2 = YN
      X2 = XM
      YI = YI*.5
      GO TO 20

```

```

3E Y1 = YN
   Y1 = XN
   Y2 = Y2*0.5
2C CONTINUE
2E XZERO = XN
   RETURN
2CE WRITE (NOUT,27)
27 FORMAT(1H,'S. S. SHEATH GAP AND MOOS TEMPERATURE DETERMINATION.')
1CCE WRITE (NOUT,1007) X1H,Y1H,DELX,X1,Y1
1CCE FORMAT(1H,'30INITIAL INDEPENDENT VARIABLE =,E16.8,20X,
1 20INITIAL DEPENDENT VARIABLE =,E16.8/12H STEP SIZE =,E16.8/1H .
2 20FINAL INDEPENDENT VARIABLE =,E16.8,20X,
3 20FINAL DEPENDENT VARIABLE =,E16.8)
   STOP
   END

```

```

ORI11741
ORI11742
ORI11743
ORI11744
ORI11745
ORI11746
ORI11747
ORI11748
ORI11749
ORI11750
ORI11751
ORI11752
ORI11753
ORI11754
ORI11755

```

```

      SUBROUTINE MAXMIN(Y,YC,EY,SY,NOP)
C  CAR RIDGE INVERSE CCDE VERSION 1.0 4-1-77
      DIMENSION Y(NCF),YC(NCF)
      YMIN=1500.0
      YMAX=300.0
      DO 10 I=1,NOP
        IF(Y(I).GT.YMAX) YMAX=Y(I)
        IF(YC(I).GT.YMAX) YMAX=YC(I)
        IF(Y(I).LT.YMIN) YMIN=Y(I)
        IF(YC(I).LT.YMIN) YMIN=YC(I)
10 CONTINUE
      IYMAX=IFIX(YMAX/100.0)*100
      IYMIN=IFIX(YMIN/100.0)*100
1E IF(FLCAT(IYMAX+50).GT.YMAX) GO TO 2B
      IYMAX=IYMAX+50
      GO TO 1B
2E EY=FLCAT(IYMAX+50)
3E IF(FLCAT(IYMIN+50).GT.YMIN) GO TO 4B
      IYMIN=IYMIN+50
      GO TO 3B
4E EY=FLCAT(IYMIN)
      RETURN
      END

```

```

ORI11756
ORI11757
ORI11758
ORI11759
ORI11760
ORI11761
ORI11762
ORI11763
ORI11764
ORI11765
ORI11766
ORI11767
ORI11768
ORI11769
ORI11770
ORI11771
ORI11772
ORI11773
ORI11774
ORI11775
ORI11776
ORI11777
ORI11778

```

```

      SUBROUTINE FLCT(N,X,Y, SX,EX,INTELX,SY,EY,ITYPE,M,C,NUM,FX,FY,IORD)
C  CAR RIDGE INVERSE CCDE VERSION 1.0 4-1-77
C  N = # OF (X,Y) DATA POINTS (0.LT.N.LE.650)
C  X = ABSCISSA OF DATA POINT PAIRS
C  Y = ORDINATE OF DATA POINT PAIRS
C  SX = STARTING POINT FOR ABSCISSA AXIS
C  EX = END POINT FOR ABSCISSA AXIS
C  INTELX = INTERVAL ON THE ABSCISSA AXIS
C  SY = STARTING POINT FOR ORDINATE AXIS
C  EY = END POINT FOR ORDINATE AXIS
C  ITYPE = TYPE OF CALCULATION DESIRED FOR OVERLAY
C          OF (FX,FY) ON (X,Y)
C          = 1 CALCULATED VIA FITTED EQUATION
C          = 2 INTERPOLATED FROM (FX,FY) TABLE
C          = 3 NO OVERLAY DESIRED
C  M = # OF COEFFICIENTS (I.E. ORDER OF FIT) (0.LT.M.LE.20)
C  C = COEFFICIENTS OF FITTED EQUATION (.EQ.M+1)
C  NUM = NUMBER OF DATA POINTS IN (FX,FY) TABLE (NUM.LE.1250)
C  FX = IN TABLE OF X,Y PAIRS, THE 'X' CORRESPONDING TO
C       FY IN (FX,FY)-----TO BE USED FOR INTERPOLATION
C  FY = IN TABLE OF X,Y PAIRS, THE 'Y' CORRESPONDING TO
C       FX IN (FX,FY)-----TO BE USED FOR INTERPOLATION
C  IORD = ORDER OF INTERPOLATION
C  DIMENSION X(N),Y(N),C(21),LINE(129),STX(1250),STY(1250),FX(1250),
1  FY(1250)
      REAL INTX,INTY,INTVL,IMVLX,INTELX
      DATA IBLANK,ICCT,IPLUS,IAST,IX/1H,1H,,1H,,1H,,1H,/

```

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ORI11779
ORI11780
ORI11781
ORI11782
ORI11783
ORI11784
ORI11785
ORI11786
ORI11787
ORI11788
ORI11789
ORI11790
ORI11791
ORI11792
ORI11793
ORI11794
ORI11795
ORI11796
ORI11797
ORI11798
ORI11799
ORI11800
ORI11801
ORI11802
ORI11803
ORI11804
ORI11805

```

```

C CHECKING INPUT
ICHECK=0
IF(N.LE.0.OR.N.GT.650) ICHECK = 1
IF(ITYPE.EQ.1.AND.(N.LE.0.OR.N.GT.20)) ICHECK=4
IF(SX.GE.EX) ICHECK = 67
IF(INTELX.LE.0.0) GO TO 438
IF((EX-SX)/INTELX.GT.1250.0) ICHECK = 678
GO TO 448
438 IF((EX-SX).GT.(10.*(EY-SY))) ICHECK = 79
448 IF(SY.GE.EY) ICHECK = 910
IF(ICHECK.EQ.C) GO TO 178
PRINT 37, ICHECK
37 FORMAT (1H1,26HINPUT PROPER INPUT AT ARGUMENT,13)
RETURN
178 IACV = 1
C DETERMINING INTERVALS
INTVX = EX-SX
INTVY = EY-SY
INTVL = INTVY/125.0
INTVLX=INTELX
IF(INTVLX.LE.0.0) INTVLX=INTVL
C PRINTING HEADING
PRINT 47,SY,EY,SX,EX,INTVL,INTVLX
47 FORMAT (1H ,12X,6HY FROM,1PE15.8,3. TO,E15.8,24H AS A FUNCTION OF
1X FROM,1PE15.8,3H TC,E15.8/22X,21H WITH Y INTERVAL SIZE,E15.8,25H
2AND WITH X INTERVAL SIZE,E15.8//)
IF(SX.GT.0.0.OR.EX.LT.0.0) PRINT 465,SX
465 FORMAT(1H ,35X,43HTHE Y AXIS HAS BEEN SHIFTED FROM 0.0 TO X =,
11PE16.8//)
IF(SY.GT.0.0.OR.EY.LT.0.0) PRINT 456,SY
456 FORMAT(1H ,35X,43HTHE X AXIS HAS BEEN SHIFTED FROM 0.0 TO Y =,
11PE16.8//)
C DETERMINING AXIS POSITION
IXT = INTVX/INTVLX + 1.5
JX = ABS(SX)/INTVLX + 1.5
JY = ABS(SY)/INTVL + 4.5
IF(SY.GT.0.0.OR.EY.LT.0.0) JY=4
IF(SX.GT.0.0.OR.EX.LT.0.0) JX=1
C DETERMINING LINE DEFINITIONS
XL = SX
DC 100 I12=1,IXT
C BLANKING LINE AND SUPPRESSING SKIP OVER PAGE PERFORATION
DC 60 I=2,129
LINE(I) = IBLANK
CC CONTINUE
LINE(I) = IAST
C GENERATING Y VALUES AND STORING X AND Y VALUES
STX(I12) = XL
GO TO (68,71,72),ITYPE
CC PI = M+1
YL = 0.0
DO 70 I1=1,M1
IF(XL.EQ.0.0.AND.I1.EQ.1) YL = C(I1)
IF(XL.EQ.0.0) GO TO 70
YL = C(I1)*XL**((I1-1) + YL
70 CONTINUE
GO TO 78
71 CALL FINDS(XL,YL,FX,FY,NUM,IORD,1DT)
GO TO 78
72 YL = C.01*SY
78 CONTINUE
STY(I12) = YL
C PRECALCULATING SUBSCRIPT OF LINE
KKK = YL/INTVL + FLOAT(JY) + 0.5
IF(SY.GT.0.0.OR.EY.LT.0.0)KKK=(YL-SY)/INTVL +FLOAT(JY) + 0.5
C INPUTTING AXES
LINE(JY) = IOCT
IF(I12.NE.JX) GO TO 58
DC 80 JK=4,129
LINE(JK) = IOCT
CC CONTINUE
C ADDING PLSSES
DC 90 JK=JY,129.5
LINE(JK) = IPLUS
50 CONTINUE
IPLST = JY - 4
IF(IPLST.LT.5) GO TO 58
DO 110 JPK=5,IPLST.5
KPL = JY - JPK
LINE(KPL) = IPLUS
110 CONTINUE
CC IF(I12.NE.1) GO TO 320
DO 300 MOLL=1,IXT
IXIX = JX - 5*(1-MOLL)
IF(IXIX.LT.5) GO TO 320
300 CONTINUE
320 IF(((I12-IXIX)-((I12-IXIX)/5*5).EQ.0) LINE(JY) = IPLUS
C ADDING PLOTTED POINT
IF(KKK.LT.4) GO TO 140
IF(KKK.GT.129) GO TO 140
LINE(KKK) = IX
140 CONTINUE

```

OR1118C6
 OR1118C7
 OR1118C8
 OR1118C9
 OR111810
 OR111811
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 OR111897

```

C  ADGNG INPLT DATA
  IF(IMCV.GT.4) GC TO 220
15C IF(XL-X(IMCV))200,210,230
20C IF(XL-X(IMCV) + INTVLX/2.0)220,210,210
23C IF((XL-X(IMCV)).LT.INTVLX/2.0) GO TO 210
  IMOV = IMOV + 1
  IF(IMOV.GT.4) GC TO 220
  GC TO 190
21C KKKK = Y(IMCV)/INTVL + FLOAT(JY) + 0.5
  IF(SY.EY.0.0.CH.EY.LT.0.0)KKKK=(Y(IMOV)-SY)/INTVL+FLOAT(JY)+0.5
  IMOV = IMOV + 1
  IF(KKKK.LT.4) GC TO 220
  IF(KKKK.GT.129) GO TO 220
  LINE(KKKK) = IAST
22C PRINT 57, LINE
  IF FORMAT (129A1)
  XL = XL + INTVLX
10C CONTINUE
  RETURN
  END

```

OR111858
 OR111859
 OR11190C
 OR1119C1
 OR1119C2
 OR1119C3
 OR1119C4
 OR1119C5
 OR1119C6
 OR1119C7
 OR1119C8
 OR1119C9
 OR11191C
 OR111911
 OR111912
 OR111913
 OR111914
 OR111915
 OR111916
 OR111917

```

C  SUBROUTINE FINDS(X0,FX0,X,Y,SIZE,ORDER,TEST)
C  CAK RIDGE INVERSE CODE   VERSION 1.0   4-1-77
C
C  INTEGER*4 SIZE,ORDER,TEST
C  DIMENSION X(SIZE),Y(SIZE)
C
C  NTERMS=ORDER + 1
C  NTE=NTERMS/2
C  TEST=0
C  DO 10 I=1,SIZE
C  IF(X0.LE.X(I)) GC TO 8
10C CONTINUE
  TEST=1
  GC TO 58
  IF(X0.GE.X(I)) GC TO 18
  FX0 = Y(I)
  RETURN
18 IF(I.LE.NTE) TEST = -1
  IF(I.GT.SIZE-NTE) TEST = 1
  IF(TEST) 28,38,48
2E NSTART = 1
  NSTOP = NTERMS
  GC TO 68
4E IF(I.GT.SIZE-NTE+1) GC TO 58
  TEST = 0
5E NSTART = SIZE-ORDER
  NSTOP = SIZE
  GC TO 68
3E NSTART = I-NTE
  NSTOP = NSTART + ORDER
6E FXC = 0.0
  DO 20 J=NSTART,NSTOP
  PROD = 1.0
  DO 30 J=NSTART,NSTOP
  IF(I.EQ.J) GC TO 30
  PROD = PROD*(X0-X(J))/(X(I)-X(J))
30C CONTINUE
20 FXC = FX0 + FFCO*Y(I)
  RETURN
  END

```

OR111918
 OR111919
 OR11192C
 OR111921
 OR111922
 OR111923
 OR111924
 OR111925
 OR111926
 OR111927
 OR111928
 OR111929
 OR11193C
 OR111931
 OR111932
 OR111933
 OR111934
 OR111935
 OR111936
 OR111937
 OR111938
 OR111939
 OR11194C
 OR111941
 OR111942
 OR111943
 OR111944
 OR111945
 OR111946
 OR111947
 OR111948
 OR111949
 OR11195C
 OR111951
 OR111952
 OR111953
 OR111954
 OR111955
 OR111956
 OR111957
 OR111958
 OR111959
 OR11196C
 OR111961

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C *****OR112012
C *****OR112013
C *****OR112014
C *****OR112015
C *****OR112016
C *****OR112017
C *****OR112018
C *****OR112019
C *****OR112020
C *****OR112021
C *****OR112022
C *****OR112023
C *****OR112024
C *****OR112025
C *****OR112026
C *****OR112027
C *****OR112028
C *****OR112029
C *****OR112030
C *****OR112031
C *****OR112032
C *****OR112033
C *****OR112034
C *****OR112035
C *****OR112036
C *****OR112037
C *****OR112038
C *****OR112039
C *****OR112040

```

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COMMON /GAPCAL/GF3,GF1(3),TNSB,TND58,TND5,TNS,QDPI,GPCAL,FEED,      ORI1204C
1      TMAX,ICDE                                                       ORI12041
DIMENSION ZEN(3),TCL(15),SGV(7),ALPHA(2,5)                          ORI12042
DATA ALPHA/' F',' ' 'ORCE','JCLE','D CO','ATE','NVEC','BOIL'      ORI12043
1      'TICH','ING '/'                                                ORI12044
DATA ZERG/3*0.0/                                                       ORI12045
C      THERMOCOUPLE POWER LEVELS                                       ORI12046
DATA TCL /1HA,1HB,1HC,1HD,1HE,1HF,1HG,1HH,1HI,1HJ,1HK,1HL,1HM,    ORI12047
1      1HN,1HO/                                                        ORI12048
C                                                                           ORI12049
C      PIN SHEATH GROOVE NUMBERS:                                       ORI12050
DATA SGV /1HA,1HB,1HC,1HD,1HE,1HF,1HN/                               ORI12051
C                                                                           ORI12052
C      P10. AND CASE DESCRIPTION                                         ORI12053
IMOD=IFIX(FLCAT/ITCAUM-300000)/1000.0)                               ORI12054
ISGV=IFIX(FLCAT/ITCAUM-300000-1ROD*1000)/100.0)                     ORI12055
ITCL=ITCAUM-300000-1ROD*1000-ISGV*100                                ORI12056
NBROD=1ROD*300                                                         ORI12057
ISECS=IFIX(FLOAT(IS(4))/4.0)                                           ORI12058
WRITE(NOUT,7)ITCAUM,NBROD,SGV(ISGV),TCL(ITCL),IS(2),IS(3),ISECS    ORI12059
WRITE(1,7)ITCAUM,NBROD,SGV(ISGV),TCL(ITCL),IS(2),IS(3),ISECS      ORI12060
CALL DATE(IS,NCLT)                                                       ORI12061
WRITE(NOUT,8) (FED(I),I=1,17),NOD6,NMGD,NM,NOD2                     ORI12062
WRITE(1,8) (MED(I),I=1,17),NOD6,NMGD,NM,NOD2                         ORI12063
7 FORMAT(1H1,I6,22(1H*),20H CASE INFORMATION ,20(1H*),//          ORI12064
1      T2,6(1H*),* THERMOCOUPLE NUMBER: TE-,13,2A1,T45,*TIME:,    ORI12065
2      13,*,*,12,*,*,12,6X,*DATE: *)                                OF12066
8 FORMAT(T2,6(1H*),17A,.,                                              ORI12067
1      //,T2,30HTCTAL NUMBER OF RADIAL NODES =,13,/,              OF 12068
2      T7,38HMAGNESIUM CKIOE CORE NODES 1 THROUGH,14,/,          ORI12069
3      T7,27HINCCNEL-600 HEATER NODES .13,8H THROUGH,14)          ORI12070
IF(NCL.GT.0)WRITE(NOUT,17)NM,NOD3                                     ORI12071
IF(NCL.GT.0)WRITE(1,17)NM,NOD3                                         ORI12072
17 FORMAT(T7,27HCLPRO-NICKEL HEATER NODES .13,8H THROUGH,14)      ORI12073
WRITE(NOUT,27)NC,NCD4,NB,NOD5,N3,NOD6,RHEAT(2),RHEAT(3)            ORI12074
WRITE(1,27)NC,NCD4,NB,NOD5,N3,NOD6,RHEAT(2),RHEAT(3)               ORI12075
27 FORMAT(T7,27HECRN NITRIDE NODES .13,8H THROUGH,14,/,          ORI12076
1      T7,27HINNER S.S.SHEATH NODES .13,8H THROUGH,14,/,        ORI12077
2      T7,27HCLTER S.S.SHEATH NODES .13,8H THROUGH,14,/,        ORI12078
3      T2,28HCLTSIDE RADIUS OF MGO CORE =,E13.6,4H FT.,/,        ORI12079
4      T2,33HCLTSIDE RADIUS OF INCONEL LAYER =,E13.6,4H FT.)      ORI12080
IF(NCL.GT.0)WRITE(NOUT,37)RHEAT(4)                                    ORI12081
IF(NCL.GT.0)WRITE(1,37)RHEAT(4)                                       ORI12082
37 FORMAT(T2,38HCLTSIDE RADIUS OF CUPRO-NICKEL LAYER =,E13.6,4H FT,.) ORI12083
WRITE(NOUT,47)RHEAT(1),I=5,7),GP8,PFA,PFR(1),PFR(2)               ORI12084
WRITE(1,47)RHEAT(1),I=5,7),GP8,PFA,PFR(1),PFR(2)                  ORI12085
47 FORMAT(T2,33HCLTSIDE RADIUS OF BORON NITRIDE =,E13.6,4H FT.,/,  ORI12086
1      T2,36HCLTSIDE RADIUS OF INNER S.S.SHEATH =,E13.6,4H FT.,/, ORI12087
2      T2,36HCLTSIDE RADIUS OF OUTER S.S.SHEATH =,E13.6,4H FT.,/, ORI12088
3      T2,41MRADIAL GAP INFORMATION: (I.E. BIAS POINT),/,         ORI12089
4      T7,41MGAP BETWEEN INNER AND OUTER S.S.SHEATHS =,F8.4,* MILORI12090
55,.,//,T2,22HPOWER PEAKING FACTORS:./,T7,7HAXIAL =,F9.6,/,      ORI12091
6      T7,18HRADIAL (INCONEL) =,F9.6,/,T7,15HRADIAL (CU-NI)=,F9.6)ORI12092
RETURN                                                                    ORI12093
C      STEADY STATE LOCAL OPERATING CONDITIONS AND PIN TEMPERATURE PROFILE ORI12094
C*****                                                                    ORI12095
E-TRY CLTES(PC,QAVG)                                                    ORI12096
C*****                                                                    ORI12097
HFR=HF*3600.0                                                           ORI12098
WRITE(NOUT,57)ITCAUM,NBROD,SGV(ISGV),TCL(ITCL),IS(2),IS(3),ISECS ORI12099
WRITE(1,57)ITCAUM,NBROD,SGV(ISGV),TCL(ITCL),IS(2),IS(3),ISECS    ORI12100
CALL DATE(IS,NOUT)                                                       ORI12101
WRITE(NOUT,58) (MED(I),I=1,17),QAVG,QTOT,HFR,TB                     ORI12102
WRITE(1,58) (MED(I),I=1,17),QAVG,QTOT,HFR,TB                         ORI12103
57 FORMAT(1H1,I6,14(1H*),36H STEADY STATE TEMPERATURE PROFILE ,20(1H*)ORI12104
1H*),//,T2,6(1H*),* THERMOCOUPLE NUMBER: TE-,13,2A1,T45,*TIME:,    ORI12105
2      13,*,*,12,*,*,12,6X,*DATE: *)                                ORI12106
58 FORMAT(T2,6(1H*),17A,.,                                              ORI12107
1      //,T2,36HQ = AVERAGE HEAT GENERATION PER FT =,          ORI12108
2      F10.6,11H BTU/SEC/FT.,/T2,24HMAXIAL PEAKING FACTOR =,F10.6,ORI12109
3      11H BTL/SEC/FT.,/T2,31HMF = OUTSIDE FILM COEFFICIENT =,E15.0,ORI12110
4      ,22H BTL/MHRT*2*DEG F),/,                                       ORI12111
5      T2,31HTB = BULK COOLANT TEMPERATURE =,F8.2,6H DEG F.,//.    ORI12112
6      T2,24HPIA TEMPERATURE PROFILE:./,                               ORI12113
7      T24,27HMCDE TEMPERATURE (DEG F))                               ORI12114
WRITE(NOUT,67)(I,T(I),I=1,NOD6)                                         ORI12115
WRITE(1,67)(I,T(I),I=1,NOD6)                                           ORI12116
67 FORMAT(24X,13,9X,F8.2)                                                ORI12117
WRITE(NOUT,69)SFLUX(1),TSURO(1),PSO(1),TSATO(1),(ALPHA(KD,I),I=1,5)ORI12118
1)                                                                    ORI12119
WRITE(1,69)SFLUX(1),TSURO(1),PSO(1),TSATO(1),(ALPHA(KD,I),I=1,5)ORI12120
1,5)                                                                    ORI12121
69 FORMAT(//,T2,18HSURFACE HEAT FLUX=,E15.8,14H BTU/MR/FT**2,/,    ORI12122
1      T2,20HSLRFACE TEMPERATURE=,F8.2,6H DEG F.,//,              ORI12123
2      T2,9HPPRESSURE=,F8.1,5H PSIA,/,                               ORI12124
3      T2,47HSATURATION TEMPERATURE (AT THE ABOVE PRESSURE)=,F8.2,ORI12125
4      6H DEG F.,//,T2,HEAT TRANSFER MODE AT THE SURFACE OF THE PORT12126
5IA:.,5A4)                                                              ORI12127
WRITE(NOUT,77)ITCAUM,NBROD,SGV(ISGV),TCL(ITCL),IS(2),IS(3),ISECS, ORI12128
1      (MED(I),I=1,17)                                                ORI12129
77 FORMAT(1H1,I6,20(1H*),21H TRANSIENT RESULTS ,29(1H*),//,        ORI12130
1      T2,6(1H*),* THERMOCOUPLE NUMBER: TE-,13,2A1,T45,*TIME:,    ORI12131

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2      13.000,12.000,12.000,T2-6(1H*),17A4, OR112132
3      //T2,20H TIME-TEMPERATURE-JOE TABLE://, OR112133
4      T7,21H TIME HAS UNITS OF SEC.//, OR112134
5      T7,30H TEMPERATURE HAS UNITS OF DEG F.//, OR112135
6      T7,25H C HAS UNITS OF BTU/SEC/FT.//, OR112136
7      T7,50H MB (BASED ON TBI) HAS UNITS OF BTU/(HR*FT**2*DEG F)://, OR112137
8      T7,35H BULK TEMPERATURE HAS UNITS OF DEG F.//, OR112138
9      T7,54H MSAT (BASED ON TSAT) HAS UNITS OF BTU/(HR*FT**2*DEG F)://, OR112139
1     T7,26H PRESSURE HAS UNITS OF PSIA.//, OR112140
11     T7,41H SATURATION TEMPERATURE HAS UNITS OF DEG F.//, OR112141
12     T7,46H SURFACE FLUX (S.F.) HAS UNITS OF BTU/HR/FT**2.//, OR112142
13     T7,38H SURFACE TEMPERATURE HAS UNITS OF DEG F.//, OR112143
14     T7,44H AVERAGE PASS FLUX HAS UNITS OF LBM/SEC/FT**2.//, OR112144
15     T7,21H GAP HAS UNITS OF MILS.//, OR112145
16     RETURN OR112146
C TRANSIENT RESPONSE OR112147
C ***** OR112148
C ENTRY OUTINS OR112149
C ***** OR112150
GO TO (78,128),NC OR112151
78 WRITE(NOUT,87)(TIME(I),I=1,JO) OR112152
87 FORMAT(//,T4,6H TIME--.12F10.4//,T2,4H NODE) OR112153
88 DO 90 I=1,NC06 OR112154
WRITE(NOUT,97)I,(TO(I,J),J=1,JO) OR112155
90 CONTINUE OR112156
97 FORMAT(1X,I3,5X,12F10.4) OR112157
WRITE(NOUT,107)(GO(I),I=1,JO) OR112158
107 FORMAT(1H0,3H0,5X,12F10.5) OR112159
117 WRITE(NOUT,117)(TBC(I),I=1,JO) OR112160
117 FORMAT(1X,3HTB,5X,12F10.4) OR112161
WRITE(NOUT,127)(HC(I),I=1,JO) OR112162
127 FORMAT(1X,3HMB,5X,12F10.1) OR112163
WRITE(NOUT,131)(TSAT(I),I=1,JO) OR112164
131 FORMAT(1X,4HMSAT,4X,12F10.1) OR112165
WRITE(NOUT,129)(HSATC(I),I=1,JO) OR112166
129 FORMAT(1X,4HMSAT,4X,12F10.1) OR112167
WRITE(NOUT,133)(FSC(I),I=1,JO) OR112168
133 FORMAT(1X,3HP,5X,12F10.1) OR112169
WRITE(NOUT,147)(SFLUX(I),I=1,JO) OR112170
147 FORMAT(1X,4HS.F,4X,12F10.1) OR112171
WRITE(NOUT,157)(TSURF(I),I=1,JO) OR112172
157 FORMAT(1X,6HS.TEMP,2X,12F10.2) OR112173
WRITE(NOUT,158)(AMFC(I),I=1,JO) OR112174
158 FORMAT(1X,8HPASS-FLX,12F10.4) OR112175
WRITE(NOUT,159)(QUALC(I),I=1,JO) OR112176
159 FORMAT(1X,8HQUALITY,12F10.5) OR112177
WRITE(NOUT,161)(DELRO(I),I=1,JO) OR112178
161 FORMAT(1X,3H GAP,5X,12F10.5) OR112179
WRITE(NOUT,171) OR112180
171 FORMAT(1X,11H RELAP PREDICTIONS (STARRED)****) OR112181
WRITE(NOUT,172)(RHBC(I),I=1,JO) OR112182
172 FORMAT(1X,3HMB,5X,12F10.1) OR112183
WRITE(NOUT,173)(RSF(I),I=1,JO) OR112184
173 FORMAT(1X,5H S.F.,3X,12F10.1) OR112185
WRITE(NOUT,174)(R'SURF(I),I=1,JO) OR112186
174 FORMAT(1X,7H S.TEMP,1X,12F10.2) OR112187
WRITE(NOUT,175)(MODEO(I),I=1,JO) OR112188
175 FORMAT(1X,9H M...MODE,19,11110) OR112189
RETURN OR112190
128 WRITE(NOUT,137)(TIME(I),I=1,JO) OR112191
137 FORMAT(1H1,T4,6H TIME--.12F10.4//,T2,4H NODE) OR112192
GO TO 88 OR112193
C FINAL ENERGY BALANCE, OUTPUT OR112194
C ***** OR112195
C ENTRY OUTFNL OR112196
C ***** OR112197
WRITE(NOUT,167)ITCMN,NBROD,SGV(1SGV),TCL(ITCL),IS(2),IS(3),ISECS OR112200
WRITE(I,167)ITCMN,NBROD,SGV(1SGV),TCL(ITCL),IS(2),IS(3), OR112201
ISECS OR112202
CALL DATE(15,NOUT) (MED(I),I=1,17),SUMCP,DELM,SUMQ,EONRT, OR112203
WRITE(NOUT,168) OR112204
168 ERRGR1,ERRGR2 (MED(I),I=1,17),SUMCP,DELM,SUMQ,EONRT, OR112205
WRITE(I,168) OR112206
168 ERRGR1,ERRGR2 OR112207
167 FORMAT(1H1,16,21(1H*),18H ENERGY BALANCE,31(1H*),//, OR112208
1 T2,6(1H*),* THERMOCOUPLE NUMBER: TE=,13,2A1,T4S,* TIME:, OR112209
2 13.000,12.000,12.000,DATE: * OR112210
168 FORMAT(1H1,17A4,//, OR112211
1 T2,39H CHANGE IN PIN INTERNAL ENERGY CONTENT =,F13.6,7H BTU/FT.//, OR112212
2 T8,72H DETERMINED BY SUMMATION OF DELTA U'S OVER THE INTERVAL FROM OR112213
3 T0 TO TEND.//T2,39H CHANGE IN PIN INTERNAL ENERGY CONTENT =, OR112214
4 F13.6,7H BTU/FT.//T8,53H DETERMINED BY DIFFERENCE IN PIN END POINT OR112215
5 ENTHALPIES.//T2,40H TCTAL HEAT INPJT = INTEGRAL OF DTOT*DT =,F13.6, OR112216
6 7H BTU/FT.//T2,54H INTEGRAL OF SURFACE FLUX VERSUS TIME CURVE #2, OR112217
7 CAPI*RO=F13.6,7H BTU/FT.//T2,42H PERCENTAGE ERROR IN OVERALL HEAT OR112218
8 BALANCE =,F11.4,8H PERCENT.//T2,45H ERROR IN OVERALL HEAT BALANCE OR112219
9 (VIA METHOD 2)=,F11.4,8H PERCENT) OR112220
RETURN OR112221
C TAPE OUTPUT-FILE NUMBER 1 OR112222
OR112223

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C***** ENTRY QLTAP(KC)
C***** GO TO(208,212),KC
202 WRITE(9)ITCAUN,NCD6,(FEAR(I),I=1,NOD6),R(NOD6)
212 WRITE(9)TIME(JC),(TO(I,J0),I=1,NOD6),OO(J0),TBO(J0),MO(J0),
1 TSATC(J0),MSATC(J0),PSQ(J0),SFLUX(J0),TSURC(J0),
2 AMFC(JC),QUALC(JC),RMB0(J0),RSFXC(J0),RTSWRC(J0),
3 MODEC(J0),(ZFC(I),I=1,3)
RETURN
END

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ORI12224
ORI12225
ORI12226
ORI12227
ORI12228
ORI12229
ORI12230
ORI12231
ORI12232
ORI12233
ORI12234

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```

C SUBROUTINE DATE(JT,NCUT)
C CAR RIDGE INVERSE CODE VERSION 1.0 4-1-77
DIMENSION JT(6),AMCATH(12),MONTH(12)
DATA AMONTH/'JAN','FEB','MAR','APR','MAY','JUNE','JULY','AUG',
1,'SEP','OCT','NOV','DEC'/'
DATA MONTH/31,29,31,30,31,30,31,31,30,31,30,31/
L=JT(1)
I=0
10 I=I+1
L=L-MONTH(I)
IF(L)20,15,10
15 AM=AMCATH(I)
IDAY=MONTH(I)
WRITE(NOUT,16) AM,IDAY
WRITE(1,16) AM,ICAY
16 FORMAT(1H+,T72,A4,I3,/)
RETURN
20 AM=AMCATH(I)
IDAY=L+ MONTH(I)
WRITE(NOUT,16) AM,ICAY
WRITE(1,16) AM,ICAY
RETURN
END

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```

ORI12235
ORI12236
ORI12237
ORI12238
ORI12239
ORI12240
ORI12241
ORI12242
ORI12243
ORI12244
ORI12245
ORI12246
ORI12247
ORI12248
ORI12249
ORI12250
ORI12251
ORI12252
ORI12253
ORI12254
ORI12255
ORI12256
ORI12257

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C*****
C*****
C*****
C***** CARD *****
C***** INPUT *****
C*****
C*****
C*****
C CARD INPUT ROUTINE
C
C
C SUBROUTINE INFUTC
C CAR RIDGE INVERSE CODE VERSION 1.0 4-1-77
COMMON /CCDAS/ITCS(348),ICHTCS(348),IS,ICH(348),ITCM(106),
1 ICHTCM(106),ICHEIE(49),ICHEEE(49),ICBW1,ICBW2,
2 IRVOL(15,3),NTRY1(348),NTRY2(106),NTRY3(49),
3 NTRY4(49),NBW1,NBW2,IC(1000),
4 NTC(348),NCHTCS(343),NK,IRSLB(15,3),NSLAB
COMMON /INPLT/ITCAUN,KICK,HED(17),IS(6),TCSS(601),TCNM(601),
1 GAVGG(601),TIMEE(601),TIMR(601),TBR(601),TSATR(601),
2 PRESUR(601),QUALR(601),AMFR(601),MBR(601),
3 SFLUXR(601),TSURR(601),MODER(601),TRPEND,JRP
4, IFF,ICS7
DIMENSION IBTCS(35),IGTCS(35),IGCH(35),IBTCM(35),IGTCM(35),
1 IBIE(49),ICS(6)
C
C NIN=5
C
C READ HEADING FOR THIS RUN
READ(NIN,3)HED
3 FORMAT(10X,17A4)

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ORI12258
ORI12259
ORI12260
ORI12261
ORI12262
ORI12263
ORI12264
ORI12265
ORI12266
ORI12267
ORI12268
ORI12269
ORI12270
ORI12271
ORI12272
ORI12273
ORI12274
ORI12275
ORI12276
ORI12277
ORI12278
ORI12279
ORI12280
ORI12281
ORI12282
ORI12283
ORI12284
ORI12285
ORI12286
ORI12287
ORI12288

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C      READ(NIN,7) ICS,ICS7,ICP
C      7 FORMAT(10X,8I5)
C      READ BAD SHEATH TC NUMBERS AND ADJUST ICHTCS
C      IF(ICS(1).EQ.0)GO TC 28
C      READ(NIN,17)NBTCS,(IBTCS(I),I=1,NBTCS)
17  FORMAT(10X,7I10)
C      DO 20 J=1,NBTCS
C      DO 20 I=1,348
C      IF(ITCS(I).EQ.IBTCS(J)) ICHTCS(I)=-999
20  CONTINUE
C      READ NEW 'GOOD' SHEATH TC NUMBERS AND THEIR CORRESPONDING SCAN CHANNELS
C      2E IF(ICS(2).EQ.0)GC TC 48
C      READ(NIN,37)NGTCS,(IGTCS(I),IGCH(I),I=1,NGTCS)
C      37 FORMAT(10X,7I10)
C      DO 40 J=1,NGTCS
C      DO 40 I=1,348
C      IF(ITCS(I).EQ.IGTCS(J)) ICHTCS(I)=IGCH(J)
40  CONTINUE
C      READ BAD MIDDLE TC NUMBERS AND ADJUST ICHTCM
C      4E IF(ICS(3).EQ.0)GC TC 68
C      READ(NIN,57)NBTCH,(IBTCH(I),I=1,NBTCH)
C      57 FORMAT(10X,7I10)
C      DO 60 J=1,NBTCH
C      DO 60 I=1,106
C      IF(ITCH(I).EQ.IBTCH(J)) ICHTCM(I)=-999
60  CONTINUE
C      READ NEW 'GOOD' MIDDLE TC NO.'S AND THEIR CORRESPONDING SCAN CHANNELS
C      6E IF(ICS(4).EQ.0)GC TC 128
C      READ(NIN,77)NGTCH,(IGTCH(I),IGCH(I),I=1,NGTCH)
C      77 FORMAT(10X,7I10)
C      DO 80 J=1,NGTCH
C      DO 80 I=1,106
C      IF(ITCH(I).EQ.IGTCH(J)) ICHTCM(I)=IGCH(J)
80  CONTINUE
C      READ D SHUNT CHANNELS
C      12E IF(ICS(5).EQ.0)GO TO 148
C      READ(NIN,137)NBSCH,(IBEIE(I),I=1,NBSCH)
C      137 FORMAT(10X,7I10)
C      DO 140 J=1,NBSCH
C      DO 140 I=1,49
C      IF(ICHEIE(I).EQ.IBEIE(J)) ICHEIE(I)=-999
140  CONTINUE
C      DO 142 I=1,49
C      IF(ICHEIE(I).GT.0)GC TC 142
C      DO 141 J=1,348
C      JMOD=IFIX(FLCAT(ITCS(J)-300000)/1000.0)
C      IF(JMOD.EQ.1) ICHTCS(J)=-999
141  CONTINUE
142  CONTINUE
C      SET-UP NTC, NCHTCS ARRAYS (DEPENDENT ON VALUE OF ICS(6))
C      14E CONTINUE
C      IT=ICS(6)
C      GO TO (158,168,178),IT
C      FOR ICS(6)=1, CRINC CALCULATIONS ARE MADE FOR ALL 'GOOD' BUNDLE
C      T/C'S ON THE DATA SYSTEM
C      15E NK=348
C      DO 160 I=1,348
C      NTC(I)=ITCS(I)
C      16C NCHTCS(I)=ICHTCS(I)
C      RETURN
C      FOR ICS(6)=2, CRINC CALCULATIONS ARE MADE FOR THE T/C'S BETWEEN
C      ATSR AND NTEND IN THE ARRAY ITCs
C      16E READ(NIN,167)NTSRT,NTEND
C      167 FORMAT(10X,2I10)
C      NK=0
C      DO 17C I=1,348
C      IF(ITCS(I).NE.NTSRT.AND.M.NE.1)GO TO 170
C      NK=NK+1
C      NTC(NK)=ITCS(I)
C      NCHTCS(NK)=ICHTCS(I)
C      M=1
C      IF(ITCS(I).EQ.NTEND)M=0
17C  CONTINUE
C      RETURN
C      FOR ICS(6)=3, CRINC CALCULATIONS ARE MADE FOR THE T/C'S SPECIFIED
C      17E READ(NIN,177)NK,(NTC(I),I=1,NK)
C      177 FORMAT(10X,7I10)
C      DETERMINE CHANNELS FOR THE NTC'S SPECIFIED
C      DO 180 I=1,NK
C      DO 180 J=1,348
C      IF(ITCS(J).EQ.NTC(I)) NCHTCS(I)=ICHTCS(J)

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ORI12285
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 ORI12379
 ORI12380

```

100 CONTINUE
RETURN
C
C      END OF MAIN CCATECL INPUT
END
C
C
C *****THIS ROUTINE READS THE RELAP-ORINC INTERFACE TAPE (NTAPE2) AND
C *****LOADS THE ENTIRE TRANSIENT DATA ON DISK (FILE 8); ENTRY INREL
C *****RETRIEVES THE TRANSIENT DATA FROM DISK AND LOADS THE RELAP ARRAYS
C *****REQUIRED BY MAIN
C
C      SUBROUTINE INTRF
C      OAK RIDGE INVERSE CODE      VERSION 1.0      4-1-77
C
C *****COMMON BLOCKS AND DIMENSIONS
COMMON /CCDAS/ ITC(348), ICHTCS(348), ISUBCH(348), ITCM(106),
1 ICHTCM(106), ICHEIE(49), ICHEEE(49), ICHB#1, ICHB#2,
2 IAVOL(15,3), NTRY1(348), NTRY2(106), NTRY3(49),
3 NTRY4(49), NTRY5(106), ICM(1000),
4 ITC(348), ICHTCS(348), NK, IRLB(15,3), NSLAB
COMMON /IMPL/ ITCM, KICK, HED(17), IS(6), TCSS(601), TCM(601),
1 CAVGG(601), TIMEE(501), TIMR(601), TBR(601), TSATR(601),
2 PRESUR(601), QUALR(601), AMFR(601), HBR(601),
3 SFUXR(601), TSURR(601), MODER(601), TRPEND, JRP
4 KRF, ICS7
COMMON /FSTCR/ F(5000)
DIMENSION SS(500), ARRAY(502), NVOL(50), IARRAY(502), AMODER(601)
EQUIVALENCE (ARRAY(1), IARRAY(1)), (AMODER(1), MODER(1))
C
C *****SET-UP I/O DEVICES FOR INPUTTING AND STORING RELAP TRANSIENT CALC
ISMB=0
ACLT=6
NTAPE2=11
REBIND NTAPE2
IRP=1
C
C *****LCAD STEADY STATE ARRAY
J=1
READ(NTAPE2) IARRAY
TIMR(J)=ARRAY(1)
NSLBS=IARRAY(2)
DO 10 I=1,50
10 AVOL(I)=IARRAY(I+2)
DO 20 I=1,500
20 SS(I)=ARRAY(I+2)
C
C *****READ INTERFACE TAPE AND TRANSFER TO DISK UNTIL TAPE EOF IS REACHED
A=0
20 READ(NTAPE2,ERR=48,END=68) ARRAY
IF(ABS(ARRAY(1)-(TIMR(J)+0.050))) .GT. 0.001) GO TO 28
J=J+1
TIMR(J)=ARRAY(1)
NLBS=IARRAY(2)
IF(NSLBS.NE.NLBS) GO TO 58
DO 30 I=3,502
N=N+1
30 F(N)=ARRAY(I)
IF(N.EQ.5000) GO TO 38
GO TO 28
38 WRITE(8) F
IRP=IRP+1
IF(IRP.EQ.61) GO TO 78
N=0
GO TO 28
48 WRITE(NOUT,47)
47 FORMAT(1H1,'***WARNING--INTRP--ERROR ENCOUNTERED IN READING RELAPOR
1 INTERFACE TAPE.'//,T22,'JOB TERMINATED.')
STOP
58 WRITE(NOUT,57) NSLBS, NLBS, TIMR(J), J
57 FORMAT(1H1,'***WARNING--INTRP--DURING THE READ OF A RELAP INTERFA
ICE TAPE, / FILE WAS',/ ,T22,'READ IN WHICH THE NO. OF SLABS DID NOT
2 MATCH THE NO. OF SLABS FROM FILE ONE.'//,T22,'JOB TERMINATED.'//,
3 T22,'NSLBS=',I7//,T22,'ARRAY(2)=',I7//,T22,'TIME OF FILE=',F10.5,
4 /,T22,'FILE NO.',I7)
STOP
68 WRITE(8) F
IRP=IRP+1

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7E JRP=J
IF(KRP.EQ.0) KRF=JRP
IRPEND=TIME(JRF)
REIND NTAPE2
REIND 8
C *****CHECK TO SEE THAT B/D TIMES (TIMEE) AND RELAP INTERFACE TIMES (TIMOR)
C *****ARE COMPATIBLE
DO 80 I=1,JRP
  J=I
  IF(ABS(TIMEE(I)-TIMR(I)).GT.0.310)GO TO 80
8C CONTINUE
  RETRN
88 WRITE(NOUT,87)TIMEE(J),TIMR(J)
87 FORMAT(1H1,'***WARNING--INTRP--RELAP AND BLOWDOWN TIMES ARE NOT
  1COMPATIBLE.'//,T22,'JOB TERMINATED.'//,T22,'TIME (B/D) =',F10.4//,
  2T22,'TIME (RELAP) =',F10.4)
  STOP
C
C ENTRY TO RETRIEVE THE NUMBER OF SLABS IN THE RELAP MODEL
ENTRY INPSLE(NISBLE)
NISBLE=NSLBS
RETURN
C *****
C *****FOR CALLS TO ENTRY INRELP, RELAP PREDICTIONS FOR VOLUME PRESSURE,
C *****VOLUME TEMPERATURE, VCL AVERAGE QUALITY, SLAB SURFACE HEAT FLUX,
C *****HEAT TRANSFER CEFF., SLAB SURFACE TEMPERATURE, AVERAGE VOL MASS
C *****FLUX, SATURATE TEMPERATURE, AND HEAT TRANSFER MODE AT THE SLAB
C *****SLAB SURFACE ARE RECOVERED FROM DISK STORAGE AND STORED IN THE APPROPRIATE
C *****ARRAYS AND RETURNED TO MAIN
C *****
C
C ENTRY INRELP
C
C *****DETERMINE PACFER VOLUME FOR THIS T/C
IRDD=FIX(FLCAT(ITCMN-300000)/1000.0)
ISGV=FIX(FLCAT(ITCMN-300000-IRDD*1000)/100.0)
ITCL=ITCMN-300000-IRDD*1000-ISGV*100
DO 90 I=1,348
  ISH=I
  IF(ITCMN.EQ.ITCS(I))GO TO 98
9C CONTINUE
92 NVOLUM=IRVOL(ITCL,ISUBCH(ISH))
  NSLAB=IRSLB(ITCL,ISUBCH(ISH))
  DO 100 I=1,NSLAB
    ISH=I
    IF(NVOL(I).EQ.NVOLUM)GO TO 108
10C CONTINUE
    WRITE(NOUT,107)ITCMN,NVOLUM,(I,NVOL(I),I=1,NSLAB)
107 FORMAT(1H1,'***WARNING--INRELP--RELAP VOLUME NUMBER ASSOCIATED WITH
  1H T/C NUMBER',I10,'//,T22,'WAS NOT FOUND IN NVOL ARRAY. JOB TERMINATOR
  2ED.'//,T22,'VOLUME NUMBER =',I5,'//,T22,'NVOL(',I3,') =',I5))
    STOP
10E CONTINUE
    IF(ISHB.EQ.ISH) GO TO 128
    ISHB=ISH
C
C *****LOAD TBR, PRESUR, QUALR, AMFR, MBR, SFLUXR, TSURR, AND MODER ARRAY
  J=1
  PRESUR(J)=SS(ISH+50)
  TBR(J)=SS(ISH+100)
  QUALR(J)=SS(ISH+150)
  SFLUXR(J)=SS(ISH+200)
  MBR(J)=SS(ISH+250)
  TSURR(J)=SS(ISH+300)
  AMFR(J)=SS(ISH+350)
  TSATR(J)=SS(ISH+400)
  AMODER(J)=SS(ISH+450)
C-----SET IRP TO 1 AND START RETRIEVAL FROM DISK (FILE 8)
  IRP=1
11E READ(8) F
  IRP=IRP+1
  DO 120 I=1,10
    J=J+1
    IF(J.GT.JRP)GO TO 128
    N=(I-1)*500
    PRESUR(J)=F(ISH+N+50)
    TBR(J)=F(ISH+N+100)
    QUALR(J)=F(ISH+N+150)
    SFLUXR(J)=F(ISH+N+200)
    MBR(J)=F(ISH+N+250)
    TSURR(J)=F(ISH+N+300)
    AMFR(J)=F(ISH+N+350)
    TSATR(J)=F(ISH+N+400)
    AMODER(J)=F(ISH+N+450)
12C CONTINUE
  GO TO 118
12E CONTINUE
  REIND 8
  RETURN
C
C *****END OF LOADING
END

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C*****THIS ROUTINE (INCLUDES ENTRIES INPTBO AND INBO) READS THE BLOW-DOWN OR112552
C*****TAPE (NTAPE1). DETERMINES THE INITIATION OF BLOWDOWN, LOADS THE OR112553
C*****NEXT 30 SECONDS OF THE BLOWDOWN PERIOD ON DISK; THEN RETRIEVES FROM OR112554
C*****THE DISK THERMOCOUPLE AND POWER RESPONSES AND LOADS THE TCSS, TCM OR112555
C*****AND GAVGG ARRAYS REQUIRED BY MAIN OR112556
C OR112557
C      SLBROUTINE INPTBO OR112558
C      CAX RIDGE INVERSE CODE      VERSION 1.0      4-1-77 OR112559
C OR112560
C*****COMMON BLOCKS AND DIMENSIONS OR112561
C      COMMON /CCOAS/ ITC(348), ICHTCS(348), ISJBCH(348), ITCM(106), OR112562
C      1 ICHTCH(106), ICHEIE(49), ICHEEE(49), ICHBW1, ICHBW2, OR112563
C      2 IFVOL(15,3), NTRY1(348), NTRY2(106), NTRY3(49), OR112564
C      3 NTRY4(49), NBW1, NBW2, IC(1000), OR112565
C      4 NTC(348), NCHTCS(348), NK, IRSLB(15,3), NSLAB OR112566
C      COMMON /INPLT/ ITCMUN, KICK, HED(17), IS(6), TCSS(601), TCMN(601), OR112567
C      1 GAVGG(601), TIMEE(601), TIMR(601), TBR(601), TSATR(601), OR112568
C      2 FRESUR(601), QUALR(601), AMFR(601), MBR(601), OR112569
C      3 SFLUXR(601), TSURR(601), MODER(601), TRPEND, JRP OR112570
C      4 IRP, ICS7 OR112571
C      COMMON /PIH/ RHT(15,7), PFFR(15,2), TCL(15), SQ(7), HLENG(49) OR112572
C      COMMON /FSTCR/ F(5000) OR112573
C      DIMENSION SUP(500), S(1000), SS(500), JT(6) OR112574
C OR112575
C*****SET-UP I/O DEVICES FOR INPUTTING AND STORING B/D DATA OR112576
C      NOUT=6 OR112577
C      NTAPE1=10 OR112578
C      REWIND NTAPE1 OR112579
C      IBO=1 OR112580
C OR112581
C*****READ SCAN TABLE FROM E/D DATA TAPE AND SET-UP ENTRY NO. ARRAY OR112582
C      READ(NTAPE1) IC, ID OR112583
C      CALL SCAN OR112584
C OR112585
C*****ZERO SUMMATION ARRAY OR112586
C      DO 10 I=1,500 OR112587
C      1C SLN(I)=0.0 OR112588
C      NSUM=0 OR112589
C OR112590
C*****FROM BEGINNING OF TAPE TO TRIP POINT DETERMINE MEANS FOR ALL ENTRIES OR112591
C      1E READ(NTAPE1, ERR=38, END=48) ID, JT, S OR112592
C-----CHECK BREAK WIRE CHANNELS FOR B/D OR112593
C      IF (S(NBW1).GT.1.0.OR.S(NBW2).GT.1.0) GO TO 58 OR112594
C      DO 20 I=1,500 OR112595
C      2C SUM(I)=SLN(I)+S(I) OR112596
C      NSUM=NSUM+1 OR112597
C      IF (S(NBW1+500).GT.1.0.OR.S(NBW2+500).GT.1.0) GO TO 78 OR112598
C      DO 30 I=1,500 OR112599
C      3C SLN(I)=SUM(I)+S(I+500) OR112600
C      ASUM=NSUM+1 OR112601
C      GO TO 18 OR112602
C      38 WRITE(NOUT,37) OR112603
C      37 FORMAT(1H1,'***WARNING--INPTBO--ERROR ENCOUNTERED IN READING BLOW-OR112604
C      1DCN DATA TAPE.'//,T22,'JOB TERMINATED. ***!****') OR112605
C      STOP OR112606
C      4E WRITE(NOUT,47) OR112607
C      47 FORMAT(1H1,'***WARNING--INPTBO--EOF ENCOUNTERED DURING SEARCH FOR OR112608
C      1TRIP POINT.'//,T22,'JOB TERMINATED.') OR112609
C      STOP OR112610
C-----BREAK FOUND IN FIRST FILE (FIRST 500 ENTRIES) OR112611
C      5E DO 60 I=1,500 OR112612
C      6C SS(I)=SUM(I)/FLCAT(NSUM) OR112613
C      DO 7C I=1,6 OR112614
C      7C IS(I)=JT(I) OR112615
C      A=0 OR112616
C      GO TO 109 OR112617
C-----BREAK FOUND IN SECOND FILE (I.E., SECOND 500 ENTRIES) OR112618
C      7E DO 80 I=1,500 OR112619
C      8C SS(I)=SUM(I)/FLCAT(NSUM) OR112620
C      DO 9C I=1,6 OR112621
C      9C IS(I)=JT(I) OR112622
C      A=0 OR112623
C      DO 100 I=501,1000 OR112624
C      A=A+1 OR112625
C      10C F(N)=S(I) OR112626
C OR112627
C*****READ BLOW-DOWN TAPE AND STORE FIRST 30 SECS OF B/D ON DISK OR112628
C      1CE READ(NTAPE1, ERR=138, END=148) ID, JT, S OR112629
C      DO 110 I=1,500 OR112630
C      A=A+1 OR112631
C      11C F(N)=S(I) OR112632
C      NDCR=2 OR112633
C      IF (N.EQ.5000) GO TO 128 OR112634
C      DO 120 I=501,1000 OR112635
C      A=A+1 OR112636
C      12C F(N)=S(I) OR112637
C      NDCR=1 OR112638
C      IF (N.EQ.5000) GO TO 128 OR112639
C      GO TO 108 OR112640
C      12E WRITE(7) F OR112641
C      IBO=IBO + 1 OR112642
C      IF (IBO.EQ.61) GO TO 158 OR112643

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      N=0
      GC TO(108,118),ADSK
      136 WRITE(NOUT,137)
      137 FORMAT(1H1,***WARNING--INPTBD--ERROR ENCOUNTERED IN READING BLOW-
      10CM DATA TAPE."/,T22,"JOB TERMINATED. ***2***")
      STOP
      146 WRITE(NOUT,147)
      147 FORMAT(1H1,***WARNING--INPTBD--EOF ENCOUNTERED DURING TRANSFER OF
      1 FIRST 30 SECCMS OF 80 DATA FROM TAPE TO DISK."/,T22,"JOB TERMIN
      2ATED.")
      STOP
      156 CONTINUE
      REWIND HTAPE1
      REWIND 7
C
C*****SET-UP TIME ARRAY
      DO 160 I=1,601
      160 TIMEE(I)=FLCAT(I-1)*0.05
      RETURN
C
C*****
C*****FOR CALLS TO ENTRY INBD. THE SHEATH T/C RESPONSE, MIDDLE T/C RESPON
C*****IF ANY), ROD AMPERAGE, AND GENERATOR VOLTAGE DURING THE BLOW-DOWN
C*****TRANSIENT ARE RECOVERED FROM DISK STORAGE, STORED IN THE APPROPRI
C*****ARRAYS AND SMOOTHED (THREE POINT SMOOTHING)
C*****
C
      ENTRY INBD
C*****SET-UP ENTRY NUMBERS FOR THIS CALL
      IRCD=IFIX(FLCAT(ITCAUN-300000)/1000.0)
      ISGV=IFIX(FLCAT(ITCAUN-300000-IRCD*1000)/100.0)
      ITCL=ITCAUN-300000-IRCD*1000-ISGV*100
      ITCNO=300000+IRCD*1000+700+ITCL
C-----DETERMINE IF THERE IS A 'GOOD' MIDDLE T/C CORRESPONDING TO ITCNUM
      DO 170 I=1,106
      IM=I
      IF(ITCNO.EQ.ITCM(I))GC TO 178
      170 CONTINUE
      ATCM=0
      GO TO 198
      178 IF(1CHITCM(IM).GT.0)GO TO 180
      ATCM=0
      GC TO 198
      180 ATCM=TRY2(IM)
C-----DETERMINE THE SHEATH T/C ENTRY NUMBER
      190 DO 200 I=1,348
      ISH=I
      IF(ITCNUM.EQ.ITCS(I))GO TO 208
      200 CONTINUE
      208 ATCS=TRY1(ISH)
C-----SET THE ENTRY NUMBERS FOR THE SHUNT AMPERAGE AND GENERATOR VOLTAGE
      NEIE=TRY3(IRCD)
      NEE=TRY4(IRCD)
C
C*****LEAD TCSS, TCNN, AND GAVGG ARRAYS
      J=1
      TCSS(J)=SS(ATCS)
      GAVGG(J)=SS(NEIE)*SS(NEE)/1000.0*(3412.9/3600.0)/MLENG(IRCD)
      IF(ATCM.NE.0)GC TO 210
      TCNN(J)=0.0
      GO TO 228
      210 TCNN(J)=SS(ATCM)
      220 CONTINUE
      IBD=1
      230 READ(7) F
      IBD=IBD+1
      DO 250 I=1,10
      J=J+1
      K=(I-1)*500
      TCSS(J)=F(ATCS+K)
      GAVGG(J)=F(NEIE+K)*F(NEE+K)/1000.0*(3412.9/3600.0)/MLENG(IRCD)
      IF(ATCM.NE.0)GC TO 248
      TCNN(J)=0.0
      GC TO 250
      240 TCNN(J)=F(ATCM+K)
      250 CONTINUE
      IF(IBD.NE.61)GC TO 230
C
C*****SMOOTH TCSS, TCNN, GAVGG DATA
      CALL SMOOTH(601,TCSS)
      CALL SMOOTH(601,TCNN)
      DO 260 I=1,601
      IF(GAVGG(I).LE.0.001)GAVGG(I)=0.0
      260 CONTINUE
      REWIND 7
C
C*****END OF LOADING AND SMOOTHING. RETURN
      RETURN
      END

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SUBROUTINE SMCCTH(N,Y)
C OAK RIDGE INVERSE CODE      VERSION 1.0      4-1-77
DIMENSION Y(N),YS(1000)
DC 5 I=2,N
IF(ABS(Y(I-1)-Y(I)),GE.100.0) Y(I)=Y(I-1)
5 CONTINUE
YS(I)=Y(I)
NN=N-1
DC 10 I=2,NN
1C YS(I)=(Y(I-1)+Y(I)+Y(I+1))/3.0
YS(N)=(Y(N-2)+Y(N-1)+Y(N))/3.0
DC 20 I=1,N
2C Y(I)=YS(I)
RETURN
END

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ORI12733
 ORI12734
 ORI12735
 ORI12736
 ORI12737
 ORI12738
 ORI12739
 ORI12740
 ORI12741
 ORI12742
 ORI12743
 ORI12744
 ORI12745
 ORI12746
 ORI12747

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SUBROUTINE COT1
C OAK RIDGE INVERSE CODE      VERSION 1.0      4-1-77
COMMON /COEFF/NTCS(348),TCM(348),DAT(348,3),PFAX(348),KD4(348),
1 CENO(348,4),VR1(348),KD1(348),CHGD(348,5),VR2(348),
2 KD2(348),GAPCF(348,3),GAPSD(348,3),VR3(348),KD3(348),
3 GAPG(348),TNODS(348),TNS(348),FEEBEE(348),ZERO(348,6),
4 PRSS(348),TMAX(348)
COMMON /INPLY/ITCNUM,KICK,MED(17),IS(6),TCSS(601),TCM(601),
1 QAVGG(601),TIMEE(601),TIMR(601),TBR(601),TSATR(601),
2 PRESUR(601),QUALR(601),AMFR(601),HBR(601),
3 SFLUXR(601),TSURR(601),MODER(601),TRPEND,JRP
4 IRP,ICS7
DIMENSION SGV(7),TCL(15),ALPHA(2,6),
1 ALPHA1(4,12),ALPHA2(4,11),ALPHA3(4,13)
DATA SGV/1HA,1HB,1HC,1HD,1HE,1HF,1HW/
DATA TCL/1HA,1HB,1HC,1HD,1HE,1HF,1HG,1HH,1HI,1HJ,1HK,
1 1HL,1HM,1HN,1HO/
DATA ALPHA1/'BY G','NDIV','RNL','RES','DNG',
1 'ISTA','76-3','NCE','868','CAL',
DATA ALPHA1/'DETE','DETE','DETE','COE','RMIN','RMIN',
1 'DEFF','ED F','ED F','ED F','ICIE','OR T','OR T',
2 'CR T','NTS','HE A','HE S','HE B','NDT',
3 'BCVE','PECI','JNDL','LOAD','SPE','FIC','E',
4 'ED F','CIFI','T/C','ER T','C IT','PO',
5 'HE A','CS/I','WER','BOVE','TCM',
6 'LEVE','DAT','PAIR','L','E***'/
DATA ALPHA2/'DETE','DETE','COE','RMIN','RMIN',
1 'FFIC','ED F','ED F','ED B','IENT','OR T','OR T',
2 'Y A','S AC','HE A','HE S','PORD','T LJ',
3 'BCVE','PECI','SIIY','ADES','SPE','FIC','FIT',
4 'FER','CIFI','T/C','THE','C T','LEVE',
5 'ABC','C PA','L','VE D','IR',
6 'ATE'/'
DATA ALPHA3/'DETE','DETE','DETE','COE','RMIN','RMIN',
1 'COE','ED F','ED F','ED B','FFIC','OR T','JR T','Y US',
2 'IENT','HE A','HE S','ING','S NO','BOVE','PECI','THE',
3 'T LC','SHE','FIC','BIAS','ADES','ATH','T/C','GAP',
4 'PER','T/C','LEVE','VAL','THE','L','UE A',
5 'ABC','S A','VE D','MEAN',
6 'ATE','GAP','*****'/

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ORI12748
 ORI12749
 ORI12750
 ORI12751
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 ORI12787

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C-----INPUT DATA FROM COEFFICIENT DATA TAPE
C-----NTAPE3=12
REVIND NTAPE3
DC 10 I=1,348
READ(NTAPE3,END=148)NTCS(I),TCM(I),(DAT(I,J),J=1,3)
READ(NTAPE3,END=148)PFAX(I),KD4(I)
READ(NTAPE3,END=148)(CBNO(I,J),J=1,4),VR1(I),KD1(I)
READ(NTAPE3,END=148)(CHGD(I,J),J=1,5),VR2(I),KD2(I),PRSS(I)
READ(NTAPE3,END=148)(GAPCF(I,J),J=1,3),(GAPSD(I,J),J=1,3),VR3(I),
1 KD3(I),GAPG(I),TNODS(I),TNS(I),FEEBEE(I),TMAX(I)
READ(NTAPE3,END=148)(ZERO(I,J),J=1,6)
1C CONTINUE
REVIND NTAPE3
RETURN
14E WRITE(6,17)
17 FCRMAT(1H1,'***WARNING--COT1--ERROR ENCOUNTERED IN READING COEFFICIENT DATA TAPE.'//,T20,'JOB TERMINATED.')
STOP
C-----
C-----ENTRY COT
C-----

```

ORI12788
 ORI12789
 ORI12790
 ORI12791
 ORI12792
 ORI12793
 ORI12794
 ORI12795
 ORI12796
 ORI12797
 ORI12798
 ORI12799
 ORI12800
 ORI12801
 ORI12802
 ORI12803
 ORI12804
 ORI12805
 ORI12806
 ORI12807
 ORI12808
 ORI12809
 ORI12810


```

C      NOLT=6
C      DO 200 J=1,348
      I=J
      IF(ITCNLM.EC.NTCS(J)) GC TO 208
200 CONTINUE
208 CONTINUE
C      NROD=FIX(FLCAT(NTCS(1)-300000)/1000.0)
      NSGV=FIX(FLCAT(NTCS(1)-300000-NROD*1000)/100.0)
      ATCL=NTCS(1)-300000-NROD*1000-NSGV*100
      NBRD=NROD + 300
C-----WRITE DATA FROM COEFFICIENT TAPE FOR ITCNM
      WRITE(NOUT,3)ITCNM,NED
      WRITE(1,3) ITCNM,NED
      3 FORMAT(1H1,16,20(1H*),25H CALIBRATION INFORMATION ,25(1H*),//,
      12,6(1H*),17A4,/)
      WRITE(NOUT,13) AEROD.SGV(NSGV),TCL(NTCL)
      WRITE(1,13) NBRD.SGV(NSGV),TCL(NTCL)
      13 FORMAT(2, '***** THEROCOUPLE NO. ',13, '---.2A1,/)
      IF(NTCN(1).NE.0) GO TC 32
      WRITE(NOUT,23)
      WRITE(1,23)
      23 FORMAT('***** MIDDLE T/C --- NONE',/)
      GO TO 42
      32 WRITE(NOUT,33) NEROD.SGV(7),TCL(NTCL)
      WRITE(1,33) NBRD.SGV(7),TCL(NTCL)
      33 FORMAT('***** MIDDLE T/C --- ',13, '---.2A1,/)
      42 WRITE(NOUT,43) (DAT(I,J),J=1,3)
      WRITE(1,43) (DAT(I,J),J=1,3)
      42 FORMAT('***** DATE OF LAST MODIFICATION : ',3A4,/)
      WRITE(NOUT,53) PFAI(1)
      WRITE(1,53) PFAI(1)
      53 FORMAT('***** AXIAL POWER PEAKING FACTOR IS : ',F7.4,/)
      WRITE(NOUT,63) (ALPHA4(KD4(I),J),J=1,6)
      WRITE(1,63) (ALPHA4(KD4(I),J),J=1,6)
      63 FORMAT('***** DETERMINED ',6A4,/)
      WRITE(NOUT,73) (ALPHA1(KD1(I),J),J=1,12), (CBNO(I,J),J=1,4), VR1(1)
      WRITE(1,73) (ALPHA1(KD1(I),J),J=1,12), (CBNO(I,J),J=1,4), VR1(1)
      73 FORMAT('***** CCEFFICIENTS FOR TEMPERATURE POLYNOMIAL FIT OF KOR12851
      1DN',/,T7,12A4,/,T7,'C(1)= ',E15.8,/,T7,'C(2)= ',E15.8,/,
      2 T7,'C(3)= ',E15.8,/,T7,'C(4)= ',E15.8,/,T7,
      3 'VARIANCE OF FIT= ',E15.8,/,T7,'UNITS FOR KBN FIT : BTU/(HR*FT*OR12854
      442/FT**2),/)
      WRITE(NOUT,83) (ALPHA2(KD2(I),J),J=1,11), (CMGO(I,J),J=1,5)
      WRITE(1,83) (ALPHA2(KD2(I),J),J=1,11), (CMGO(I,J),J=1,5)
      83 FORMAT('***** CCEFFICIENTS FOR TEMPERATURE POLYNOMIAL FIT FOR
      1KNGO',/,T7,11A4,/,T7,'C(1)= ',E15.8,/,T7,'C(2)= ',E15.8,/,T7,'C(3)
      2= ',E15.8,/,T7,'C(4)= ',E15.8,/,T7,'C(5)= ',E15.8,/)
      WRITE(NOUT,93) VR2(1),FRSS(1)
      WRITE(1,93) VR2(1),FRSS(1)
      93 FORMAT('***** VARIANCE OF FIT= ',E15.8,/,T7,'UNITS FOR KNGO FIT
      1 BTU/(HR*FT**2/FT**2),/,T7,'ACTUAL KGO POROSITY CALCULATED VIA MOR12863
      2ODIFIED',/,T15,'RUSSELL EQUATION : ',E15.8,/)
      WRITE(NOUT,103) (ALPHA3(KD3(I),J),J=1,13)
      WRITE(1,103) (ALPHA3(KD3(I),J),J=1,13)
      103 FORMAT('***** CCEFFICIENTS FOR THE THERMAL EXPANSION GAP MODELOR12865
      1 FIT',/,T7,13A4,/)
      WRITE(NOUT,113) (GAPCF(I,J),GAPSD(I,J),J=1,3)
      WRITE(1,113) (GAPCF(I,J),GAPSD(I,J),J=1,3)
      113 FORMAT('***** T7,'C(1)= ',E15.8,4X,'SD= ',E15.8,/,T7,'C(2)= ',E15.8,
      1 4X,'SD= ',E15.8,/,T7,'C(3)= ',E15.8,4X,'SD= ',E15.8,/)
      WRITE(NOUT,123) VR3(1),GAPO(1)
      WRITE(1,123) VR3(1),GAPO(1)
      123 FORMAT('***** T7,'VARIANCE OF FIT= ',E15.8,/,T7,'GAP CALCULATION AT
      1THE BIAS POINT : ',T53,F7.4,T63,'(MILS)',/)
      WRITE(NOUT,133) TNGD(1),TNG(1),FEEBEE(1)
      WRITE(1,133) TNGD(1),TNG(1),FEEBEE(1)
      133 FORMAT('***** T7,'BIAS TEMP. INSIDE S.S.S. NODAL TEMP. : ',T53,F7.1,
      1 T63,'DEG. F',/,T7,'BIAS TEMP. OUTSIDE S.S.S. NODAL TEMP. : ',T53,OR12881
      2 F7.1,T63,'DEG. F',/,T7,'BIAS FLJX : ',F10.1, ' BTU/HR/FT**2,/)
      WRITE(NOUT,143) TMAX(1)
      WRITE(1,143) TMAX(1)
      143 FORMAT('***** T7,'THE MAXIMUM TEMPERATURE FOR WHICH THE ABOVE',/,T7,
      1 'REGRESSION FIT IS APPLICABLE IS ',F8.2, ' DEG. F')
      RETURN
      END

```

```

BLOCK DATA
C CAR RIDGE INVERSE CODE      VERSION 1.0      4-1-77
C
  LOGICAL SLAB
  COMMON /MODES/AMGO,AMT,ACU,ABN,NSS1,NSS2,MOD2,MOD3,MOD4,MOD5,MOD6,
1    NP,NM,NC,AB,NS,NIN,NCUT,R(4C),ABAR(4C),RHEAT(7),
2    CLFMC,CLFMT,DLRC,OLRBN,OLRSS1,OLRSS2
  COMMON /PIN/ RMT(15,7),PFFR(15,2),TC(15),SGV(7),MLENG(49)
  COMMON /CCDAS/ITCS(34),ICHTCS(34),ISJBCN(34),ITCM(106),
1    ICHTCH(106),ICHEIE(49),ICHEEE(49),ICM8#1,ICM8#2,
2    IRVOL(15,3),NTRY1(34),NTRY2(106),NTRY3(49),
3    NTRY4(49),AB#1,NB#2,IC(100),
4    ATC(34),NCHTCS(34),MK,IRSLB(15,3),NS-AB
  COMMON /FLUSH/ SLAB(50),PFAA(15)
  DIMENSION ITC1(50),ITC2(50),ITC3(50),ITC4(49),ITC5(51),ITC6(48),
1    ITC7(50),ICM1(50),ICM2(50),ICM3(50),ICM4(49),ICM5(51),
2    ICM6(48),ICM7(50)
  EQUIVALENCE (ITC5(1),ITC1(1)),(ITC5(51),ITC2(1)),
1    (ITC5(101),ITC3(1)),(ITC5(151),ITC4(1)),
2    (ITC5(201),ITC5(1)),(ITC5(251),ITC6(1)),
3    (ITC5(299),ITC7(1)),(ICMTC5(1),ICM1(1)),
4    (ICMTC5(5),ICM2(1)),(ICMTC5(101),ICM3(1)),
5    (ICMTC5(151),ICM4(1)),(ICMTC5(201),ICM5(1)),
6    (ICMTC5(251),ICM6(1)),(ICMTC5(299),ICM7(1))
C
C-----SECTION ONE OF THIS BLOCK DATA SUBPROGRAM CONTAINS INFORMATION
C PERTINENT TO THE HEATER PIN (I.E., PIN RADIAL DIMENSIONS, PEAKING
C FACTORS--RADIAL, INITIAL FIN NOODING
C
C*****SECTION ONE
C
C RADIAL PEAKING FACTORS (CORRESPONDING TO TC POSITIONS A,B,C,D,E,
C F,G,H,I,J,K,L,M,N, AND O)
C DATA PFFR / 2*0.402283,0.573754,9*1.0,0.573754,2*0.402283,
1    2*0.597717,0.426246,9*0.0,0.426246,2*0.597717/
C
C PIN RADIAL DIMENSIONS (SIMILAR CORRESPONDENCE)
C DATA RMT / 15*0.0,2*0.007457,3,337925,0.008408,0.008725,
1    3*0.009067,2*0.008725,2*0.008408,0.007925,2*0.007467,
2    2*0.009250,3,339708,9*0.010167,0.009708,
3    2*0.009250,3*0.010157,9*0.0,3*0.010167,15*0.014333,
4    15*0.016833,15*0.017667/
C
C FIN NOODING
C DATA AMGO,AMT,ACU,ABN,NSS1,NSS2/4,2,0,3,3,3/
C
C HEATER PIN TOTAL HEATED LENGTH (RODS 1 THRU 49)
C DATA MLENG/ 11.92708, 11.89363, 11.89063, 11.92188, 11.88803,
1    11.89583, 11.89323, 11.89323, 11.93749, 11.94271, 11.90104,
2    11.94271, 11.92448, 11.90886, 11.89063, 11.88021, 11.88541,
3    11.94010, 11.94792, 11.92448, 11.89323, 11.92710, 11.90104,
4    11.92708, 11.93489, 11.93229, 11.89583, 11.88542, 11.90365,
5    11.92188, 11.92188, 11.92448, 11.93750, 11.92968, 11.89323,
6    11.92188, 11.89844, 11.94271, 11.95573, 11.93491, 11.92448,
7    11.85679, 11.88542, 11.89843, 11.88803, 11.88803, 11.90105,
8    11.88542, 11.95573/
C-----SECTION TWO OF THIS BLOCK DATA SUBPROGRAM CONTAINS INFORMATION
C INHERENT TO THE EXISTING THF SYSTEM (5/31/76)---THAT IS, THE
C BUNDLE 1 INSTRUMENTATION (SHEATH AND MIDDLE THERMOCOUPLES AND
C THEIR ASSOCIATED CCDAS SCAN CHANNEL NUMBERS), AND THE INDIVIDUAL
C ROD SHUNT AND VOLTAGE CCDAS SCAN CHANNEL NUMBERS
C
C*****SECTION TWO
C
C THERMOCOUPLE POWER LEVELS
C DATA TCL /IHA,IHB,IHC,IHD,IHE,INF,IMG,IHH,IHI,IHJ,IHK,IHL,IHM,
1    IHA,IMG/
C
C PIN SHEATH GROOVE NUMBERS:
C DATA SGV /IHA,IHB,IHC,IHD,IHE,INF,IHM/
C
C BUNDLE SHEATH THERMOCOUPLE NUMBERS (ITC1-7) AND CCDAS SCAN
C CHANNEL NUMBERS (ICM1-7)
C DATA ITC1 / 301104, 304104, 309104, 310104, 312104, 313104,
1    317104, 318104, 320104, 322104, 323104, 325104,
2    326104, 331104, 338104, 339104, 341104, 346104,
3    301105, 304105, 309105, 312105, 313105, 317105,
4    318105, 320105, 322105, 323105, 324105, 325105,
5    326105, 331105, 333105, 338105, 339105, 341105,
6    349105, 301206, 304206, 309206, 310206, 312206,
7    313206, 317206, 320206, 322206, 323206, 324206,
8    325206, 326206/
C DATA ICM1 / 202, 32, 226, 237, 60, 70,
1    255, 84, 94, 323, 333, 352,
2    108, 364, 382, 424, 162, 178,
3    203, 33, 227, 61, 71, 314,
4    85, 95, 324, 334, 343, 353,
5    109, 365, 193, 383, 425, 163,

```



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DATA ITC7 / 329108. 329109. 329310. 329312. 330104. 330105. ORI13072
1 330206. 330207. 330308. 330309. 330410. 330411. ORI13073
2 330512. 330515. 332104. 332105. 332206. 332207. ORI13074
3 332308. 332309. 332410. 332411. 332512. 332515. ORI13075
4 334104. 334105. 334206. 334207. 334308. 334309. ORI13076
5 334410. 334411. 334512. 334515. 335108. 335109. ORI13077
6 335310. 335312. 319104. 319105. 319206. 319207. ORI13078
7 319308. 319309. 319410. 319411. 319512. 319515. ORI13079
8 347108. 347109. ORI13080
DATA ICH7 / 504-499/ ORI13081
ORI13082
ORI13083
ORI13084
ORI13085
ORI13086
ORI13087
ORI13088
ORI13089
ORI13090
ORI13091
ORI13092
ORI13093
ORI13094
ORI13095
ORI13096
ORI13097
ORI13098
ORI13099
ORI13100
ORI13101
ORI13102
ORI13103
ORI13104
ORI13105
ORI13106
ORI13107
ORI13108
ORI13109
ORI13110
ORI13111
ORI13112
ORI13113
ORI13114
ORI13115
ORI13116
ORI13117
ORI13118
ORI13119
ORI13120
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ORI13122
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ORI13133
ORI13134
ORI13135
ORI13136
ORI13137
ORI13138
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ORI13140
ORI13141
ORI13142
ORI13143
ORI13144
ORI13145
ORI13146
ORI13147
ORI13148
ORI13149
ORI13150
ORI13151
ORI13152
ORI13153
ORI13154
ORI13155
ORI13156
ORI13157
ORI13158
ORI13159
ORI13160
ORI13161
ORI13162
ORI13163

```

BUNDLE MIDDLE THERMOCOUPLE NUMBERS (ITCM) AND CCDAS SCAN CHANNEL
 NUMBERS (ICHTCM)

```

DATA ITCM / 301705. 301706. 301707. 301708. 301710. 302710. ORI13085
1 303710. 304705. 304706. 304707. 304708. 304710. ORI13086
2 305710. 306710. 307710. 308711. 309705. 309706. ORI13087
3 309707. 309708. 309710. 310707. 310710. 311710. ORI13088
4 312707. 312710. 313707. 313710. 314710. 315710. ORI13089
5 316710. 317707. 317710. 318705. 318706. 318707. ORI13090
6 318708. 318710. 319707. 319710. 320707. 320710. ORI13091
7 321710. 322705. 322706. 322707. 322708. 322710. ORI13092
8 323707. 323710. 324707. 324710. 325705. 325706. ORI13093
9 325707. 325708. 325710. 326705. 326706. 326707. ORI13094
0 326708. 326710. 327710. 328710. 329710. 329710. ORI13095
1 330710. 331705. 331706. 331707. 331708. 331710. ORI13096
2 332707. 332710. 333707. 333710. 334707. 334710. ORI13097
3 335710. 336710. 337710. 338705. 338706. 338707. ORI13098
4 338708. 338710. 339705. 339706. 339707. 339708. ORI13099
5 339710. 340710. 341707. 341710. 342710. 343710. ORI13100
6 344710. 345710. 346710. 347710. 348710. 349705. ORI13101
7 349706. 349707. 349708. 349710/ ORI13102
DATA ICHTCM / 456. 455. 457. -999. 458. -999. ORI13103
1 83. 0. 0. 0. 190. 0. ORI13104
2 -999. 0. 0. 79. -999. -999. ORI13105
3 249. 0. 0. 345. 426. -999. ORI13106
4 0. 0. 0. 0. -999. 0. ORI13107
5 -999. 192. 503. 450. -999. 452. ORI13108
6 -999. 453. -499. -499. 0. -999. ORI13109
7 0. 459. 461. 460. 462. -999. ORI13110
8 86. 238. 0. 451. -999. -999. ORI13111
9 -999. -999. 454. 0. 0. 0. ORI13112
0 -999. 0. 0. 0. -499. -499. ORI13113
1 -499. 0. -999. -999. -999. -499. ORI13114
2 -499. -499. -999. -999. -499. -499. ORI13115
3 -499. 0. 0. 0. 0. 0. ORI13116
4 0. 0. 0. 0. 0. 0. ORI13117
5 0. 0. -999. 0. 0. -999. ORI13118
6 0. -999. 0. -499. -999. 0. ORI13119
7 0. 0. -999. 0/ ORI13120
INDIVIDUAL PCD SHUNT CHANNELS (ICHEIE)
DATA ICHEIE / 409. 149. 410. 150. 391. 3. ORI13121
1 390. 408. 411. 151. 2. 389. ORI13122
2 388. 6. 407. 412. 148. 4. ORI13123
3 5. 387. 7. 414. 413. 406. ORI13124
4 134. 397. 396. 398. 405. 415. ORI13125
5 145. 144. 403. 396. 399. 404. ORI13126
6 147. 146. 133. 402. 401. 400. ORI13127
7 130. 131. 132. 392. 393. 394. ORI13128
8 395/ ORI13129
INDIVIDUAL PCD VOLTAGE CHANNELS (ICHEEE)
DATA ICHEEE / 158. 159. 158. 159. 156. 156. ORI13130
1 156. 158. 158. 158. 156. 155. ORI13131
2 156. 156. 158. 158. 159. 156. ORI13132
3 156. 156. 156. 158. 158. 158. ORI13133
4 156. 157. 156. 157. 158. 158. ORI13134
5 159. 159. 157. 157. 157. 158. ORI13135
6 159. 159. 159. 157. 157. 157. ORI13136
7 159. 159. 159. 157. 157. 157. ORI13137
8 157/ ORI13138
BUNDLE PARAMETER (TC)-DESIGNATING WHICH SUBCHANNEL A TC SHOULD  

BE ASSOCIATED WITH. (I.E., 1-CENTRAL, 2-WALL, 3-CORNER)
DATA ISUBCH / 2. 2. 7*1. 2. 7*1. 3. 3. 1. 6*1. 1. ORI13139
1 9*1. 3. 1. 1. 6*1. 1. 4*1. 1. 1. 1. ORI13140
2 4*1. 2. 2. 1. 7*1. 2. 8*1. 1. 2. 2. ORI13141
3 2. 1. 1. 1. 2. 2. 5*1. 2. 2. 4*1. 1. 2. ORI13142
4 5*1. 2. 2*1. 1. 5*1. 1. 3. 2. 1. 1. 2. ORI13143
5 1. 2. 2. 2. 1. 2. 1. 3. 2. 5*1. 2. 2. ORI13144
6 4*1. 2. 2. 5*1. 2. 2*1. 2. 4*1. 2. 2. 2. ORI13145
7 1. 2. 2. 2. 2. 2. 2. 2. 2. 3. 2. ORI13146
8 2. 1. 1. 2. 3. 2. 5*1. 2. 4*1. 1. 2. 5*1. ORI13147
9 2. 2*1. 2. 5*1. 2. 3. 2. 2. 2. 1. 3. ORI13148
0 2. 7*1. 2. 9*1. 2. 3. 2. 3. 2. 2. 1. ORI13149
1 2. 1. 1. 2. 5*1. 2. 4*1. 2. 2. 5*1. 2. 2*1. ORI13150
2 2. 2*1. 3*1. 2. 2. 2. 2. 2. 2. 2. 3. ORI13151
3 2. 2*1. 3. 1. 1. 3. 1. 6*1. 2. 9*1. 3. 7*1. ORI13152
4 2. 2. 2. 1. 3. 1. 6*1. 2. 9*1. 3. 7*1. ORI13153
5 2. 2. 2. 2. 30*1. 2. 2. 2. 2. 10*1. 2. 2/ ORI13154

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C
C BREAK-DIRE CCDAS CHANNEL NUMBERS
C DATA ICHN01, ICHN02/142, 143/
C
C *****RELAP REF. VOLUMES (REFER TO RELAP TEST SECTION MODEL)---MODEL FOR
C *****TESTS 101 THROUGH 105 HAS 27 HEATER SLABS (SLABS 1-25, 44, AND 45),
C *****VOLUMES 7-15 REPRESENT CENTRAL CHANNELS, VOLUMES 16-24 REPRESENT
C *****ALL CHANNELS, VOLUMES 25-33 REPRESENT CORNER CHANNELS
C
C DATA IRVOL/ 7. 7. 8. 9. 10. 11. 11. 12. 12. 13.
1 13. 14. 15. 15. 15. 15. 15. 15. 15. 15.
2 22. 23. 24. 24. 24. 24. 24. 24. 24. 24.
4 25. 25. 26. 27. 28. 29. 29. 30. 30. 31.
5 31. 32. 33. 33. 33. 33. 33. 33. 33. 33.
C
C *****SLABS 1-9 REPRESENT SLABS FACING CENTRAL CHANNELS.
C *****SLABS 10-18 REPRESENT SLABS FACING WALL CHANNELS.
C *****SLABS 19-25, 44, 45 REPRESENT SLABS FACING CORNER CHANNELS
C DATA IRSLB/ 1. 1. 2. 3. 4. 5. 5. 6. 6.
1 7. 7. 8. 9. 9. 9. 9. 9. 9.
2 10. 10. 11. 12. 13. 14. 14. 15. 15.
3 16. 16. 17. 18. 18. 18. 18. 18. 18.
4 19. 19. 20. 21. 22. 22. 22. 23. 23.
5 24. 24. 25. 45. 45. 45. 45. 45. 45.
C
C *****LOGICAL VARIABLE FOR SLABS IN RELAP
C DATA SLAB/25*.TRUE., 18*.FALSE., 2*.TRUE., 5*.FALSE./
C *****AVERAGE (MEAN) AXIAL PEAKING FACTORS (PER T/C LEVEL)
C DATA PFAA/2.00, 4.2081, 0.59566, 1.04775, 1.29236, 3* 1.67942.
1 2* 1.29091, 2* 1.03735, 0.59143, 0.42068, 0.08/
END

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ORI13164
ORI13165
ORI13166
ORI13167
ORI13168
ORI13169
ORI13170
ORI13171
ORI13172
ORI13173
ORI13174
ORI13175
ORI13176
ORI13177
ORI13178
ORI13179
ORI13180
ORI13181
ORI13182
ORI13183
ORI13184
ORI13185
ORI13186
ORI13187
ORI13188
ORI13189
ORI13190
ORI13191
ORI13192
ORI13193
ORI13194
ORI13195

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APPENDIX D

ORINC SUBROUTINE LIST AND ORINC MAIN LOGIC

This section consists of one table and one figure. Table D-1 contains a list of all subroutines, subprograms, and multiple subroutine entry points in ORINC along with a brief description of their function in the code. Figure D-1 is a flowchart (with clarifying comments) of the logic in the main driving routine. The logic flow in Fig. D-1 may be subdivided into six distinct areas: program set-up, individual problem set-up, steady-state calculations, transient calculations, final individual problem output, and program wrap-up. Program set-up and wrap-up are once-through sections. The other four stages are nested inside a main control loop with each pass through the loop evaluating one thermocouple throughout a transient.

Table D-1. ORINC subroutines and subprograms

Subroutine name	Description and/or comments
RADI	Sets up r and $\bar{r}$ arrays [via Eqs. (II.11) and (II.12)], given the pin geometry (RHEAT) and number of nodes per substrate; also calculates Δr^2 for each substrate and sets up element nodding.
STEADY	Generates steady-state temperature profile in the pin given the power input (QDPI) and the sheath thermocouple response (TCS); also determines mode of heat transfer at the surface via a call to TSMIN
TSMIN	Determines mode of heat transfer based on minimum surface temperature (if nucleate boiling heat transfer coefficient is realistic, i.e., >0), then loads proper nodal temperatures, surface temperature, and heat transfer coefficient in the steady-state arrays
TRANS	Directs transient calculations: calculates radial heat generation for each node (loads Q array), calculates gap radiation heat-transfer coefficients, calls PROP which loads component physical properties, calls GAPTNS which calculates the sheath gap width, calls HEATR which loads the $\bar{H}_F$ matrix, calls BVECTR which loads the $\bar{B}_F$ vector, manipulates the forward matrices to form the $\bar{H}_I$ matrix [Eq. (II.63)] and the $\bar{B}_I$ vector [Eq. (II.70)], calls SOLVE which solves the system of equations, loads the $\bar{T}_I$ vector
HEATR	Loads the forward tridiagonal coefficient matrix $\bar{H}_F$ [Eq. (II.36)].
BVECTR	Loads the forward column vector of knowns $\bar{B}_F$ [Eq. (II.46)]
PROP	Determines pin component physical properties (i.e., density ρ , heat capacity Cp_1 , and thermal conductivity k_1) and loads the C , K , and $KGAP$ arrays
ENTHAL	Calculates total pin internal energy content given the pin radial temperature profile. (Summation of $\pi \Delta r^2 \rho_1 H_1$)
ENERGY	Calculates the change in pin internal energy content for the present integration step from the 'previous time' nodal temperatures and the 'present time' nodal temperatures. {Summation of $\pi \Delta r^2 \rho_1 Cp_1 [T_1(t+\Delta t) - T_1(t)]$ }

Table D-1. (Continued)

Subroutine name	Description and/or comments
GAP	Mathematical model of the thermo-mechanical behavior of the gap between the sheaths and the thermal transfer across the gap. Since the inside node temperature (TND5) is determined by the steady-state sheath thermocouple response, the solution of GAP(T) for GAP(TNS) = 0 (by subroutine FALSE) allows the calculation of the gap at the steady-state conditions just prior to blowdown
GAPTNS	Calculates the gap between the sheaths during the transient from the previous time nodal temperatures [i.e., T(NOD5) and T(NS)] using the linear thermo-mechanical gap model. (Appendix B, last section)
MNFLX0	Computes mean transient surface heat flux, surface temperature, and pin first node temperature for each heat slab in the RELAP core model for THTF bundle 1. A call to MNFLX0 initiates the summation routines
MNFLX1 (multiple entry point in MNFLX0)	Computes sums of the surface heat flux, surface temperature, and pin first node temperature for each heat slab for each transient time step
MNFLX2 (multiple entry point in MNFLX0)	Computes means of the surface heat flux, surface temperature, and pin first node temperature for each heat slab for each transient time step
	Writes mean arrays to tape (unit 13) and to paper (or microfiche).
SOLVE	Solves a system of n equations with n unknowns by obtaining the inverse of the coefficient matrix of the system (i.e., $\bar{H}_I^{-1}$ via a call to INVERT) and then solving for the unknown column vector $\bar{T}_I$ by Eqs. (II.75) and (II.76).
INVERT	Inverts a matrix in its own space using the Gauss-Jordan method as arranged by H. Rutishauser with full pivoting
FALSE	Given a function of x , $F(x)$, FALSE determines the value of x for which $F(x) = 0$ via the method of false position or <i>reguli falsi</i>
MAXMIN	Determines the maximum and minimum required for the plotting subroutine (PLOT)

Table D-1. (Continued)

Subroutine name	Description and/or comments
PLOT	The line plot routine (PLOT) plots y vs x on the normal computer output device (line printer or microfiche). The capability exists for overlaying (FX, FY) on (X, Y).
FINDS	This interpolation routine (any order) calculates the dependent variable value (FX0) given an (X, Y) table and the independent variable value (X0).
SCAN	Sets up the entry number arrays; i.e., given the CCDAS scan table (500 channels) SCAN determines the position (entry number) in the scan table for given channel numbers. The entry number arrays are 'indexes' or 'pointers'.
OUTPUT	Primary output subroutine with multiple entry points. Outputs pin and case information: thermocouple number, time, date, nodding, radial dimensions. (To the primary output device, unit 6, and to disk, file No. 1.)
OUTSS (multiple entry point in OUTPUT)	Outputs steady-state local operating conditions and steady-state pin temperature profile. (To the primary output device, unit 6, and to disk, file No. 1.)
OUTTNS (multiple entry point in OUTPUT)	Outputs results of transient (inverse) calculations to the normal computer output device (unit 6, line printer or microfiche).
OUTFNL (multiple entry point in OUTPUT)	Outputs results of the overall energy balance. (To the primary output device, unit 6, and to disk, file No. 1.)
OUTTAP (multiple entry point in OUTPUT)	Outputs results of transient (inverse) calculations to tape (file No. 1 of unit 9.)
DATE	Decodes CCDAS time code [JT(1)] into the month and date and outputs to unit 6.
INPUTO	Reads primary controls input (unit 5) and adjusts 'base case' channel arrays to account for failed instruments and/or additional instruments, also creates the NTC and NCHTCS arrays (arrays which contain the thermocouple numbers and CCDAS channel numbers for which inverse calculations are to be made).
INPTAP	Reads the RELAP-ORINC interface tape (unit 11) and transfers entire transient data to temporary storage on disk (direct access device), file No. 8. Also loads the RELAP steady-state arrays.

Table D-1. (Continued)

Subroutine name	Description and/or comments
INFSLB (multiple entry point in INPTRP)	Retrieves the number of slabs in the RELAP core model for output in MNFLX2.
INRELP (multiple entry point in INPTRP)	Retrieves RELAP predictions for volume pressure, volume temperature, volume average quality, slab surface heat flux, heat transfer coefficient, slab surface temperature, average volume mass flux, saturation temperature, and heat transfer mode at the slab surface from disk storage and loads the appropriate arrays for return to MAIN.
JPTBD	Reads the blowdown engineering units tape (unit 10), determines the initiation of blowdown, determines the steady-state conditions prior to blowdown (calculates the mean responses for approximately 15 sec before blowdown initiation), and transfers 30 sec of transient data to temporary storage on disk (direct access device) file No. 7.
INBD (multiple entry point in INPTBD)	Each call to INBD retrieves the following transient information from disk for the specified thermocouple (ITCNUM): the sheath thermocouple response, the middle thermocouple response (if any), rod amperage, and generator voltage. The linear heat rate is computed and loaded (QAVGG), the thermocouple responses are smoothed (via call to SMOOTH) and loaded (TCSS and TCMM).
SMOOTH	Three point smooths the Y array and returns the smoothed array in its own space. A 100.0 point discriminator (between time steps) is included.
CDT1	Reads the coefficient data tape (unit 12).
CDT (multiple entry point in CDT1)	Outputs the regression information for the specified thermocouple (ITCNUM) to disk (file No. 1) and the normal computer output device (unit 6, paper or microfiche).
BLOCK DATA	Initiates arrays and variables with information pertinent to THTF bundle 1 heaters, bundle 1 instrumentation, and the RELAP core model for bundle 1. Part one of the BLOCK DATA contains individual pin total heated lengths, initial pin nodding, pin radial dimensions (as a function of thermocouple level), and pin radial power peaking factors (as a function of thermocouple level).

Table D-1. (Continued)

Subroutine name	Description and/or comments
BLOCK DATA	<p>Part two of the BLOCK DATA contains the sheath thermocouple levels, groove numbers, the sheath thermocouple numbers and their corresponding CCDAS scan channel numbers, the middle thermocouple numbers and their corresponding CCDAS scan channel numbers, the individual rod shunt and voltage channels, the break-wire channel numbers, and a parameter which designates which subchannel flow the thermocouple is associated with.</p> <p>Part three of the BLOCK DATA contains information relative to the RELAP test section model for THTF blowdown tests 100 through 105: core reference volumes and slab numbers.</p>

Fig. D-1. Logic flow in ORINC Main.

SET-UP STAGE: set-up of primary I-O devices, input of main control parameters, read tape input, create temporary files on disk.

Problem Set-Up: start of main control loop, load all pertinent information for one thermocouple (ITCNUM): load coefficient arrays, load transient data, load RELAP interface data.

Main control loop, NK thermocouples are evaluated.

Thermocouple number to be evaluated for this pass; ITCNUM is a six digit number where

3 — designates bundle T/C
 — level number
 — groove number
 — rod number

Check to see if the thermocouple is good for the blowdown that is being evaluated.

Break ITCNUM down into rod number, groove number and level number.

The INVERSE calculations are not applicable for '0' level thermocouples.

Zero the interface gap array.

Search coefficient data tape
thermocouple number array
(NTCS) for ITCNUM

Load axial peaking factor.

Load thermal conductivity
coefficients for boron nitride.

Load thermal conductivity
coefficients for magnesium
oxide.

Load the porosity and the
method (KOD2) by which the k_{MgO}
is to be calculated.

Load regression coefficients
for linear gap expansion model.

Set up R and RBAR arrays and pin element nodding.

Load radial peaking factors given the level (ITCL).

Output information on pin nodding, radial dimensions and peaking factors

Load blowdown input arrays:
 TCSS - sheath T/C response;
 QAVGG - linear heat input rate;
 TCMM - middle T/C response, if any, otherwise zeros loaded;
 TIMEE - time in seconds from blowdown

Load RELAP interface input arrays:
 TIMR - time in seconds from blowdown;
 TBR - bulk fluid temperature;
 TSATR - saturation temperature;
 PRESSUR - volume pressure;
 QUALR - volume fluid quality;
 AMFR - average volume mass flux;
 HBR - heat transfer coefficient;
 SFLUXR - surface heat flux;
 TSURR - surface temperature;
 MODER - mode of heat transfer at surface
 TRPEND - time of last file on RELAP interface tape
 JRP - number of files on RELAP interface tape

STEADY-STATE: adjust Δgap_4 at steady state, if necessary; calculate steady-state pin temperature profile and heat transfer coefficient; calculate steady-state pin internal energy content; zero $\bar{B}_I$ and $\bar{H}_I$; set-up output scratch matrices; calculate $\bar{v}$; initialize transient counters.

Determine steady-state temperature profile in pin

Calculate steady-state surface temperature and surface heat flux.

Determine pin initial internal energy content (HINIT)

Zero $\bar{B}_I$ and $\bar{H}_I$

Initialize scratch output matrices:

- TIME (-)
- TO(I,-) — pin s.s. nodal temperatures
- HO(-) — heat transfer coefficient
- QO(-) — local linear heat input rate
- TBO(-) — fluid bulk averaged temperature (RELAP)
- PSO(-) — fluid volume pressure (RELAP)
- TSATO(-) — volume saturation temperature (RELAP)
- HSATO(-) — heat transfer coefficient based on difference between TSURO and TSATO
- AMFO(-) — average volume mass flux (RELAP)
- QUALO(-) — average volume quality (RELAP)
- RHBO(-) — heat transfer coefficient (RELAP)
- RSFXO(-) — surface heat flux (RELAP)
- RTSURO(-) — surface temperature (RELAP)
- MODEO(-) — heat transfer mode at the surface (RELAP)

Initialize lines counter at 18
(includes No. of lines for headings
for transient output)

Output the steady state local
operating conditions and pin
temperature profile and headings
for transient output.

Zero summations for change in
internal energy, heat input,
and surface heat flux.

TRANSIENT CALCULATIONS: solves the inverse heat conduction problem for every analysis interval; outputs inverse results to tape (file 1, unit 9) every analysis interval; outputs scratch matrices to unit 6 every 12 analysis intervals; computes sums of change in internal energy, heat input and surface heat flux.

Check on LINES:

if <68, print on same page as
the last call to OUTTNS;
if ≥68, skip to the top of
the next page and call OUTTNS.

Output the scratch matrices to unit 6.

Zero the scratch matrix counter.

Check on time step counter:

if FALSE, return to 38 and
start the next transient time
step calculation;
if TRUE, kick out of transient
loop

Output the scratch matrices to unit 6.

Zero the scratch matrix counter and initialize the line counter.

Check on time step counter - same as before

FINAL OUTPUT FOR ITCNUM: computes final pin internal energy content, computes error (by two methods) in overall heat balance, outputs heat balance calculations, checks for presence of middle thermocouple [if so, a line plot overlaying the calculated center line temperature (TCM) with the observed response (TCM) is made].

Check for presence of middle thermocouple —
if there is no corresponding middle T/C for ITCNUM, zeros were loaded in the TCM array

No. of data points in the TCM and TCM arrays

Check to see if time trip (IRP) is less than the number of RELAP files (JRP) which is always ≤ 601 (the number of blowdown files loaded on disk).

Plotting parameters for PLOT.

Determine the maximum and minimum values in the TCM and TCM arrays

No. of data points in the TCM and TCMM arrays. ITYPE specifies the type calculation required for the overlay plot in PLOT.

If interpolation is required for the overlay, the order of interpolation.

Produces line plot overlay of TCM and TCMM versus TIME on unit 6.

Loading VAR array.

Write VAR array to tape (file 1, unit 9) - denotes end of data for ITCNUM.

Wrap-up Stage: closes files on unit 9, retrieves case information from disk, computes mean fluxes.

APPENDIX E

Examples of ORINC Unit 6 Output

Example No.	Description	Page
1	THTF Blowdown Test 104 (Preliminary, BD104.BE.P1), Thermocouple No. TE-322AE	182
2	THTF Blowdown Test 104 (Preliminary, BD104.BE.P1), Thermocouple No. TE-318BG	203
3	THTF Blowdown Test 104 (Preliminary, BD104.BE.P1), Thermocouple No. TE-304CH	224
4	THTF Blowdown Test 104 (Preliminary, BD104.BE.P1), Thermocouple No. TE-301DJ	245

Example 1. THTF Blowdown Test 104 (Preliminary, BD104-BE.P1),
Thermocouple TE-322AE

322105*****CALCULATION INFORMATION*****

***** THTF BLOW-DOWN TEST NO.134-PREREIMINARY-BD104-BE.P1*

***** THERMOCOUPLE NO. 322-AE

***** MIDDLE T/C --- 322-ME

***** DATE OF LAST MODIFICATION : FEB. 17, 1977

***** AXIAL POWER PEAKING FACTOR IS : 1.2887
DETERMINED BY INDIV RESISTANCE CAL.

***** COEFFICIENTS FOR TEMPERATURE POLYNOMIAL FIT OF KBN
DETERMINED FOR THE ABOVE SPECIFIC T/C'S/ITCH PAIR

C(1)= 0.19285920E-02
C(2)= -0.64025931E-02
C(3)= 0.39877744E-04
C(4)= 0.43318349E-09

VARIANCE OF FIT= 0.20306700E-02
UNITS FOR KBN FIT : B²U/(HR*FT**2/FT*F)

***** COEFFICIENTS FOR TEMPERATURE POLYNOMIAL FIT FOR KNGO
DETERMINED FOR THE ABOVE SPECIFIC T/C PAIR

C(1)= 0.80919914E-01
C(2)= -0.11090219E-01
C(3)= 0.75405496E-05
C(4)= -0.23598382E-08
C(5)= 0.30801392E-12

VARIANCE OF FIT= 0.64749342E-02
UNITS FOR KNGO FIT : BTU/(HR*FT**2/FT*F)

ACTUAL KGO POROSITY CALCULATED VIA MODIFIED
RUSSELL EQUATION : 0.17787468E-00

***** COEFFICIENTS FOR THE THERMAL EXPANSION GAP MODEL FIT
DETERMINED BY USING THE BIAS GAP VALUE AS A MEAN GAP

C(1)= 0.0 SD= 0.0
C(2)= 0.0 SD= 0.0
C(3)= 0.0 SD= 0.0

VARIANCE OF FIT= 0.0

GAP CALCULATION AT THE BIAS POINT : 0.0341 (MILS)

BIAS TEMP. INSIDE S.S.S. NODAL TEMP. : 722.7 DEG. F
BIAS TEMP. OUTSIDE S.S.S. NODAL TEMP. : 657.7 DEG. F
BIAS FLUX : 404005.8 BTU/HR/FT**2

THE MAXIMUM TEMPERATURE FOR WHICH THE ABOVE
REGRESSION FIT IS APPLICABLE IS 0.0 DEG. F

322105***** CASE INFORMATION *****

***** THERMOCOUPLE NUMBER: TC-322AE TIME: 13:33:18 DATE: JULY 9

***** THTF BLOW-DOWN TEST NO.104*PRELIMINARY*BD104.BE.P1*

TOTAL NUMBER OF RADIAL NODES = 15
 MAGNESIUM OXIDE CORE NODES 1 THROUGH 4
 INCONEL-600 HEATER NODES 5 THROUGH 6
 BORON NITRIDE NODES 7 THROUGH 9
 INNER S.S.SHEATH NODES 10 THROUGH 12
 OUTER S.S.SHEATH NODES 13 THROUGH 15

OUTSIDE RADIUS OF MGO CORE = 0.872500E-02 FT.
 OUTSIDE RADIUS OF INCONEL LAYER = 0.101670E-01 FT.
 OUTSIDE RADIUS OF BORON NITRIDE = 0.143330E-01 FT.
 OUTSIDE RADIUS OF INNER S.S.SHEATH = 0.168330E-01 FT.
 OUTSIDE RADIUS OF OUTER S.S.SHEATH = 0.176670E-01 FT.

RADIAL GAP INFORMATION: (I.E. BIAS POINT)
 GAP BETWEEN INNER AND OUTER S.S.SHEATHS = 0.0341 MILS

POWER PEAKING FACTORS:
 AXIAL = 1.288719
 RADIAL (INCONEL) = 1.000000
 RADIAL (CU-NI) = 0.0

322105***** STEADY STATE TEMPERATURE PROFILE *****

***** THERMOCOUPLE NUMBER: TC-322AE TIME: 13:33:18 DATE: JULY 9

***** THTF BLOW-DOWN TEST NO.104*PRELIMINARY*BD104.BE.P1*

Q = AVERAGE HEAT GENERATION PER FT = 9.667375 BTU/SEC/FT
 J*AXIAL PEAKING FACTOR = 12.458530 B.U/SEC/FT
 HF = OUTSIDE FILM COEFFICIENT = 0.71955742E 04 BTU/(HR*FT**2*DEG F)
 TB = BULK COOLANT TEMPERATURE = 572.72 DEG F

PIN TEMPERATURE PROFILE:

NODE	TEMPERATURE (DEG F)
1	1024.73
2	1024.73
3	1024.73
4	1024.73
5	1024.73
6	1004.21
7	947.24
8	884.02
9	834.38
10	792.84
11	755.59
12	721.63
13	656.02
14	641.41
15	634.31

SURFACE HEAT FLUX= 0.40404250E 06 BTU/HR/FT**2
 SURFACE TEMPERATURE= 628.87 DEG F

PRESSURE= 2341.7 PSIA
 SATURATION TEMPERATURE (AT THE ABOVE PRESSURE)= 658.51 DEG F

HEAT TRANSFER MODE AT THE SURFACE OF THE PIN: FORCED CONVECTION

322105***** TRANSIENT RESULTS *****

***** THERMOCOUPLE NUMBER: TE-322AE TIME: 13133:18

***** TMTF BLOW-DOWN TEST NO.104*PRELIMINARY*BD104.BE.PI*

TIME-TEMPERATURE-NODE TABLE:

TIME HAS UNITS OF SEC
TEMPERATURE HAS UNITS OF DEG F
Q HAS UNITS OF BTU/SEC/FT
H0 (BASED ON T0) HAS UNITS OF BTU/(HR*FT**2*DEG F)
GULK TEMPERATURE HAS UNITS OF DEG F
HSAT (BASED ON TSAT) HAS UNITS OF BTU/(HR*FT**2*DEG F)
PRESSURE HAS UNITS OF PSIA
SATURATION TEMPERATURE HAS UNITS OF DEG F
SURFACE FLUX (S.F.) HAS UNITS OF BTU/HR/FT**2
SURFACE TEMPERATURE HAS UNITS OF DEG F
AVERAGE MASS FLUX HAS UNITS OF LBM/SEC/FT**2
GAP HAS UNITS OF MILS

TIME-- NODE	C.0	C.0500	C.1000	C.1500	C.2000	C.2500	C.3000	C.3500	C.4000	C.4500	C.5000	C.5500
1	1014.7349	1024.7334	1024.7319	1024.7302	1024.7290	1024.7288	1024.7307	1024.7380	1024.7617	1024.7761	1024.8127	1024.8686
2	1024.7349	1024.7334	1024.7317	1024.7307	1024.7329	1024.7427	1024.7666	1024.8142	1024.8914	1025.0739	1025.1538	1025.3420
3	1024.7349	1024.7358	1024.7341	1024.7361	1024.7542	1024.8030	1024.9048	1025.0708	1025.3118	1025.6206	1025.9932	1026.4143
4	1024.7349	1024.7478	1024.7358	1024.7520	1024.8271	1024.9919	1025.3000	1025.7366	1026.3062	1026.9441	1027.5583	1028.3730
5	1024.7349	1024.7732	1024.7263	1024.7817	1024.9558	1025.2820	1025.8562	1026.5671	1027.4417	1028.3042	1029.2807	1030.1030
6	1004.2126	1004.2432	1004.4019	1004.2708	1004.4661	1004.4918	1005.5554	1006.3669	1007.3391	1008.3700	1009.3583	1010.1279
7	947.2422	947.2456	947.2317	947.3276	947.6392	948.2207	949.0493	950.0488	951.1382	952.2748	953.2080	954.0544
8	884.0190	883.9954	884.0022	884.1870	884.7158	885.6299	886.7612	888.0469	889.3781	890.4866	891.4565	892.1775
9	834.3799	834.3240	834.3608	834.6868	835.5229	836.8508	838.3016	839.8699	841.2824	842.4824	843.3394	843.6621
10	792.8420	792.7412	792.8333	793.3740	794.6433	796.4946	798.2739	800.1384	801.8823	802.8230	803.4195	803.7354
11	755.5901	755.4163	755.6184	756.4990	758.4001	760.8277	763.0039	765.1846	766.8731	767.7764	768.0813	767.9780
12	721.6270	721.3367	721.7478	723.1387	725.9204	729.2376	731.9822	733.4841	735.0959	736.8080	738.3299	738.3740
13	656.8223	656.3140	657.8027	660.4319	665.7122	670.9878	672.9734	676.2637	678.1418	677.0755	674.9390	673.3293
14	645.4092	644.8140	646.4014	649.4444	655.2700	660.8848	662.7051	666.1758	666.7078	666.6399	664.0479	661.2576
15	634.3066	633.6101	635.2571	638.9099	645.3145	651.2556	652.7889	656.4870	658.5513	656.8298	653.4089	651.4878
Q	12.45853	12.46942	12.43228	12.46151	12.46151	12.46228	12.46151	12.45228	12.46018	12.44306	12.46018	12.44018
TR	572.7200	575.1226	593.9583	614.7683	629.6624	630.1345	628.5176	628.0981	627.3538	626.8413	626.8548	627.0005
HS	7195.6	7172.9	1101.3.7	19943.8	32598.7	20867.5	18596.1	14783.6	16149.5	14942.4	18403.0	21099.6
TSAT	658.5	629.7	629.3	629.0	629.0	629.1	628.5	628.1	627.4	626.8	626.7	626.7
HSAT	-13630.5	-25868.8	20204.4	78432.2	32598.7	20867.5	18596.1	14783.6	16149.5	14942.4	18403.0	21099.6
P	2341.7	1915.5	1910.0	1905.6	1914.9	1921.4	1899.4	1893.7	1884.2	1876.8	1874.3	1886.1
S.F.	404042.6	408700.7	396145.4	379637.2	354900.6	344487.1	361503.2	380544.1	374190.0	369918.6	395380.7	398584.3
S.TEMP	628.87	628.11	629.93	633.80	640.58	646.64	647.96	651.81	650.56	651.60	648.14	646.17
MASS-FLX	742.5525	32.8161	325.6885	573.3679	706.3606	739.2546	546.0664	384.0720	398.3825	454.0647	484.0647	373.0420
QUALITY	0.0	0.0	0.0	0.0	0.00973	0.07176	0.15023	0.21029	0.24214	0.26308	0.28040	0.28416
GAP	0.03410	0.03410	0.03410	0.03410	0.03410	0.03410	0.03410	0.03410	0.03410	0.03410	0.03410	0.03410
RELAP PREDICTIONS (STARRED)												
HR	655.7	2729.3	4107.2	40262.4	41325.2	41341.5	40687.7	8093.6	1621.6	1401.6	1442.9	1271.7
S.F.	412677.1	459763.8	422404.9	411720.9	423242.6	419295.1	423628.1	240073.1	9622.3	146372.9	172060.8	163427.4
S.TEMP	640.90	646.59	639.51	638.79	639.95	640.32	638.96	660.29	701.14	731.28	748.91	755.92
M.T.MODE	1	4	2	2	2	2	4	4	4	9	9	9

TIME--	17.8000	19.8500	19.9000	19.9500	20.0000
1	445.5242	445.4624	445.6058	445.3547	445.3088
2	445.2358	445.1975	445.1648	445.1379	445.1152
3	445.0002	444.9851	444.9780	444.9739	444.9724
4	444.8076	444.8237	444.8440	444.8606	444.8765
5	444.7122	444.7578	444.7944	444.8179	444.8420
6	444.6792	444.7402	444.7820	444.8054	444.8328
7	444.6553	444.7358	444.7786	444.7979	444.8296
8	444.6416	444.7607	444.7903	444.7971	444.8372
9	444.7063	444.8079	444.8074	444.7988	444.8547
10	444.8086	444.8811	444.8242	444.7981	444.8870
11	445.0208	444.9810	444.8210	444.7878	444.9507
12	445.3501	445.0596	444.7693	444.7693	445.0596
13	445.3699	445.0344	444.4832	444.7302	445.4558
14	445.5867	444.9800	444.4158	444.7327	445.5479
15	445.7905	444.8713	444.3311	444.7480	445.6663

	0.0	U.0	0.0	0.0	0.0
Q	495.3445	492.6504	490.0651	487.9845	485.4363
MS	177.0	-124.3	-75.9	23.2	127.2
TSAT	336.9	334.6	336.3	336.0	335.7
MSAT	-77.9	55.0	52.2	-9.1	-45.9
P	113.2	112.8	112.3	111.8	111.4
S.F.	-8873.6	5947.7	3477.5	-994.9	-5049.5
S.TEMP	445.92	444.78	444.28	444.76	445.74
MASS-PLX	11.71469	11.5469	11.4315	11.1058	10.9061
QUALITY	1.00000	1.00000	1.00000	1.00000	1.00000
GAP	0.03410	0.03410	0.03410	0.03410	0.03410

	0.0	U.0	0.0	0.0	0.0
RELAP PREDICTIONS (STARRED)					
MS	59.4	58.7	-17.7	56.9	56.3
S.F.	-3332.1	-3153.7	-2934.9	-2753.6	-2626.5
S.TEMP	439.22	439.24	439.26	439.27	439.28
M.T.MODE	8	8	8	8	8

322105***** ENERGY BALANCE *****

***** THERMOCOUPLE NUMBER: Tc-322AE TIME: 13133118 DATE: JULY 8

***** THTF BLOW-DOWN TEST NO.104*PRELIMINARY*BD104.BE.P1*

CHANGE IN PIN INTERNAL ENERGY CONTENT = 23.693939 BTU/PT
 DETERMINED BY SUMMATION OF DELTA U'S OVER THE INTERVAL FROM T=0 TO TEND.
 CHANGE IN PIN INTERNAL ENERGY CONTENT = 23.661026 BTU/PT
 DETERMINED BY DIFFERENCE IN PIN END POINT ENTHALPIES.
 TOTAL HEAT INPUT = INTEGRAL OF QTOT*DT = 24.281754 BTU/PT

INTEGRAL OF SURFACE FLUX VERSUS TIME CURVE *2.0*PI*RO= 47.954315 BTU/PT

PERCENTAGE ERROR IN OVERALL HEAT BALANCE = 0.0446 PERCENT
 ERROR IN OVERALL HEAT BALANCE (VIA METHOD 2)= 0.0241 PERCENT

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OVERLAY OF MIDDLE THERMOCOUPLE RESPONSE (ASTERISKS) VS ORINC-PREDIC

Y from 400.0 to 1100.0 as a function of X from 0.0 to 20.

Y interval size 5.6 and with X interval size 0.05. T

X axis has been shifted from 0.0 to Y = 400.0.

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OVERLAY OF MIDDLE THERMOCOUPLE RESPONSE (ASTERISKS) VS ORINC-PREDICTED RESPONSE (XS)

Y from 400.0 to 1100.0 as a function of X from 0.0 to 20.0 with

Y interval size 5.6 and with X interval size 0.05. The

X axis has been shifted from 0.0 to $Y = 400.0$.

3

Example 2. THTF Blowdown Test 104 (Preliminary, BD104.BE.P1),
Thermocouple TE-318BG

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318207***** CALIBRATION INFORMATION *****
***** THTF BLOW-DOWN TEST NO.104*PRELIMINARY*BD104.BE.P1*
***** THERMOCOUPLE NO. 318-BG
***** MIDDLE T/C --- 318-M
***** DATE OF LAST MODIFICATION : FEB. 17,1977
***** AXIAL POWER PEAKING FACTOR IS : 1.6659
      DETERMINED BY INDIV RESISTANCE CAL.
***** COEFFICIENTS FOR TEMPERATURE POLYNOMIAL FIT OF KBN
      DETERMINED FOR THE ABOVE SPECIFIC T/C'S/ITCM PAIR
      C(1)= 0.22228317E-02
      C(2)= -0.75014196E-02
      C(3)= 0.38024659E-07
      C(4)= 0.58936656E-09
      VARIANCE OF FIT= 0.14253893E-02
      UNITS FOR KBN FIT : BTU/(HR*FT**2/FT*F)
***** COEFFICIENTS FOR TEMPERATURE POLYNOMIAL FIT FOR KMGD
      DETERMINED FOR THE ABOVE SPECIFIC T/C PAIR
      C(1)= 0.72101888E-01
      C(2)= -0.10450133E-01
      C(3)= 0.79769643E-05
      C(4)= -0.29365270E-08
      C(5)= 0.45424298E-12
      VARIANCE OF FIT= 0.43312866E-03
      UNITS FOR KMGD FIT : BTU/(HR*FT**2/FT*F)
      ACTUAL MGD POROSITY CALCULATED VIA MODIFIED
      RUSSELL EQUATION : 0.18648702E 00
***** COEFFICIENTS FOR THE THERMAL EXPANSION GAP MODEL FIT
      DETERMINED FOR THE ABOVE HEATH T/C
      C(1)= 0.33019318E-02      SD= 0.98535599E-01
      C(2)= -0.34422360E-01      SD= 0.14225680E-01
      C(3)= 0.14774037E-04      SD= 0.70639717E-05
      VARIANCE OF FIT= 0.57968035E-04
      GAP CALCULATION AT THE BIAS POINT :          0.0553 (MILS)
      BIAS TEMP. INSIDE S.S.S. NODAL TEMP. :          817.2 DEG. F
      BIAS TEMP. OUTSIDE S.S.S. NODAL TEMP. :          701.4 DEG. F
      BIAS FLUX : 533145.6 BTU/HR/FT**2
      THE MAXIMUM TEMPERATURE FOR WHICH THE ABOVE
      REGRESSION FIT IS APPLICABLE IS 817.17 DEG. F

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310207***** CASE INFORMATION *****

***** THERMOCOUPLE NUMBER: TC-31886 TIME: 13:33:18 DATE: JULY 8

***** THTF BLOW-DOWN TEST NO.104*PRELIMINARY*BD104.BE.P1*

TOTAL NUMBER OF RADIAL NODES = 15
 MAGNESIUM OXIDE CORE NODES 1 THROUGH 4
 INCONEL-600 HEATER NODES 5 THROUGH 6
 BORON NITRIDE NODES 7 THROUGH 9
 INNER S.S.SHEATH NODES 10 THROUGH 12
 OUTER S.S.SHEATH NODES 13 THROUGH 15

OUTSIDE RADIUS OF MGO CORE = 0.906700E-02 FT.
 OUTSIDE RADIUS OF INCONEL LAYEN = 0.101670E-01 FT.
 OUTSIDE RADIUS OF BORON NITRIDE = 0.143330E-01 FT.
 OUTSIDE RADIUS OF INNER S.S.SHEATH = 0.168330E-01 FT.
 OUTSIDE RADIUS OF OUTER S.S.SHEATH = 0.176670E-01 FT.

RADIAL GAP INFORMATION: (I.E. DIAS POINT)
 GAP BETWEEN INNER AND OUTER S.S.SHEATHS = 0.0553 MILS

POWER PEAKING FACTORS:
 AXIAL = 1.665879
 RADIAL (INCONEL) = 1.009033
 RADIAL (CU-NI) = 0.0

310207***** STEADY STATE TEMPERATURE PROFILE *****

***** THERMOCOUPLE NUMBER: TC-31886 TIME: 13:33:18 DATE: JULY 8

***** THTF BLOW-DOWN TEST NO.104*PRELIMINARY*BD104.BE.P1*

Q = AVERAGE HEAT GENERATION PER FT = 9.877511 BTU/SEC/FT
 Q*AXIAL PEAKING FACTOR = 16.494727 BTU/SEC/FT
 HF = OUTSIDE FILM COEFFICIENT = 0.11408825E 06 BTU/(HR*FT**2*DEG F)
 TB = BULK COOLANT TEMPERATURE = 597.23 DEG F

PIN TEMPERATURE PROFILE:

NODE	TEMPERATURE (DEG F)
1	1180.47
2	1180.47
3	1180.47
4	1180.47
5	1180.47
6	1161.45
7	1095.88
8	1017.79
9	936.90
10	975.26
11	858.05
12	614.88
13	699.25
14	664.42
15	669.98

SURFACE HEAT FLUX= 0.53364325E 06 BTU/HR/FT**2
 SURFACE TEMPERATURE= 662.91 DEG F

PRESSURE= 2337.2 PSIA
 SATURATION TEMPERATURE (AT THE ABOVE PRESSURE)= 658.24 DEG F

HEAT TRANSFER MODE AT THE SURFACE OF THE PIN: NUCLEATE BOILING

318207***** TRANSIENT RESULTS *****

***** THERMOCOUPLE NUMBER: TC-31886 TIME: 13133118

***** THYF BLOW-DOWN TEST NO.104*PRECININARY*BD104.BE.PI*

TIME-TEMPERATURE-NODE TABLE

TIME HAS UNITS OF SEC
TEMPERATURE HAS UNITS OF DEG F
C HAS UNITS OF BTU/SEC/FT
HB (BASED ON TB) HAS UNITS OF BTU/(HR*FT**2*DEG F)
SULK TEMPERATURE HAS UNITS OF DEG F
HSAT (BASED ON TSAT) HAS UNITS OF BTU/(HR*FT**2*DEG F)
PRESSURE HAS UNITS OF PSIA
SATURATION TEMPERATURE HAS UNITS OF DEG F
SURFACE FLUX (S.F.) HAS UNITS OF BTU/HR/FT**2
SURFACE TEMPERATURE HAS UNITS OF DEG F
AVERAGE MASS FLUX HAS UNITS OF LBM/SEC/FT**2
GAP HAS UNITS OF MILS

TIME-- NODE	0.0	0.0500	0.1000	0.1500	0.2000	0.2500	0.3000	0.3500	0.4000	0.4500	0.5000	0.5500
1	1180.4722	1180.4697	1180.4668	1180.4636	1180.46	1180.4539	1180.4434	1180.4275	1180.4036	1180.3706	1180.3279	1180.2764
2	1180.4722	1180.4690	1180.4641	1180.4556	1180.4377	1180.4043	1180.3479	1180.2649	1180.1616	1180.0107	1179.8511	1179.6946
3	1180.4722	1180.4636	1180.4492	1180.4126	1180.3348	1180.1982	1179.9885	1179.7139	1179.3848	1179.0276	1178.7036	1178.5164
4	1180.4722	1180.4399	1180.3943	1180.2527	1179.9739	1179.8457	1178.9834	1178.3013	1177.6182	1177.0073	1176.7019	1177.0222
5	1180.4722	1180.3857	1180.3066	1179.9753	1179.4031	1178.6245	1177.6250	1176.7305	1176.8542	1176.2527	1175.4312	1176.9229
6	1161.4834	1161.3589	1161.2405	1160.9801	1160.2439	1159.3809	1158.3250	1157.3779	1156.4873	1155.9092	1156.2280	1158.0289
7	1095.9821	1095.7729	1095.5691	1095.1096	1094.3215	1093.2846	1092.1445	1091.1091	1090.2817	1089.7942	1090.8356	1093.1472
8	1017.7926	1017.6101	1017.4449	1016.8822	1015.4256	1014.0161	1012.8874	1011.7297	1011.0800	1010.9243	1012.7878	1017.3059
9	954.9648	954.5945	954.3322	953.0344	953.4790	951.6936	950.0037	949.4468	948.9571	949.4199	952.9144	959.9299
10	905.2871	904.7346	903.9187	902.8063	900.3860	898.1753	897.1616	896.1445	896.0945	897.2354	903.1316	913.4924
11	858.0600	857.1733	856.3161	854.0264	851.1328	848.4631	847.9485	846.9504	847.8530	849.7314	859.3567	874.2964
12	814.0777	813.4260	811.8704	809.1050	805.2339	802.1919	802.7449	801.6754	803.2979	806.8923	822.0879	842.7920
13	699.2451	695.5605	693.0342	687.5110	680.6467	677.6428	683.9348	679.9312	687.3076	694.6989	733.6238	771.6287
14	664.4226	660.2668	677.6167	671.8938	664.2161	661.2737	668.6172	664.0911	672.4844	680.8013	723.7019	764.2820
15	669.9849	668.2297	662.3073	658.8799	647.9480	645.2163	653.9377	648.8024	658.3301	667.3884	718.8166	758.5225
Q	16.44673	16.44675	16.44910	16.45723	16.45723	16.46910	16.44675	16.44910	16.45723	16.45723	16.45723	16.44673
TS	597.2317	603.8637	616.2478	626.9021	629.8120	630.8387	628.7839	628.3586	627.6916	627.2026	627.0391	627.6384
HB	114008.3	10362.8	14453.8	30652.8	60610.0	91538.1	29059.4	46461.7	21204.0	14325.8	2829.3	1255.2
TSAT	658.2	629.7	629.7	629.7	629.8	630.8	628.8	628.4	627.7	627.2	627.0	627.6
HSAT	114093.4	20042.3	22138.2	30652.8	60610.0	91538.1	29059.4	46461.7	21204.0	14325.8	2829.3	1255.2
P	2337.2	1916.3	1916.3	1904.6	1917.0	1904.6	1903.0	1897.2	1888.1	1881.6	1879.8	1887.5
S.F.	533643.3	561865.2	569955.8	587818.2	607079.4	591801.8	526197.3	579296.3	506307.2	483094.8	241878.4	161649.1
S-TEMP	662.91	657.78	655.04	648.07	639.84	637.30	646.89	640.77	651.66	660.92	712.32	786.42
MASS-FLX	742.655.8	10.7608	489.1338	809.7434	340.0901	412.7217	362.8401	290.1663	374.0044	429.6301	445.6406	480.2319
QUALITY	0.0	0.0	0.0	0.00003	0.04106	0.09500	0.16403	0.23122	0.23953	0.25893	0.26670	0.26128
GAP	0.05828	0.05828	0.05498	0.05493	0.05493	0.05399	0.05395	0.05474	0.05434	0.05613	0.05869	0.05900
RELAP PRECITONS (STARRD)												
QMB	64313.2	8637.5	48338.3	48930.9	47150.7	48086.2	12650.3	2987.2	1147.2	1319.2	1386.5	1242.2
S.F.	524929.9	188178.4	377192.5	562913.4	880866.1	507951.9	393252.4	237615.5	156606.4	21.795.0	247865.6	233632.3
S-TEMP	666.40	651.21	641.79	640.26	641.45	642.51	659.90	708.78	764.17	791.54	805.82	815.88
H.T.MODE	2	4	2	2	2	2	4	4	9	9	9	9

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[illegible][illegible]

[illegible][illegible]

TIME--	13.6000	13.8500	13.9000	13.9500	14.0000	14.0500	14.1000	14.1500	14.2000	14.2500	14.3000	14.3500
MODE	1	2	3	4	5	6	7	8	9	10	11	12
TS	530.3007	530.3318	530.3707	530.4134	530.4616	530.5150	530.5744	530.6391	530.7093	530.7850	530.8664	530.9530
HR	526.4744	526.5328	526.5905	526.6469	526.7031	526.7598	526.8160	526.8717	526.9278	526.9844	527.0415	527.0990
TSAT	526.4744	526.5328	526.5905	526.6469	526.7031	526.7598	526.8160	526.8717	526.9278	526.9844	527.0415	527.0990
MA	526.4744	526.5328	526.5905	526.6469	526.7031	526.7598	526.8160	526.8717	526.9278	526.9844	527.0415	527.0990
TEMP	526.4744	526.5328	526.5905	526.6469	526.7031	526.7598	526.8160	526.8717	526.9278	526.9844	527.0415	527.0990
QUALITY	526.4744	526.5328	526.5905	526.6469	526.7031	526.7598	526.8160	526.8717	526.9278	526.9844	527.0415	527.0990
RELAP	526.4744	526.5328	526.5905	526.6469	526.7031	526.7598	526.8160	526.8717	526.9278	526.9844	527.0415	527.0990
PREDICTIONS	526.4744	526.5328	526.5905	526.6469	526.7031	526.7598	526.8160	526.8717	526.9278	526.9844	527.0415	527.0990
CHART MODE	526.4744	526.5328	526.5905	526.6469	526.7031	526.7598	526.8160	526.8717	526.9278	526.9844	527.0415	527.0990

TIME--	14.4000	14.4500	14.5000	14.5500	14.6000	14.6500	14.7000	14.7500	14.8000	14.8500	14.9000	14.9500
MODE	1	2	3	4	5	6	7	8	9	10	11	12
TS	537.6000	537.6311	537.6622	537.6933	537.7244	537.7555	537.7866	537.8177	537.8488	537.8799	537.9110	537.9421
HR	537.6000	537.6311	537.6622	537.6933	537.7244	537.7555	537.7866	537.8177	537.8488	537.8799	537.9110	537.9421
TSAT	537.6000	537.6311	537.6622	537.6933	537.7244	537.7555	537.7866	537.8177	537.8488	537.8799	537.9110	537.9421
MA	537.6000	537.6311	537.6622	537.6933	537.7244	537.7555	537.7866	537.8177	537.8488	537.8799	537.9110	537.9421
TEMP	537.6000	537.6311	537.6622	537.6933	537.7244	537.7555	537.7866	537.8177	537.8488	537.8799	537.9110	537.9421
QUALITY	537.6000	537.6311	537.6622	537.6933	537.7244	537.7555	537.7866	537.8177	537.8488	537.8799	537.9110	537.9421
RELAP	537.6000	537.6311	537.6622	537.6933	537.7244	537.7555	537.7866	537.8177	537.8488	537.8799	537.9110	537.9421
PREDICTIONS	537.6000	537.6311	537.6622	537.6933	537.7244	537.7555	537.7866	537.8177	537.8488	537.8799	537.9110	537.9421
CHART MODE	537.6000	537.6311	537.6622	537.6933	537.7244	537.7555	537.7866	537.8177	537.8488	537.8799	537.9110	537.9421

[illegible]

TIME--	13.6000	13.6500	13.7000	13.7500	15.0000	15.9000	15.9500	16.0000	16.0500	16.1000	16.1500
ND0.	513.2690	512.0033	510.7273	509.4262	508.1167	506.8100	505.5128	504.2208	501.5237	500.1597	498.8729
1	508.9582	507.7272	506.4965	505.2617	504.0290	502.7943	501.5628	500.3308	499.0957	497.8607	496.6279
2	504.6473	503.4395	502.2360	501.0317	499.8235	498.6153	497.4071	496.1989	494.9907	493.7825	492.5743
3	499.3364	498.1437	496.9509	495.7582	494.5654	493.3727	492.1800	490.9873	489.7946	488.6019	487.4092
4	494.0255	492.8437	491.6619	490.4801	489.2983	488.1165	486.9347	485.7530	484.5712	483.3894	482.2076
5	488.7146	487.5437	486.3729	485.2021	484.0312	482.8604	481.6896	480.5188	479.3480	478.1772	477.0064
6	483.4037	482.2437	481.0838	479.9239	478.7640	477.6041	476.4442	475.2843	474.1244	472.9645	471.8046
7	478.0928	476.9437	475.7946	474.6455	473.4964	472.3473	471.1982	470.0491	468.9000	467.7509	466.6018
8	472.7819	471.6437	470.5055	469.3673	468.2291	467.0909	465.9527	464.8145	463.6763	462.5381	461.4000
9	467.4710	466.3437	465.2155	464.0873	462.9591	461.8309	460.7027	459.5745	458.4463	457.3181	456.1900
10	462.1601	461.0437	460.0055	458.8673	457.7291	456.5909	455.4527	454.3145	453.1763	452.0381	450.9000
11	456.8492	455.7437	454.6355	453.5273	452.4191	451.3109	450.2027	449.0945	447.9863	446.8781	445.7700
12	451.5383	450.4437	449.3455	448.2473	447.1491	446.0509	444.9527	443.8545	442.7563	441.6581	440.5600
13	446.2274	445.1437	444.0555	442.9673	441.8791	440.7909	439.7027	438.6145	437.5263	436.4381	435.3500
14	440.9165	440.0037	439.0955	438.1873	437.2791	436.3709	435.4627	434.5545	433.6463	432.7381	431.8300
15	435.6056	434.7037	433.8055	432.9073	432.0091	431.1109	430.2127	429.3145	428.4163	427.5181	426.6200
16	430.2947	429.4037	428.5155	427.6273	426.7391	425.8509	424.9627	424.0745	423.1863	422.2981	421.4100
17	424.9838	424.1037	423.2255	422.3473	421.4691	420.5909	419.7127	418.8345	417.9563	417.0781	416.2000
18	419.6729	418.8037	417.9355	417.0673	416.1991	415.3309	414.4627	413.5945	412.7263	411.8581	410.9900
19	414.3620	413.5037	412.6455	411.7873	410.9291	410.0709	409.2127	408.3545	407.4963	406.6381	405.7800
20	409.0511	408.2037	407.3555	406.5073	405.6591	404.8109	403.9627	403.1145	402.2663	401.4181	400.5700
21	403.7402	402.9037	402.0655	401.2273	400.3891	399.5509	398.7127	397.8745	397.0363	396.1981	395.3600
22	398.4293	397.6037	396.7755	395.9473	395.1191	394.2909	393.4627	392.6345	391.8063	390.9781	390.1500
23	393.1184	392.3037	391.4855	390.6673	389.8491	389.0309	388.2127	387.3945	386.5763	385.7581	384.9400
24	387.8075	387.0037	386.2055	385.4073	384.6091	383.8109	383.0127	382.2145	381.4163	380.6181	379.8200
25	382.4966	381.7037	380.9155	380.1173	379.3191	378.5209	377.7227	376.9245	376.1263	375.3281	374.5300
26	379.2177	378.4237	377.6255	376.8273	376.0291	375.2309	374.4327	373.6345	372.8363	372.0381	371.2400
27	375.9388	375.1437	374.3455	373.5473	372.7491	371.9509	371.1527	370.3545	369.5563	368.7581	367.9600
28	372.6599	371.8637	371.0655	370.2673	369.4691	368.6709	367.8727	367.0745	366.2763	365.4781	364.6800
29	369.3810	368.5837	367.7855	366.9873	366.1891	365.3909	364.5927	363.7945	362.9963	362.1981	361.4000
30	366.1021	365.3037	364.5055	363.7073	362.9091	362.1109	361.3127	360.5145	359.7163	358.9181	358.1200
31	362.8232	362.0237	361.2255	360.4273	359.6291	358.8309	358.0327	357.2345	356.4363	355.6381	354.8400
32	359.5443	358.7437	357.9455	357.1473	356.3491	355.5509	354.7527	353.9545	353.1563	352.3581	351.5600
33	356.2654	355.4637	354.6655	353.8673	353.0691	352.2709	351.4727	350.6745	349.8763	349.0781	348.2800
34	352.9865	352.1837	351.3855	350.5873	349.7891	348.9909	348.1927	347.3945	346.5963	345.7981	345.0000
35	349.7076	348.9037	348.1055	347.3073	346.5091	345.7109	344.9127	344.1145	343.3163	342.5181	341.7200
36	346.4287	345.6237	344.8255	344.0273	343.2291	342.4309	341.6327	340.8345	340.0363	339.2381	338.4400
37	343.1498	342.3437	341.5455	340.7473	339.9491	339.1509	338.3527	337.5545	336.7563	335.9581	335.1600
38	339.8709	339.0637	338.2655	337.4673	336.6691	335.8709	335.0727	334.2745	333.4763	332.6781	331.8800
39	336.5920	335.7837	334.9855	334.1873	333.3891	332.5909	331.7927	330.9945	330.1963	329.3981	328.6000
40	333.3131	332.5037	331.7055	330.9073	330.1091	329.3109	328.5127	327.7145	326.9163	326.1181	325.3200
41	330.0342	329.2237	328.4255	327.6273	326.8291	326.0309	325.2327	324.4345	323.6363	322.8381	322.0400
42	326.7553	325.9437	325.1455	324.3473	323.5491	322.7509	321.9527	321.1545	320.3563	319.5581	318.7600
43	323.4764	322.6637	321.8655	321.0673	320.2691	319.4709	318.6727	317.8745	317.0763	316.2781	315.4800
44	320.1975	319.3837	318.5855	317.7873	316.9891	316.1909	315.3927	314.5945	313.7963	312.9981	312.2000
45	316.9186	316.1037	315.3055	314.5073	313.7091	312.9109	312.1127	311.3145	310.5163	309.7181	308.9200
46	313.6397	312.8237	312.0255	311.2273	310.4291	309.6309	308.8327	308.0345	307.2363	306.4381	305.6400
47	310.3608	309.5437	308.7455	307.9473	307.1491	306.3509	305.5527	304.7545	303.9563	303.1581	302.3600
48	307.0819	306.2637	305.4655	304.6673	303.8691	303.0709	302.2727	301.4745	300.6763	299.8781	299.0800
49	303.8030	302.9837	302.1855	301.3873	300.5891	299.7909	298.9927	298.1945	297.3963	296.5981	295.8000
50	300.5241	299.7037	298.9055	298.1073	297.3091	296.5109	295.7127	294.9145	294.1163	293.3181	292.5200
51	297.2452	296.4237	295.6255	294.8273	294.0291	293.2309	292.4327	291.6345	290.8363	290.0381	289.2400
52	293.9663	293.1437	292.3455	291.5473	290.7491	289.9509	289.1527	288.3545	287.5563	286.7581	285.9600
53	290.6874	289.8637	289.0655	288.2673	287.4691	286.6709	285.8727	285.0745	284.2763	283.4781	282.6800
54	287.4085	286.5837	285.7855	284.9873	284.1891	283.3909	282.5927	281.7945	280.9963	280.1981	279.4000
55	284.1296	283.3037	282.5055	281.7073	280.9091	280.1109	279.3127	278.5145	277.7163	276.9181	276.1200
56	280.8507	280.0237	279.2255	278.4273	277.6291	276.8309	276.0327	275.2345	274.4363	273.6381	272.8400
57	277.5718	276.7437	275.9455	275.1473	274.3491	273.5509	272.7527	271.9545	271.1563	270.3581	269.5600
58	274.2929	273.4637	272.6655	271.8673	271.0691	270.2709	269.4727	268.6745	267.8763	267.0781	266.2800
59	271.0140	270.1837	269.3855	268.5873	267.7891	266.9909	266.1927	265.3945	264.5963	263.7981	263.0000
60	267.7351	266.9037	266.1055	265.3073	264.5091	263.7109	262.9127	262.1145	261.3163	260.5181	259.7200
61	264.4562	263.6237	262.8255	262.0273	261.2291	260.4309	259.6327	258.8345	258.0363	257.2381	256.4400
62	261.1773	260.3437	259.5455	258.7473	257.9491	257.1509	256.3527	255.5545	254.7563	253.9581	253.1600
63	257.8984	257.0637	256.2655	255.4673	254.6691	253.8709	253.0727	252.2745	251.4763	250.6781	249.8800
64	254.6195	253.7837	252.9855	252.1873	251.3891	250.5909	249.7927	248.9945	248.1963	247.3981	246.6000
65	251.3406	250.5037	249.7055	248.9073	248.1091	247.3109	246.5127	245.7145	244.9163	244.1181	243.3200
66	248.0617	247.2237	246.4255	245.6273	244.8291	244.0309	243.2327	242.4345	241.6363	240.8381	240.0400
67	244.7828	243.9437	243.1455	242.3473	241.5491	240.7509	239.9527	239.1545	238.3563	237.5581	236.7600
68	241.5039	240.6637	239.8655	239.0673	238.2691	237.4709	236.6727	235.8745	235.0763	234.2781	233.4800
69	238.2250	237.3837	236.5855	235.7873	234.9891	234.1909	233.3927	232.5945	231.7963	230.9981	230.2000
70	234.9461	234.1037	233.3055	232.5073	231.7091	230.9109	230.1127	229.3145	228.5163	227.7181	226.9200
71	231.6672	230.8237	230.0255	229.2273	228.4291	227.6309	226.8327	226.0345	225.2363	224.4381	223.6400
72	228.3883	227.5437	226.7455	225.9473	225.1491	224.3509	223.5527	222.7545	221.9563	221.1581	220.3600
73	225.1094	224.2637	223.4655	222.6673	221.8691	221.0709	220.2727	219.4745	218.6763	217.8781	217.0800
74	221.8305	220.9837	220.1855	219.3873	218.5891	217.7909	216.9927	216.1945	215.3963	214.5981	213.8000
75	218.5516	217.7037	216.9055	216.1073	215.3091	214.5109	213.7127	212.9145	212.1163	211.3181	210.5200
76	215.2727	214.4237	213.6255	212.8273	212.0291	211.2309	210.4327	209.6345	208.8363	208.0381	207.2400
77	212.0000	211.1437	210.3455	209.5473	208.7491	207.9509	207.1527	206.3545	205.5563	204.7581	203.9600
78	208.7211	207.8637	207.0655	206.2673	205.4691	204.6709	203.8727	203.0745	202.2763	201.4781	200.6800
79	205.4422	204.5837	203.7855	202.9873	202.1891	201.39					

TIME--	18.6000	18.6500	18.7000	18.7500	18.8000	18.8500	18.9000	18.9500	19.0000	19.0500	19.1000	19.1500
MODE												
1	444.5803	443.8782	443.2102	442.5791	441.9834	441.4219	440.8933	440.3972	439.9319	439.4961	439.0876	438.7044
2	440.6421	440.1199	439.6431	439.2080	438.8059	438.4312	438.0811	437.7548	437.4583	437.1807	436.9194	436.6733
3	437.1733	436.8611	436.5821	436.3743	436.1670	435.9607	435.7546	435.5487	435.3430	435.1377	434.9327	434.7280
4	434.2004	434.1449	434.1267	434.0923	434.0168	433.9338	433.8672	433.8428	433.8301	433.7900	433.7207	433.6463
5	432.7488	432.8889	432.9958	433.0396	432.9946	432.9619	432.9461	432.9408	432.9391	432.9018	432.8234	432.7183
6	432.3282	432.5325	432.6733	432.7317	432.6846	432.6477	432.6120	432.5892	432.5684	432.5196	432.5498	432.6030
7	431.8574	432.1826	432.3227	432.3845	432.3186	432.2552	432.1926	432.1649	432.1689	432.1653	432.1278	432.1396
8	431.4707	431.8601	432.0227	432.0587	431.9389	431.8041	431.6641	431.5077	431.3274	431.1290	430.9261	430.7175
9	431.2744	431.7190	431.8220	431.8003	431.6982	431.5724	431.4247	431.2547	431.0642	430.8528	430.6201	430.3660
10	431.2410	431.6819	431.6348	431.5234	431.3833	431.2197	431.0347	430.8278	430.6003	430.3528	430.0857	429.7980
11	431.5496	431.7939	431.6138	431.4836	431.3172	431.1167	430.8934	430.6489	430.3857	430.1069	429.8144	429.5088
12	432.2634	431.9722	431.6079	431.1866	430.7286	430.2344	429.7064	429.1484	428.5644	427.9582	427.3339	426.6944
13	436.5876	432.2705	429.0682	426.2178	422.6794	418.3572	413.2764	407.4484	400.9764	422.5754	430.4048	438.6048
14	437.0840	432.1370	428.7756	425.0703	420.2742	414.3872	407.4184	400.3644	428.9343	427.2039	430.8328	438.2080
15	437.6448	431.8301	428.3830	423.9390	418.7793	412.8257	406.0188	436.3381	428.2337	427.2039	430.8328	438.2080
Q	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TD	535.2744	534.4780	533.4182	533.7588	531.5793	530.7544	531.3875	533.3864	536.4270	540.5242	544.0708	548.0857
MB	218.1	-167.1	-172.3	-34.8	-189.8	335.0	-46.1	224.2	-207.4	-119.4	70.7	247.1
TSAT	339.6	339.2	338.8	338.3	337.8	337.4	336.9	336.5	336.0	335.5	335.0	334.5
MSAT	-212.7	186.1	203.2	40.3	229.8	-330.6	48.3	-217.1	355.1	148.2	-85.9	-266.6
P	117.1	117.1	116.1	115.4	114.6	113.8	113.0	112.3	111.6	110.9	110.2	109.5
S.F.	-20934.0	17197.2	18149.9	364.7	20137.8	-32170.5	4584.7	-21747.2	32307.9	13582.4	-8154.4	-26094.5
S.TEMP	437.95	431.88	428.09	428.89	428.48	424.73	431.95	436.66	427.78	427.00	430.65	436.60
MASS-FLX	18.1481	17.7063	17.3787	16.9473	16.5292	13.9495	12.6426	11.2865	9.7994	7.9891	6.9834	7.6048
QUALITY	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
GAP	0.06918	0.06933	0.06840	0.06783	0.06793	0.06793	0.06793	0.06842	0.06894	0.06978	0.06982	0.06815
RELAP PREDICTIONS (STARRED)	85	83	80.8	77.7	73.4	68.7	63.6	58.5	52.0	43.9	39.3	41.8
*S.F.	21842.9	21352.9	20580.1	19736.7	18768.3	17792.4	16826.2	14833.3	13063.2	10851.9	9517.2	10132.5
*S.TEMP	789.64	788.78	788.12	787.65	787.30	787.06	786.96	787.80	787.17	787.49	787.82	788.05
*H.T.MODE	8	8	8	8	8	8	8	8	8	8	8	8

TIME--	19.2000	19.2500	19.3000	19.3500	19.4000	19.4500	19.5000	19.5500	19.6000	19.6500	19.7000	19.7500
MODE												
1	438.3459	438.0107	437.6978	437.4063	437.1360	436.8845	436.6521	436.4375	436.2380	436.0527	435.8799	435.7185
2	436.4451	436.2354	436.0432	435.8674	435.7061	435.5603	435.4272	435.3044	435.1882	435.0779	434.9707	434.8687
3	434.8945	434.7979	434.7129	434.6367	434.5718	434.5173	434.4670	434.4185	434.3613	434.3030	434.2388	434.1667
4	433.6569	433.6731	433.6807	433.6885	433.7041	433.7292	433.7407	433.7388	433.7186	433.6870	433.6404	433.5762
5	433.0974	433.1787	433.2231	433.2622	433.2866	433.2956	433.2841	433.2538	433.2082	433.1514	433.0847	433.0077
6	432.9402	433.0422	433.0928	433.1414	433.1856	433.2252	433.2592	433.2847	433.3002	433.2967	433.2733	433.2363
7	432.7771	432.9006	432.9492	432.9990	433.0457	433.0894	433.1231	433.1477	433.1614	433.1592	433.1481	433.1287
8	432.6548	432.7644	432.8108	432.8538	432.8938	432.9307	432.9644	432.9949	433.0214	433.0439	433.0624	433.0767
9	432.5392	432.7405	432.7224	432.8196	432.8227	432.8204	432.8128	432.8001	432.7823	432.7593	432.7319	432.6999
10	432.7085	432.7095	432.6145	432.7654	432.8510	432.9162	432.9618	432.9888	432.9968	432.9854	432.9549	432.9100
11	432.9673	432.6750	432.4636	432.7588	433.1799	433.1343	432.8615	432.4933	432.6996	432.8245	432.9679	433.0717
12	433.4282	432.8544	432.2632	432.8455	433.4282	433.1370	432.6147	432.1849	432.2632	432.8488	433.0717	433.0717
13	435.9385	431.2048	431.2722	433.7566	434.8936	432.8337	431.0128	432.9924	430.5981	433.5315	433.6675	431.0408
14	436.2043	430.9011	431.1804	433.8368	436.0752	432.7283	430.8479	433.0767	430.3496	433.7063	429.3269	431.0020
15	436.4839	430.4143	431.1018	434.2097	436.2917	432.8413	430.8136	433.2380	430.0110	433.9973	428.8191	431.0251
Q	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TD	543.5596	541.2883	538.9490	536.2090	534.3076	531.3525	528.0176	520.7659	517.7937	516.2859	515.1072	512.1047
MB	89.9	-210.8	-126.6	-85.3	-66.0	-46.1	-26.7	97.2	-171.6	175.9	-268.0	42.3
TSAT	336.3	336.6	336.9	337.2	337.5	337.8	338.1	338.4	338.7	339.0	339.3	339.6
MSAT	-25.8	250.9	19.0	-131.8	-86.9	100.8	119.0	-89.4	164.9	-150.0	253.7	-36.5
P	112.4	112.9	113.3	113.7	114.2	114.6	115.0	115.4	115.8	116.2	116.6	117.0
S.F.	-9655.3	23442.5	1793.0	-12807.2	-8809.2	9507.4	11063.4	-8492.3	18098.8	-14438.6	23047.2	-3424.0
S.TEMP	436.63	430.07	431.08	434.10	435.42	436.40	437.46	438.46	439.49	440.51	441.51	442.51
MASS-FLX	8.1899	8.8222	9.4042	10.0625	10.6948	11.0623	11.9427	11.9234	12.4748	12.1896	12.0271	11.9819
QUALITY	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
GAP	0.06895	0.06892	0.06801	0.06868	0.06854	0.06854	0.06825	0.06799	0.06817	0.06793	0.06789	0.06778
RELAP PREDICTIONS (STARRED)	44.7	47.5	49.9	53.0	54.9	57.1	58.6	60.2	63.2	61.5	61.0	60.6
*S.F.	10907.7	11691.8	12387.4	13283.7	13814.3	14507.0	15143.8	15834.3	16779.5	16378.1	16291.0	16322.0
*S.TEMP	787.91	787.60	787.20	786.71	786.13	785.60	784.98	784.30	783.55	782.94	782.42	781.92
*H.T.MODE	8	8	8	8	8	8	8	8	8	8	8	8

1

OVERLAY OF MIDDLE THERMOCOUPLE RESPONSE (ASTERISKS)

Y from 400.0 to 1300.0 as a function of X

Y interval size 7.2 and with X interval

X axis has been shifted from 0.0 to

2

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OVERLAY OF MIDDLE THERMOCOUPLE RESPONSE (ASTERISKS) VS ORINC-PREDICTED RESPONSE (XS)

Y from 400.0 to 1300.0 as a function of X from 0.0 to 20.0 with
Y interval size 7.2 and with X interval size 0.05. The
X axis has been shifted from 0.0 to Y = 400.0.

304308***** CASE INFORMATION *****

***** THERMOCOUPLE NUMBER: TC-304CH TIME: 13:33:18 DATE: JULY 8

***** THTF BLOW-DOWN TEST NO.104*PRELIMINARY*BD104.BE.PI*

TOTAL NUMBER OF RADIAL NODES = 15
 MAGNESIUM OXIDE CORE NODES 1 THROUGH 4
 INCONEL-600 HEATER NODES 5 THROUGH 6
 BORON NITRIDE NODES 7 THROUGH 9
 INNER S.S.SHEATH NODES 10 THROUGH 12
 OUTER S.S.SHEATH NODES 13 THROUGH 15

OUTSIDE RADIUS OF NGO CORE = 0.90670E-02 FT.
 OUTSIDE RADIUS OF INCONEL LAYER = 0.891670E-01 FT.
 OUTSIDE RADIUS OF BORON NITRIDE = 0.143330E-01 FT.
 OUTSIDE RADIUS OF INNER S.S.SHEATH = 0.168330E-01 FT.
 OUTSIDE RADIUS OF OUTER S.S.SHEATH = 0.176670E-01 FT.

RADIAL GAP INFORMATION: (I.E. DIAS POINT)
 GAP BETWEEN INNER AND OUTER S.S.SHEATHS = 0.0826 MILS

POWER PEAKING FACTORS:
 AXIAL = 1.681979
 RADIAL (INCONEL) = 1.000000
 RADIAL (CU-NI) = 0.0

304308***** STEADY STATE TEMPERATURE PROFILE *****

***** THERMOCOUPLE NUMBER: TC-304CH TIME: 13:33:18 DATE: JULY 8

***** THTF BLOW-DOWN TEST NO.104*PRELIMINARY*BD104.BE.PI*

Q = AVERAGE HEAT GENERATION PER FT = 9.790415 BTU/SEC/FT
 Q*AXIAL PEAKING FACTOR = 18.467270 BTU/SEC/FT
 HF = OUTSIDE FILM COEFFICIENT = 0.10324196E 03 BTU/(HR*FT**2*DEG F)
 TB = BULK COOLANT TEMPERATURE = 619.45 DEG F

PIN TEMPERATURE PROFILE:

NODE	TEMPERATURE (D.G F)
1	1229.66
2	1229.66
3	1229.66
4	1229.66
5	1229.66
6	1211.32
7	1142.37
8	1050.90
9	997.21
10	945.42
11	898.09
12	856.36
13	819.47
14	784.64
15	670.19

SURFACE HEAT FLUX = 0.53405006E 06 BTU/HR/FT**2
 SURFACE TEMPERATURE = 663.11 DEG F

PRESSURE = 2332.5 PSIA
 SATURATION TEMPERATURE (AT THE ABOVE PRESSURE) = 657.94 DEG F

HEAT TRANSFER MODE AT THE SURFACE OF THE PIN: NUCLEATE BOILING

304308***** TRANSIENT RESULTS *****

***** THERMOCOUPLE NUMBER: TE-304CH TIME: 13:33:18

***** TMTP BLCG-DOWN TEST NO.104*PRELIMINARY*BD104.BE.P1*

TIME-TEMPERATURE-NODE TABLE:
 TIME HAS UNITS OF SEC
 TEMPERATURE HAS UNITS OF DEG F
 Q HAS UNITS OF BTU/SEC/FT
 MB (BASED ON TB) HAS UNITS OF BTU/(HR*FT**2*DEG F)
 BULK TEMPERATURE HAS UNITS OF DEG F
 MSAT (BASED ON TSAT) HAS UNITS OF BTU/(HR*FT**2*DEG F)
 PRESSURE HAS UNITS OF PSIA
 SATURATION TEMPERATURE HAS UNITS OF DEG F
 SURFACE FLUX (S.F.) HAS UNITS OF BTU/HR/FT**2
 SURFACE TEMPERATURE HAS UNITS OF DEG F
 AVERAGE MASS FLUX HAS UNITS OF LBM/SEC/FT**2
 GAP HAS UNITS OF MILS

TIME--	0.0	0.0500	0.1000	0.1500	0.2000	0.2500	0.3000	0.3500	0.4000	0.4500	0.5000	0.5500
NODE												
1	1220.6633	1220.6614	1220.6592	1220.6570	1220.6543	1220.6492	1220.6409	1220.6270	1220.6089	1220.5818	1220.5480	1220.4983
2	1220.6633	1220.6606	1220.6570	1220.6504	1220.6377	1220.6128	1220.5691	1220.4998	1220.4048	1220.2813	1220.1279	1220.9480
3	1220.6633	1220.6597	1220.6499	1220.6248	1220.5842	1220.4814	1220.2788	1220.0437	1220.7466	1220.4021	1220.0212	1220.6108
4	1220.6633	1220.6521	1220.6187	1220.5178	1220.2859	1220.9033	1220.4048	1227.8079	1227.1338	1226.4824	1225.7712	1225.0920
5	1220.6633	1220.6337	1220.5574	1220.3169	1220.8069	1220.0787	1227.2606	1226.3611	1225.4131	1224.6847	1223.7834	1222.9993
6	1211.0220	1210.9929	1210.9028	1210.6279	1210.0532	1209.2524	1208.3853	1207.4485	1205.4695	1205.6160	1204.8101	1204.0093
7	1142.3672	1142.3359	1142.2139	1141.8433	1141.1064	1140.1641	1139.2280	1138.2766	1137.2991	1136.4448	1135.7024	1134.9050
8	1050.8962	1050.8467	1050.6360	1050.0103	1047.8999	1046.6992	1045.7112	1044.7939	1043.7889	1043.0203	1042.4312	1041.6211
9	997.2068	997.1211	996.7783	995.8135	994.2087	992.7949	991.8633	990.9114	989.9448	989.3274	988.9197	988.0022
10	943.4236	943.2815	944.7410	943.2734	941.0313	939.4653	938.7041	937.7288	936.7285	936.3330	936.1174	934.9297
11	898.8909	898.6526	897.0069	895.5845	892.4902	890.9453	890.5525	889.4636	888.4077	888.3540	888.3835	885.6370
12	856.3579	855.9654	854.0685	851.3562	847.2188	846.1155	846.3914	845.0117	843.9082	844.4602	844.7361	841.9741
13	699.4697	698.6663	694.7378	685.1206	675.7334	678.9028	683.2642	679.3518	678.1472	682.6116	683.7590	674.1560
14	684.6375	683.7292	679.4216	669.0084	659.1299	663.1580	667.9819	663.5203	662.4048	667.4424	668.8608	667.9277
15	670.1899	669.1377	664.3552	652.9504	642.6062	647.9502	653.2434	647.9465	647.0293	652.8430	653.7996	641.7610
Q	16.46727	16.46417	16.46417	16.46417	16.46417	16.46417	16.46417	16.45212	16.44008	16.45212	16.44008	16.44008
MB	619.4834	617.2334	627.7915	628.5891	630.0339	631.0908	628.9185	628.5107	627.31	627.8344	627.4136	627.7139
TSAT	103291.6	12089.6	19337.4	37212.9	144078.2	57846.4	31020.4	49368.4	48.3.6	28895.7	26207.1	102856.1
MSAT	657.9	637.5	629.6	628.6	630.0	631.1	628.9	628.3	627.9	627.5	627.4	627.7
P	103294.6	17211.4	20619.0	37212.9	144078.2	57846.4	31020.4	49368.4	48818.6	28899.7	26207.1	102856.1
S.F.	2332.5	1927.1	1914.2	1900.3	1920.0	1934.4	1904.8	1899.3	1891.2	1886.1	1884.5	1888.5
S.TEMP	534080.1	560848.9	562708.5	606653.3	619684.0	549300.4	533299.1	578415.4	564571.9	527447.6	540493.7	609025.8
MASS-FLX	663.11	661.97	666.99	644.39	640.59	640.11	640.23	639.48	638.75	648.58	646.58	633.64
QUALITY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GAP	0.08264	0.08264	0.08264	0.08264	0.08264	0.08264	0.08264	0.08264	0.08264	0.08264	0.08264	0.08264
REL AP	PRECISIONS (STARRED)											
MB	55751.2	21067.4	42793.8	41513.4	41525.3	42255.0	40086.4	11939.6	3400.7	2329.5	2562.0	3238.8
S.F.	397408.0	273401.4	434857.1	438704.7	424706.7	428882.7	429040.4	330527.2	206076.4	202946.8	251507.6	316586.3
S.TEMP	665.07	643.65	640.22	639.03	640.12	641.30	639.66	656.27	668.49	714.66	725.59	728.34
M.T.MODE	2	4	2	2	2	2	4	4	4	4	4	4

[illegible][illegible]

[illegible][illegible]

[illegible][illegible]


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TIME--
1 19.8000 19.8500 19.9000 19.9500 20.0000
2 417.0149 416.4707 415.9290 415.3916 414.8623
3 412.5530 414.0042 413.4781 412.9626 422.4883
4 409.0438 409.5148 408.9709 408.4240 407.8749
5 408.1247 407.6707 407.2118 406.7550 406.2988
6 407.6300 407.1086 406.6003 406.0917 405.5855
7 406.6071 406.4417 405.1953 405.3760 405.5633
8 405.9668 405.7097 405.3527 404.9923 404.5398
9 405.1726 404.9709 404.7645 404.5597 404.3503
10 404.7323 404.5142 404.2982 404.0829 403.8684
11 404.1249 403.9082 403.6928 403.4789 403.2656
12 394.7739 403.5580 403.3431 399.4451 396.5243
13 394.1780 403.7550 400.5337 399.1343 396.0989
14 393.5662 404.4412 399.7211 398.7808 395.4739
15
0 0.0 0.0 0.0 0.0 0.0
DB 137.021 336.9872 J16.3779 336.2458 336.8661
MA 172.2 310.4 304.4 304.4 304.4
TSA 373.2 -320.1 240.4 208.2 409.0
P 113.6 113.2 112.7 112.2 111.8
S.F. 20874.8 -35409.4 16841.4 12607.6 24243.8
S.TEMP 393.27 404.97 399.64 398.60 398.11
MASS-FLX 11.7312 11.5424 11.3165 11.0851 10.8944
QUALITY 0.9837 0.9838 0.9838 0.9840 0.9792
GASRELAP PRODUCTIONS 151682014 0.9826 0.9824 0.9792 0.9826
END 462.0 338.1 600.1 746.0 806.8
S.S.F. 43604.2 46386.9 56128.2 59899.6 61222.5
S.S.TEMP 472.02 426.85 421.57 416.55 411.93
S.H.T.MODE

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304308***** ENERGY BALANCE *****
***** THERMOCOUPLE NUMBER: TC-304CH TIME: 1313318 DATE: JULY 8
***** THP BLOW-DOWN TEST NO.1049PRELIMINARYRD104.BE.F18
CHANGE IN PIN INTERNAL ENERGY CONTENT = 35.376093 BTU/FT
DETERMINED BY SUMMATION OF DELTA U'S OVER THE INTERVAL FROM T=0 TO TEND.
CHANGE IN PIN INTERNAL ENERGY CONTENT = 35.340485 BTU/FT
OBTAINED BY DIFFERENCE IN PIN END POINT ENTHALPIES.
TOTAL HEAT INPUT + INTEGRAL OF JDTOTDT = 32.080856 BTU/FT
INTEGRAL OF SURFACE FLUX VERSUS TIME CURVE #2.0491#RD= 07.438065 BTU/FT
PERCENTAGE ERROR IN OVERALL HEAT BALANCE = 0.0260 PERCENT
ERROR IN OVERALL HEAT BALANCE (VIA METHOD 2) = 0.0248 PERCENT

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OVERLAY OF MIDDLE THERMOCOUPLE RESPONSE (ASTERISKS) VS ORINC-PREDICTED RESPO

Y from 400.0 to 1250.0 as a function of X from 0.0 to 20.0 with
Y interval size 6.8 and with X interval size 0.05. The
X axis has been shifted from 0.0 to Y = 400.0.

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OF MIDDLE THERMOCOUPLE RESPONSE (ASTERISKS) VS ORINC-PREDICTED RESPONSE (XS)

Y from 400.0 to 1250.0 as a function of X from 0.0 to 20.0 with

Y interval size 6.8 and with X interval size 0.05. The

X axis has been shifted from 0.0 to $Y = 400.0$.

Example 4. THTF Blowdown Test 104 (Preliminary, BD104.BE.r1),
Thermocouple TE-301DJ

301410***** CALIBRATION INFORMATION *****

***** THTF BLOW-DOWN TEST NO.104*PRELIMINARY*BD104.BE.P1*

***** THERMOCOUPLE NO. 301-DJ

***** MIDDLE T/C --- 301-MJ

***** DATE OF LAST MODIFICATION : FEB. 17,1977

***** AXIAL POWER PEAKING FACTOR IS : 1.3012
DETERMINED BY INDIV RESISTANCE CAL.

***** COEFFICIENTS FOR TEMPERATURE POLYNOMIAL FIT OF KBN
DETERMINED FOR THE ABOVE SPECIFIC T/C PAIR
C(1)= 0.20661514E-02
C(2)= -0.70098327E-02
C(3)= 0.11629254E-05
C(4)= -0.10709340E-09

VARIANCE OF FIT= 0.10591008E-02
UNITS FOR KBN FIT : BTU/(HR*FT**2/FT**2)

***** COEFFICIENTS FOR TEMPERATURE POLYNOMIAL FIT FOR KMGD
DETERMINED FOR THE ABOVE SPECIFIC T/C PAIR
C(1)= 0.77045890E-01
C(2)= -0.99152625E-02
C(3)= 0.79940228E-05
C(4)= -0.28400076E-08
C(5)= 0.37483886E-12

VARIANCE OF FIT= 0.23220004E-02
UNITS FOR KMGD FIT : BTU/(HR*FT**2/FT**2)

ACTUAL KGD POROSITY CALCULATED VIA MODIFIED
RUSSELL EQUATION : 0.10666609E 00

***** COEFFICIENTS FOR THE THERMAL EXPANSION GAP MODEL FIT
DETERMINED BY USING THE BIAS GAP VALUE AS A MEAN GAP

C(1)= 0.0 SD= 0.0
C(2)= 0.0 SD= 0.0
C(3)= 0.0 SD= 0.0

VARIANCE OF FIT= 0.0

GAP CALCULATION AT THE BIAS POINT : 0.0449 (MILS)

BIAS TEMP. INSIDE S.S.S. NODAL TEMP. : 769.5 DEG. F
BIAS TEMP. OUTSIDE S.S.S. NODAL TEMP. : 691.9 DEG. F
BIAS FLUX : 409625.6 BTU/HR/FT**2

THE MAXIMUM TEMPERATURE FOR WHICH THE ABOVE
REGRESSION FIT IS APPLICABLE IS 0.0 DEG. F

301410***** CASE INFORMATION *****

***** THERMOCOUPLE NUMBER: Tc-3010J TIME: 13133:18 DATE: JULY 8

***** THTF BLOW-DOWN TEST NO.104*PRELIMINARY*BD104.RE.P1*

TOTAL NUMBER OF RADIAL NODES = 15
 MAGNESIUM OXIDE CORE NODES 1 THROUGH 4
 INCONEL-600 HEATER NODES 5 THROUGH 6
 BORON NITRIDE NODES 7 THROUGH 9
 INNER S.S.SHEATH NODES 10 THROUGH 12
 OUTER S.S.SHEATH NODES 13 THROUGH 15

CUTSIDE RADIUS OF NGO CORE = 0.872500E-02 FT.
 OUTSIDE RADIUS OF INCONEL LAYER = 0.101670E-01 FT.
 CUTSIDE RADIUS OF BORON NITRIDE = 0.143330E-01 FT.
 CUTSIDE RADIUS OF INNER S.S.SHEATH = 0.168330E-01 FT.
 CUTSIDE RADIUS OF OUTER S.S.SHEATH = 0.176670E-01 FT.

RADIAL GAP INFORMATION: (I.E. GAPS CENT)
 GAP BETWEEN INNER AND OUTER S.S.SHEATHS = 0.0449 MILS

POWER PEAKING FACTORS:
 AXIAL = 1.301200
 RADIAL (INCONEL) = 1.000000
 RADIAL (CU-NI) = 0.0

301410***** STEADY STATE TEMPERATURE PROFILE *****

***** THERMOCOUPLE NUMBER: Tc-3010J TIME: 13133:18 DATE: JULY 8

***** THTF BLOW-DOWN TEST NO.104*PRELIMINARY*BD104.RE.P1*

Q = AVERAGE HEAT GENERATION PER FT = 9.707630 BTU/SEC/FT
 Q*AXIAL PEAKING FACTOR = 12.631567 BTU/SEC/FT
 HF = OUTSIDE FILM COEFFICIENT = 0.92599000E 05 BTU/(HR*FT**2*DEG F)
 TB = BULK COOLANT TEMPERATURE = 615.79 DEG F

PIN TEMPERATURE PROFILE:

NODE	TEMPERATURE (DEG F)
1	1062.53
2	1062.53
3	1062.53
4	1062.53
5	1062.53
6	1062.07
7	986.91
8	926.52
9	879.10
10	836.59
11	801.48
12	767.67
13	690.19
14	678.78
15	667.68

SURFACE HEAT FLUX= 0.40965431E 06 BTU/HR/FT**2
 SURFACE TEMPERATURE= 662.25 DEG F

PRESSURE= 2330.6 PSIA.
 SATURATION TEMPERATURE (AT THE ABOVE PRESSURE)= 657.82 DEG F

HEAT TRANSFER MODE AT THE SURFACE OF THE PIN: NUCLEATE BOILING

301413***** TRANSIENT RESULTS *****

***** THERMOCOUPLE NUMBER: TC-301DJ TIME: 13:33:16

***** THTF BLOW-DOWN TEST NO.134-PRELIMINARY-BD104.BE.P1*

TIME-TEMPERATURE-NODE TABLE:

TIME HAS UNITS OF SEC
TEMPERATURE HAS UNITS OF DEG F
Q HAS UNITS OF BTU/SEC/FT
MO (BASED ON TB) HAS UNITS OF BTU/(HR*FT**2*DEG F)
BULK TEMPERATURE HAS UNITS OF DEG F
MSAT (BASED ON TSAT) HAS UNITS OF BTU/(HR*FT**2*DEG F)
PRESSURE HAS UNITS OF PSIA
SATURATION TEMPERATURE HAS UNITS OF DEG F
SURFACE FLUX (S.F.) HAS UNITS OF BTU/HR/FT**2
SURFACE TEMPERATURE HAS UNITS OF DEG F
AVERAGE MASS FLUX HAS UNITS OF LBW/SEC/FT**2
GAP HAS UNITS OF MILS

TIME--	0.0	0.0500	0.1000	0.1500	0.2000	0.2500	0.3000	0.3500	0.4000	0.4500	0.5000	0.5500
NOOF												
1	1062.5305	1062.5291	1062.5271	1062.5226	1062.5144	1062.4976	1062.4663	1062.4167	1062.3440	1062.2441	1062.1145	1061.9546
2	1062.5305	1062.5283	1062.5229	1062.5063	1062.4680	1062.3940	1062.2747	1062.1025	1061.8757	1061.8569	1061.2717	1060.9265
3	1062.5305	1062.5286	1062.5105	1062.4521	1062.3245	1062.1064	1061.7905	1061.3813	1060.8594	1060.3601	1059.7837	1059.1824
4	1062.5305	1062.5288	1062.5080	1062.2937	1061.9856	1061.4397	1060.7744	1060.0039	1059.1524	1058.3525	1057.6278	1056.7156
5	1062.5305	1062.5303	1062.5031	1062.0579	1061.4663	1060.6469	1059.6866	1058.6538	1057.6565	1056.6582	1055.7385	1054.8469
6	1062.0693	1062.0601	1061.8896	1061.4749	1060.7663	1059.8228	1058.7478	1057.6292	1056.5686	1055.6320	1054.8223	1053.8663
7	986.9063	986.8716	986.8318	986.0508	985.1228	983.9578	982.7190	981.4905	980.3633	979.3174	978.3511	977.6285
8	926.5181	926.4385	926.3220	925.0908	923.7459	922.2493	920.8132	919.4697	918.3606	917.3633	916.4363	915.5400
9	879.0958	878.9467	878.7634	876.8621	875.0588	873.2231	871.6680	870.3164	869.2412	868.3535	867.4790	866.6196
10	838.5859	838.3367	837.2419	835.1946	832.8369	830.6829	829.0886	827.7563	826.8411	826.0430	825.3124	824.3750
11	801.4849	801.0576	799.3176	796.3564	793.3594	790.9426	789.4612	788.2087	787.0381	786.2647	786.0532	785.2212
12	767.6709	766.9600	764.2471	760.0864	756.4800	753.9824	752.8721	751.7620	751.4844	750.9292	750.0942	749.7634
13	690.1936	688.5740	682.2771	674.2495	669.3936	667.3147	667.9316	667.1753	666.3386	667.9100	666.8352	665.9766
14	678.7808	674.9367	669.9478	661.2896	656.3658	654.4580	655.4321	654.6863	656.1355	658.6711	654.8398	653.6870
15	667.6794	668.5568	657.7134	648.3789	643.5146	641.8767	643.3027	642.5783	644.3101	643.7488	642.8378	641.7007
Q	12.63683	12.63683	12.62883	12.62883	12.62883	12.62883	12.62883	12.62883	12.63683	12.62883	12.63683	12.63683
TB	615.7903	615.7354	621.2067	625.4888	629.0378	630.6062	628.7576	627.9943	628.2141	627.9553	627.8069	627.6421
MB	92599.0	9556.7	15174.1	29635.3	58848.8	90896.8	51133.1	52254.6	41572.8	43892.4	49825.7	53688.6
TSAT	657.8	632.7	629.4	628.6	630.3	630.6	628.8	628.0	628.2	628.0	627.8	627.6
MSAT	92601.8	18503.5	20766.9	34616.3	69851.4	90896.8	51133.1	52254.6	41572.8	43892.8	49825.7	53688.6
P	2330.6	1956.7	1911.4	1900.4	1924.0	1927.8	1902.6	1892.3	1895.3	1891.8	1889.8	1887.6
S.F.	409654.3	422650.9	461023.9	486355.6	476750.1	461874.0	441209.9	445988.3	429683.8	436538.2	440134.9	438893.0
S.TEMP	662.25	659.95	651.59	641.90	637.14	638.68	637.39	636.83	638.85	637.90	636.64	635.82
MASS-FLX	626.8466	36.8512	398.8416	433.6838	494.1956	532.3049	537.3252	223.8468	366.0630	389.6218	371.1694	376.3526
QUALITY	0.0	0.0	0.0	0.0	0.0	0.00313	0.01818	0.03200	0.08199	0.05977	0.05977	0.05977
CAP	0.04486	0.04486	0.04486	0.04486	0.04486	0.04486	0.04486	0.04486	0.04486	0.04486	0.04486	0.04486
RELAP PREDICTIONS (STARRED)												
MSD	50465.3	47880.0	39513.8	38241.4	38172.1	38309.5	37892.3	37484.8	37204.9	37107.2	36937.4	36541.3
MS.F.	326025.1	547768.5	389383.5	371200.3	356340.5	363170.7	361169.8	354231.1	354360.1	352198.3	346532.6	346532.6
MS.TEMP	664.29	644.09	639.26	638.29	639.65	639.65	638.35	637.65	637.74	637.51	637.35	637.05
MS.T.MODE	2	4	2	2	2	2	2	2	2	2	2	2

TIME--	3.0000	3.0500	3.1000	3.1500	3.2000	3.2500	3.3000	3.3500	3.4000	3.4500	3.5000	3.5500
MODE												
1	925.8947	917.0825	938.2722	899.6347	890.8884	882.2610	873.7568	865.3884	857.0781	848.8283	840.6070	833.0313
2	871.1121	862.9459	854.1458	845.9175	837.8645	829.9905	822.2957	814.7808	807.4438	800.2842	793.2993	786.4866
3	817.9832	810.1577	802.3767	795.2368	788.1321	781.2542	774.5933	768.1418	761.8867	755.8201	749.9333	744.2217
4	767.7009	760.9168	754.6226	748.1881	742.2097	736.4705	730.9497	725.6226	720.4873	715.5349	710.7388	706.1846
5	738.7488	732.6731	726.8977	721.4065	716.1863	711.1284	706.3074	701.6736	697.1963	692.8770	688.7186	684.7017
6	728.4426	722.9904	717.9049	713.1811	708.8037	704.6093	697.4175	693.0081	688.7390	684.6296	680.6788	676.8472
7	715.0361	709.5708	704.4280	699.5808	694.9011	690.4539	686.1965	682.1038	678.1336	674.3193	670.6823	667.1338
8	698.6783	694.0713	689.4827	685.1504	681.0602	677.1736	673.1841	669.4702	665.8869	662.4304	659.1290	655.8744
9	684.4853	680.1213	676.0847	672.2632	668.4956	664.9486	661.5308	658.2188	654.9363	651.6840	648.4698	645.2787
10	669.6794	665.9844	662.5254	659.2339	656.0474	652.7812	649.7378	646.7886	643.8503	641.1003	638.4773	635.8863
11	653.9067	650.9976	648.1628	645.5031	642.9687	639.7944	637.1880	634.6039	631.8789	629.0360	627.3818	625.8734
12	638.5237	636.8713	634.3274	632.0835	629.2781	627.3137	625.0679	622.8216	620.2839	618.6064	616.6418	614.9958
13	620.8811	619.5908	618.5471	617.4973	616.8310	616.4889	616.2544	616.0332	615.8085	615.6461	615.5085	615.4023
14	598.1318	596.6602	595.7185	594.8398	594.1394	592.5378	590.9817	589.4287	587.3613	585.7079	584.4812	583.4123
15	589.8010	591.9287	590.9988	590.2927	587.4949	588.3706	586.7830	585.5481	583.2613	584.2460	582.7742	582.8284
Q	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TS	576.2515	575.3848	574.5394	573.7432	572.9653	572.1458	571.3369	570.5227	569.7004	568.8770	568.0493	567.2164
MS	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8
TSAT	576.3	576.3	576.3	576.3	576.3	576.3	576.3	576.3	576.3	576.3	576.3	576.3
MSAT	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8	1753.8
P	1288.3	1288.3	1288.3	1288.3	1288.3	1288.3	1288.3	1288.3	1288.3	1288.3	1288.3	1288.3
S.F.	19158.9	186175.9	189800.9	183171.2	189191.4	147413.7	151816.6	148786.2	148985.1	128811.1	133758.7	124033.6
S.TEMP	587.18	589.68	588.68	588.04	588.18	588.36	588.70	588.53	588.22	588.48	588.94	589.02
MASS-PLX	17.1503	17.9860	18.0568	18.4391	17.3824	16.4341	15.8409	14.2844	12.9174	11.4923	9.7931	8.0324
QUALITY	0.00468	0.00431	0.01071	0.01837	0.01984	0.02332	0.02712	0.03153	0.03674	0.04288	0.04803	0.04802
GAP	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488
RELAP PREDICTIONS (STARRED)=**												
MS	181.3	186.0	186.7	191.8	184.3	175.4	168.0	157.4	148.4	132.8	117.7	101.2
TS.F.	492.9846	490.1207	487.3071	484.8889	482.3364	479.8895	477.5164	475.2463	473.0334	470.8984	468.8032	466.8418
S.TEMP	849.44	848.33	847.01	845.57	844.41	843.49	843.12	842.76	842.48	842.22	842.00	841.82
M.T.MODE	9	9	9	9	9	9	9	9	9	9	9	9

TIME--	3.6000	3.6500	3.7000	3.7500	3.8000	3.8500	3.9000	3.9500	4.0000	4.0500	4.1000	4.1500
MODE												
1	825.3025	817.7266	810.3076	803.0474	795.9500	789.0166	782.2480	775.6467	769.2100	762.9390	756.8318	750.8879
2	779.8450	773.3718	767.0720	760.9387	754.9719	749.1682	743.5259	738.0405	732.7087	727.5269	722.4824	717.6021
3	738.6812	733.3113	728.1049	723.0728	718.1919	713.4609	708.8735	704.4258	700.1111	695.9272	691.8677	687.9294
4	701.6311	697.3232	693.1770	689.1797	685.3157	681.5769	677.9592	674.4578	671.0671	667.7832	664.5967	661.5129
5	680.8487	677.1563	673.6228	670.2224	666.9294	663.7458	660.6680	657.6951	654.8171	652.0322	649.3857	646.7168
6	673.2202	669.7429	666.4211	663.2227	660.1211	657.1252	654.2310	651.4399	648.7378	646.1243	643.5828	641.1409
7	663.7786	660.5933	657.5898	654.6366	651.7781	649.0300	646.3740	643.8213	641.3485	638.9517	636.6187	634.3328
8	652.9846	650.1207	647.3071	644.5889	642.3364	639.8895	637.5164	635.2463	633.0334	630.8984	628.8032	626.8418
9	643.4336	640.9912	638.6470	636.3164	634.0082	631.8223	629.7078	627.6958	625.7122	623.8079	621.9158	620.2073
10	633.7319	631.6777	629.6631	627.8896	626.5020	624.6147	623.1781	621.7817	620.4066	618.2419	616.8713	615.4804
11	623.4180	621.8125	620.1292	618.2837	616.4104	614.8708	613.2885	611.8125	610.2832	608.8458	607.3179	606.2712
12	613.6500	612.4258	611.0198	609.3325	607.6443	606.5195	605.1128	603.9871	602.8798	601.4536	600.0480	599.4829
13	599.5317	599.7285	598.7771	597.2585	595.9929	594.9217	593.5138	592.4188	591.4958	590.3484	589.0664	588.2190
14	586.1431	586.5420	585.6145	584.0996	582.9048	581.3796	580.2634	579.2329	578.9690	578.4899	577.9450	577.8815
15	582.8606	583.4670	582.3168	580.9870	579.8699	580.6411	579.4839	579.6331	578.3118	578.3792	578.6641	578.8674
Q	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TS	566.4119	565.6638	564.4936	564.1140	563.3396	562.8571	561.7720	560.9827	560.1497	559.3933	558.9216	558.2634
MS	7841.8	6656.9	6919.2	7348.2	7266.3	6743.6	6195.0	5297.6	4714.0	4919.3	4202.7	4972.7
TSAT	565.4	565.7	564.9	564.1	563.3	562.6	561.8	561.0	560.2	559.4	558.7	558.1
MSAT	7641.6	6656.9	6919.2	7348.2	7266.3	6743.6	6195.0	5297.6	4714.0	4919.3	4202.7	4972.7
P	1192.7	1185.6	1178.4	1171.2	1164.0	1156.8	1149.5	1142.3	1135.1	1127.9	1121.4	1114.0
S.F.	116430.4	107474.0	111348.5	112904.6	109182.7	96083.2	100921.7	92083.0	99085.3	87467.1	91671.8	78618.9
S.TEMP	581.24	581.97	580.99	579.44	578.32	578.06	578.06	578.36	578.99	577.17	575.70	577.87
MASS-PLX	6.9102	6.5887	6.0666	5.9022	5.8235	5.7460	5.7399	5.7099	5.7177	5.7386	5.8546	5.3903
QUALITY	0.06256	0.06727	0.07180	0.07594	0.07997	0.08394	0.08786	0.09178	0.09568	0.09964	1.00000	1.00000
GAP	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488	0.04488
RELAP PREDICTIONS (STARRED)=**												
MS	87.3	84.6	79.0	76.6	75.9	75.0	74.8	74.6	74.6	74.8	73.9	86.0
TS.F.	24300.0	23646.6	22167.7	21593.6	21489.4	21250.3	21254.0	21251.3	21268.3	21360.7	21007.2	15796.0
S.TEMP	844.84	843.39	843.79	846.07	846.15	846.11	845.98	845.76	845.98	845.17	844.86	848.04
M.T.MODE	9	9	9	9	9	9	9	9	9	9	9	9

[illegible][illegible]


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TIME--
1 19.0000 19.0000 19.0000 19.0000 19.0000 20.0000
2 10.4150 10.4150 10.4150 10.4150 10.4150 10.4150
3 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150
4 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150
5 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150
6 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150
7 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150
8 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150
9 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150
10 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150
11 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150
12 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150
13 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150
14 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150
15 40.4150 40.4150 40.4150 40.4150 40.4150 40.4150

T0 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
T1 376.000 376.000 376.000 376.000 376.000 376.000
T2 376.000 376.000 376.000 376.000 376.000 376.000
T3 376.000 376.000 376.000 376.000 376.000 376.000
T4 376.000 376.000 376.000 376.000 376.000 376.000
T5 376.000 376.000 376.000 376.000 376.000 376.000
T6 376.000 376.000 376.000 376.000 376.000 376.000
T7 376.000 376.000 376.000 376.000 376.000 376.000
T8 376.000 376.000 376.000 376.000 376.000 376.000
T9 376.000 376.000 376.000 376.000 376.000 376.000
T10 376.000 376.000 376.000 376.000 376.000 376.000
T11 376.000 376.000 376.000 376.000 376.000 376.000
T12 376.000 376.000 376.000 376.000 376.000 376.000
T13 376.000 376.000 376.000 376.000 376.000 376.000
T14 376.000 376.000 376.000 376.000 376.000 376.000
T15 376.000 376.000 376.000 376.000 376.000 376.000

S.F. 250.00 250.00 250.00 250.00 250.00 250.00
S.TEMP 400.00 400.00 400.00 400.00 400.00 400.00
S.DELTA 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000
QUALITY 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
GAC 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
RELAP PREDICTIONS
S.F. 53.1 53.1 53.1 53.1 53.1 53.1
S.TEMP 809.5 809.5 809.5 809.5 809.5 809.5
S.DELTA 540.80 540.80 540.80 540.80 540.80 540.80
M.Y.MODE

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***** ENERGY BALANCE *****
***** THERMOCOUPLE NUMBER: T2-3010J TIME: 1313110 DATE: JULY 8 *****
***** THTP BLOW-DOWN TEST NO.104-PRELIMINARY8D104-8E.P1 *****
CHANGE IN PIN INTERNAL ENERGY CONTENT = 20.11425 BTU/PT
CHANGE IN PIN INTERNAL ENERGY CONTENT U.S. STANDARD FROM T=0 TO TEND.
CHANGE IN PIN INTERNAL ENERGY CONTENT = 20.11425 BTU/PT
CHANGE IN PIN INTERNAL ENERGY CONTENT = 20.11425 BTU/PT
TOTAL HEAT INPUT = INTEGRAL OF Q(T)DT = 20.21078 BTU/PT
INTEGRAL OF SURFACE FLUX VERSUS TIME CURVE = 2.00100 = 92.718078 BTU/PT
PERCENTAGE ERROR IN OVERALL HEAT BALANCE = 0.0348 PERCENT
ERROR IN OVERALL HEAT BALANCE (VIA METHOD 2) = 0.0058 PERCENT

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1

OVERLAY OF MIDDLE THERMOCOUPLE RESPONSE (ASTE

Y from 400.0 to 1100.0 as a function

Y interval size 5.6 and with X

X axis has been shifted from

2

OVERLAY OF MIDDLE THERMOCOUPLE RESPONSE (ASTERISKS) VS ORINC-PREDICTED RESPONSE (XS)

Y from 400.0 to 1100.0 as a function of X from 0.0 to 20.0 with
Y interval size 5.6 and with X interval size 0.05. The
X axis has been shifted from 0.0 to $Y = 400.0$.