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LUCAS HEIGHTS RESEARCH LABORATORIES

AN IMPROVED THERMAL MODEL FOR THE
COMPUTER CODE NAIAD

by

M.T. RAINBOW *

*CSIRO Division of Mineral Physics

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ABSTRACT

An improved thermal model, based on the concept of heat slabs, has been incorporated as an option into the thermal hydraulic computer code NAIAD. The heat slabs are one-dimensional thermal conduction models with temperature independent thermal properties which may be internal and/or external to the fluid. Thermal energy may be added to or removed from the fluid via heat slabs and passed across the external boundary of external heat slabs at a rate which is a linear function of the external surface temperatures. The code input for the new option has been restructured to simplify data preparation. A full description of current input requirements is presented.

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COMPRESSIBLE FLOW; COMPUTER CALCULATIONS; FINITE DIFFERENCE METHOD; FLOW MODELS; HEAT TRANSFER; N CODES; STEADY-STATE CONDITIONS; TRANSIENTS; TWO-PHASE FLOW

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1. INTRODUCTION

The NAIAD code [Trimble and Turner 1974] is a computer program for the calculation of steady state and transient behaviour of compressible two-phase fluid in networks. Originally the code was developed for the analysis of two-phase water flow (including loss-of-coolant accident (LOCA)) in nuclear reactor cooling systems. However, the structure of the code is such that it is relatively simple to apply it more generally to problems of fluid flow in networks. This was demonstrated quite recently by Turner [1981] who applied the code very successfully to a large natural gas reticulation network.

Numerous improvements have been made to the hydraulic section of the code over recent years. However, the fuel model, which describes the addition or removal of thermal energy to or from the hydraulic fluid, has remained in its original simple form. A single thermal node fuel or pipe wall model is coupled to each hydraulic node and the flow of thermal energy is restricted to passage between such a node and the fluid.

An improved thermal model, based on the concept of heat slabs, has been incorporated into NAIAD. The main features of this model are as follows:

- (i) The heat slabs are one-dimensional thermal conduction models with temperature-independent thermal properties.
- (ii) The heat slab models have been formulated in cylindrical geometry. However, since the wetted perimeters of heat slabs may be specified independently of the radial dimensions, rectangular geometry may be simulated in some situations.
- (iii) The boundary condition at heat slab surfaces in contact with the hydraulic fluid is the convective heat transfer equation:

$$q_s = -k \left. \frac{\partial T}{\partial r} \right|_s = h(T_s - T_c)$$

where q is the heat flux, k is the thermal conductivity, T is the temperature, r is the radial distance, h is a heat transfer coefficient, subscript s denotes the heat slab surface, and subscript c denotes the hydraulic fluid (coolant).

- (iv) Associated with each hydraulic node the user may specify
- (a) Any combination of one external (to the coolant) heat slab type (pipe wall) and several internal heat slab types (fuel elements), or
 - (b) direct heating.

- (v) External heat slabs are in the form of hollow cylinders. They are subject to the boundary condition that the external boundary heat flux (q_b) is a linear function of the external surface temperature (T_b), i.e.

$$q_b = BH \times T_b + BQ \quad .$$

The parameters BH and BQ must be specified by the user. Such a boundary condition may find application in heat exchange problems and it is, of course, applicable to the fully insulated case (BH = BQ = 0). In the case of natural gas networks, it could also be used as an alternative to the present method of solving the steady state ground temperature problem by transient calculation [Turner 1981].

- (vi) Internal heat slabs, in the form of solid cylinders, are subject to the boundary condition that there is zero heat flux on the cylinder axis. They may consist of one or two materials. In the case of two materials, an inner material in the form of a solid cylinder is surrounded immediately by a second material in the form of a hollow cylinder. Any inter-material gap is assumed to be of zero extent.
- (vii) The direct heating model allows thermal energy to be added to or removed from the coolant with no heat slab specification. Apart from its non-calculation of temperatures, this option is similar to the original fuel model in NAIAD.
- (viii) Implicit coupling of the thermal model to the hydraulic model has been retained.

The heat slab model has been incorporated into NAIAD in parallel with the original fuel model in such a way that previously prepared problems will still run.

If the new model is selected, the required input data stream is quite different. The flowpaths are specified in terms of various nodal types supplied by the user. Initially, external and internal heat slab and direct heating types are specified. Hydraulic mode types are then specified in terms of heat slab types or direct heating types and various geometric and hydraulic parameters. Finally, each hydraulic node along the flowpaths is specified as a particular hydraulic node type. This mode of problem specification has been incorporated to ease input data preparation and eliminate much of the repetition that is often a feature of input data streams which specify the original fuel model of NAIAD.

This report should be read in conjunction with the original NAIAD report [Trimble and Turner 1974] which presents a full description of the code. Included in the present report are descriptions of the heat slab model, its implementation and full details of the existing input requirements of NAIAD.

2. HEAT SLAB MODEL

The heat slab model associated with any hydraulic node may consist of

- (a) any combination of one external heat slab and several internal heat slabs, or
- (b) direct heating.

2.1 External Heat Slab Model

The external heat slab model, shown in Figure 1, consists of a hollow cylindrical section of material of internal radius, r_{ehs} , and thickness th_{ehs} . The heat slab is divided into n_e regions of equal radial thickness, Δr_e , where n_e is the number of thermal nodes specified for the slab. The axial extent of the slab associated with the hydraulic node of interest (node J) extends from midway between node J-1 and node J (or a start of flowpath) to midway between node J and node J+1 (or an end of flowpath).

The flow of thermal energy is described by the following set of equations.

Boundary condition at external boundary:

$$BH \times T_b + BQ = q_b = -k_e \left. \frac{\partial T}{\partial r} \right|_b \quad (2.1.1)$$

Heat conduction through slab:

$$\begin{aligned} \Lambda_e \frac{\partial T}{\partial t} &= k_e \nabla^2 T + Q_e \\ &= k_e \frac{\partial^2 T}{\partial r^2} + \frac{k_e}{r} \frac{\partial T}{\partial r} + Q_e \end{aligned} \quad (2.1.2)$$

Boundary condition at heat slab/coolant interface:

$$k_e \left. \frac{\partial T}{\partial r} \right|_{ehs} = q_{ehs} = h_{ehs} \times (T_{ehs} - T_c) \quad (2.1.3)$$

where q_b is the thermal flux at the external boundary from the heat slab ($W m^{-2}$), T_b is the surface temperature at the external boundary (K), BH is the boundary heat transfer parameter ($W m^{-2} K^{-1}$), BQ is the boundary heat flux parameter ($W m^{-2}$), k_e is the thermal conductivity of heat slab material ($W m^{-1} K^{-1}$), r is the radial distance (m), Λ_e is the volumetric heat capacity of the heat slab material ($J m^{-3} K^{-1}$), Q_e is the volumetric thermal power production in the heat slab ($W m^{-3}$), q_{ehs} is the thermal flux at heat slab/coolant interface from the heat slab ($W m^{-2}$), T_{ehs} is the surface temperature of the heat slab adjacent to the coolant (K), h_{ehs} is the heat slab to coolant heat transfer coefficient ($W m^{-2} K^{-1}$), subscript b denotes the external boundary, subscript e denotes the external heat slab material, subscript ehs denotes the heat slab/coolant interface, and subscript c denotes the coolant.

Equations (2.1.1) to (2.1.3) are the basis for a set of finite difference equations for the nodal and surface temperatures of the heat slab. Spatial derivatives are replaced by fully implicit central difference approximations. Time derivatives are replaced by the backward difference approximation. This formulation results in truncation errors of $O(\Delta t) + O(\Delta r^2)$. These are of the same order as those for the finite difference formulation of the hydraulic equations in NAIAD. Because of this, a Crank-Nicholson formulation, which would yield truncation errors of $O(\Delta t^2) + O(\Delta r^2)$, has not been implemented.

Equation (2.1.1) and linear extrapolation over temperature yield the following equation for the unknown temperatures T'_b and T'_{ne} (see figure 1)

$$BH \times T'_b + BQ = -k_e \frac{T'_b - T'_{ne}}{\Delta r_e / 2} \quad (2.1.4)$$

where superscript ' denotes the parameter value at the end of a finite time step of Δt .

Equation (2.1.2) and linear extrapolation yield the following equation for T'_b , T'_{ne} and T'_{ne-1} :

$$\begin{aligned} \frac{\Lambda_e}{\Delta t} (T'_{ne} - T_{ne}) &= \frac{k_e}{\Delta r_e^2} (2T'_b - 3T'_{ne} + T'_{ne-1}) \\ &+ \frac{k_e}{2r_{ne}\Delta r_e} (2T'_b - T'_{ne} - T'_{ne-1}) + Q'_{ne} \end{aligned} \quad (2.1.5)$$

For nodes $ne - 1$ to $2e$, equation (2.1.2) yields:

$$\begin{aligned} \frac{\Lambda_e}{\Delta t} (T'_j - T_j) &= \frac{k_e}{\Delta r_e^2} (T'_{j+1} - 2T'_j + T'_{j-1}) \\ &+ \frac{k_e}{2r_j\Delta r_e} (T'_{j+1} - T'_{j-1}) + Q'_j, \quad j=ne-1, \dots, 2e \end{aligned} \quad (2.1.6)$$

Equation (2.1.2) and linear extrapolation yield the following equation for T'_{2e} , T'_{1e} and T'_{ehs} :

$$\begin{aligned} \frac{\Lambda_e}{\Delta t} (T'_{1e} - T_{1e}) &= \frac{k_e}{\Delta r_e^2} (T'_{2e} - 3T'_{1e} + 2T'_{ehs}) \\ &+ \frac{k_e}{2r_{1e}\Delta r_e} (T'_{2e} + T'_{1e} - 2T'_{ehs}) + Q'_{1e} \end{aligned} \quad (2.1.7)$$

In the special case of one thermal node only, equation (2.1.2) and linear extrapolation yield the following equation which replaces the set of equations (2.1.5) to (2.1.7) :

$$\begin{aligned} \frac{\Lambda_e}{\Delta t} (T'_{1e} - T_{1e}) &= \frac{k_e}{\Delta r_e^2} (2T'_b - 4T'_{1e} + 2T'_{ehs}) \\ &+ \frac{k_e}{r_{1e} \Delta r_e} (T'_b - T'_{ehs}) + Q'_{1e} \end{aligned} \quad (2.1.5a)$$

The left section of equation (2.1.3) yields the following equation for T'_{1e} , T'_{ehs} and q'_{ehs} :

$$k_e \frac{(T'_{1e} - T'_{ehs})}{\Delta r_e / 2} = q'_{ehs} \quad (2.1.8)$$

Equations (2.1.4) to (2.1.8) inclusive comprise a set of finite difference equations for the temperatures of external heat slabs.

2.2 Internal Heat Slab Model

The internal heat slab model, shown in figure 2, consists of a solid cylindrical section of radius r_{ihs} . The heat slab may consist of one or two materials. If the specified radial thickness of the outer material, th_0 , is less than r_{ihs} , an inner material of radius $r_i = r_{ihs} - th_0$ is assumed. The outer and inner sections are divided into n_o and n_i regions of radial thicknesses Δr_o and Δr_i respectively. The axial extent of the slab associated with the hydraulic node of interest is as defined for the external heat slab model (section 2.1).

The flow of thermal energy is described by the following set of equations.

Heat conduction through the inner material:

$$\begin{aligned} \Lambda_i \frac{\partial T}{\partial t} &= k_i \nabla^2 T + Q_i \\ &= k_i \frac{\partial^2 T}{\partial r^2} + \frac{k_i}{r} \frac{\partial T}{\partial r} + Q_i \end{aligned} \quad (2.2.1)$$

Boundary condition at the surface of the inner material:

$$q_{is} = -k_i \left. \frac{\partial T}{\partial r} \right|_{is} = h_g \times (T_{is} - T_{os}) = q_g \quad (2.2.2)$$

Boundary condition at gap surface of outer material:

$$q_g = h_g \times (T_{is} - T_{os}) = -k_o \left. \frac{\partial T}{\partial r} \right|_{os} = q_{os} \quad (2.2.3)$$

Heat conduction through outer material:

$$\Lambda_o \frac{\partial T}{\partial t} = k_o \frac{\partial^2 T}{\partial r^2} + \frac{k_o}{r} \frac{\partial T}{\partial r} + Q_o \quad (2.2.4)$$

Boundary condition at heat slab/coolant interface:

$$-k_o \left. \frac{\partial T}{\partial r} \right|_{ihs} = q_{ihs} = h_{ihs} \times (T_{ihs} - T_c) \quad (2.2.5)$$

where q_{ihs} is the thermal flux at the heat slab/coolant interface from the heat slab ($W m^{-2}$), h_g is the inter-material gap heat transfer coefficient ($W m^{-2} K^{-1}$), subscript i denotes inner material, subscript is denotes surface of inner material, subscript g denotes inter-material gap, subscript os denotes inner surface of outer material, subscript o denotes outer material, and subscript ihs denotes heat slab surface adjacent to coolant.

As in section 2.1, equations (2.2.1) to (2.2.5) are the basis for a set of finite difference equations for the nodal and surface temperatures of the heat slab.

Inner material and inter-material gap

Equation (2.2.1) is used, with symmetry considerations, to yield the following equation for T_{ni} and T_{ni-1} (see figure 2):

$$\begin{aligned} \frac{\Lambda_i}{\Delta t} (T'_{ni} - T_{ni}) &= \frac{k_i}{\Delta r_i^2} (-T'_{ni} + T'_{ni-1}) \\ &+ \frac{k_i}{2r_{ni}\Delta r_i} (-T'_{ni} + T'_{ni-1}) + Q'_{ni} \end{aligned} \quad (2.2.6)$$

Equation (2.2.1) is used to derive the following equation for nodes $ni - 1$ to $2i$:

$$\begin{aligned} \frac{\Lambda_j}{\Delta t} (T'_j - T_j) &= \frac{k_j}{\Delta r_j^2} (T'_{j+1} - 2T'_j + T'_{j-1}) \\ &+ \frac{k_j}{2r_j \Delta r_j} (-T'_{j+1} + T'_{j-1}) + Q'_j, \quad j=ni-1, \dots, 2i \end{aligned} \quad (2.2.7)$$

Equation (2.2.1) and either linear or parabolic extrapolation over temperature yield the following equation for T'_{2i} , T'_{1i} and T'_{is} :

$$\begin{aligned} \frac{\Lambda_i}{\Delta t} (T'_{1i} - T_{1i}) &= \frac{k_i}{\Delta r_i^2} (T'_{2i} - (2 + \beta)T'_{1i} + 2\alpha T'_{is}) \\ &+ \frac{k_i}{2r_{1i} \Delta r_i} (-T'_{2i} - \beta T'_{1i} + 2\alpha T'_{is}) + Q'_{1i} \end{aligned} \quad (2.2.8)$$

The user may specify whether linear or parabolic extrapolation over temperature is to be used to estimate the temperature at the surface of the solid cylindrical component of internal heat slabs. Linear extrapolation is recommended for general use when the forms of temperature distributions are unknown (especially during transients). Parabolic extrapolation would be appropriate if it is known that the temperature distributions in solid cylindrical components of internal heat slabs are always parabolic or nearly so. This pertains in the special case of a quasi-stationary system with uniform heat production. Parabolic extrapolation of temperatures in the hollow cylindrical components (outer material) of internal heat slabs or in external heat slabs is not appropriate in a quasi-stationary system and is not permitted by the code. Linear extrapolation is always used in these cases.

If the linear extrapolation option is specified, $\alpha = 1$ and $\beta = 1$. For parabolic extrapolation

$$\alpha = (r_{1i} + 0.5 \times \Delta r_i) / (r_{1i} + 0.25 \times \Delta r_i), \quad \text{and}$$

$$\beta = (r_{1i} + 0.75 \times \Delta r_i) / (r_{1i} + 0.25 \times \Delta r_i) \quad .$$

In the special case of a single thermal node in the inner material, equation (2.2.1), together with symmetry considerations and extrapolation, yields the following equation:

$$\begin{aligned} \frac{\lambda_i}{\Delta t} (T'_{1i} - T_{1i}) &= \frac{k_i}{\Delta r_i^2} (-(1 + \beta)T'_{1i} + 2\alpha T'_{is}) \\ &+ \frac{k_i}{2r_{1i}\Delta r_i} (-(1 + \beta)T'_{1i} + 2\alpha T'_{is}) + Q'_{1i} \end{aligned} \quad (2.2.6a)$$

which replaces equations (2.2.6) to (2.2.8).

For T'_{1i} , T'_{is} and T'_{os} , equation (2.2.2) and extrapolation yield:

$$-\frac{k_i}{\Delta r_i} (2\alpha T'_{is} - (1 + \beta)T'_{1i}) = h_g \times (T'_{is} - T'_{os}) \quad (2.2.9)$$

Equation (2.2.3) and extrapolation yield the following equation for T'_{is} , T'_{os} and T'_{no} :

$$h_g \times (T'_{is} - T'_{os}) = \frac{k_o}{\Delta r/2} (T'_{os} - T'_{no}) \quad (2.2.10)$$

Extrapolation to the inner material/gap interface may be linear or parabolic. Linear extrapolation is used for the gap/outer material interface.

Outer Material

If an inner material exists, equation (2.2.4) and linear extrapolation yield the following equation for T'_{os} , T'_{no} and T'_{no-1} :

$$\begin{aligned} \frac{\lambda_o}{\Delta t} (T'_{no} - T_{no}) &= \frac{k_o}{\Delta r_o^2} (2T'_{os} - 3T'_{no} + T'_{no-1}) \\ &+ \frac{k_o}{2r_{no}\Delta r_o} (-2T'_{os} + T'_{no} + T'_{no-1}) + Q'_{no} \end{aligned} \quad (2.2.11)$$

If there is no inner material, equation (2.2.4) and symmetry considerations yield the following equations for T'_{no} and T'_{no-1} :

$$\begin{aligned} \frac{\lambda_o}{\Delta t} (T'_{no} - T_{no}) &= \frac{k_o}{\Delta r_o^2} (-T'_{no} + T'_{no-1}) \\ &+ \frac{k_o}{2r_{no}\Delta r_o} (-T'_{no} + T'_{no-1}) + Q'_{no} \end{aligned} \quad (2.2.11a)$$

Equation (2.2.4) yields the following equations for nodes no-1 to 2o :

$$\begin{aligned} \frac{\Lambda_o}{\Delta t} (T'_j - T_j) &= \frac{k_o}{\Delta r_o^2} (T'_{j+1} - 2T'_j + T'_{j-1}) \\ &+ \frac{k_o}{2r_j \Delta r_o} (-T'_{j+1} + T'_{j-1}) + Q'_j, \quad j=no-1, \dots, 2o \end{aligned} \quad (2.2.12)$$

Equation (2.2.4) and extrapolation yield the following equation for T'_{2o} , T'_{1o} and T'_{ihs} .

$$\begin{aligned} \frac{\Lambda_o}{\Delta t} (T'_{1o} - T_{1o}) &= \frac{k_o}{\Delta r_o^2} (T'_{2o} - (2 + \beta)T'_{1o} + 2\alpha T'_{ihs}) \\ &+ \frac{k_o}{2r_{1o} \Delta r_o} (-T'_{2o} - \beta T'_{1o} + 2\alpha T'_{ihs}) + Q'_{1o} \end{aligned} \quad (2.2.13)$$

where the expressions for the extrapolation parameters α and β are as defined for the case of an inner material of an internal heat slab, except that r_{1i} is replaced by r_{1o} . If there is an inner material, linear extrapolation is used. Otherwise the extrapolation to the heat slab/coolant interface may be either linear or parabolic.

In the special case of a single thermal node in the outer material, when an inner material exists, equation (2.2.4) and linear extrapolation yield the following equation for T'_{os} , T'_{1o} and T'_{ihs} :

$$\begin{aligned} \frac{\Lambda_o}{\Delta t} (T'_{1o} - T_{1o}) &= \frac{k_o}{\Delta r_o^2} (2T'_{os} - 4T'_{1o} + 2T'_{ihs}) \\ &+ \frac{k_o}{r_{1o} \Delta r_o} (-T'_{os} + T'_{ihs}) + Q'_{1o} \end{aligned} \quad (2.2.11b)$$

which replaces equations (2.2.11) to (2.2.13).

In the special case of a single thermal node in the outer material when no inner material exists, equation (2.2.4), symmetry considerations and extrapolation (linear or parabolic) yield the following equation for T'_{1o} and T'_{ihs} :

$$\begin{aligned} \frac{\Lambda_0}{\Delta t} (T'_{10} - T_{10}) &= \frac{k_0}{\Delta r_0^2} (-(1 - \beta)T'_{10} + 2\alpha T'_{ihs}) \\ &+ \frac{k_0}{2r_{10}\Delta r_0} (-(1 + \beta)T'_{10} + 2\alpha T'_{ihs}) + Q'_{10} \end{aligned} \quad (2.2.6b)$$

which replaces equations (2.2.6) to (2.2.13).

The left section of equation (2.2.5) and extrapolation yield the following equation for T'_{10} , T'_{ihs} and q'_{ihs} :

$$-\frac{k_0}{\Delta r_0} (-(1 + \beta)T'_{10} + 2\alpha T'_{ihs}) = q'_{ihs} \quad (2.2.14)$$

If there is an inner material, linear extrapolation is used. Otherwise either linear or parabolic extrapolation may be selected.

Equations (2.2.6) through (2.2.14) comprise the set of finite difference equations for internal heat slabs.

2.3 Direct heating

The direct heating model is very simple. All power generated at a direct heating node along a flowpath is passed directly to the coolant via the associated hydraulic node. No heat slabs are specified and heat slab temperatures are not calculated.

The flux from a direct heating node to the coolant is given by :

$$q'_{dJ} = PC'_J/p_J \quad (2.3.1)$$

where PC'_J is the thermal power production per unit length along the flowpath at hydraulic node J (W m^{-1}), p_J is the wetted perimeter at hydraulic node J (m), and subscript dJ denotes the directly heated hydraulic node J .

Note: The wetted perimeter for a directly heated hydraulic node is calculated from the hydraulic equivalent diameter (see subsection 4.3.4) by assuming a circular flowpath cross section.

3. METHOD OF SOLUTION

The method of solution for the steady state and transient calculations is discussed in this section. The actual solution of the finite difference equations proceeds, in all cases, according to a forward elimination-back substitution method in which all quantities stay nicely in scale [Richtmyer 1957].

3.1 Steady State Solution

Initially, at each hydraulic node not directly heated, forward elimination is performed, with $1/\Delta t \approx 0.0$ on the sets of finite difference equations ((2.1.4) to (2.1.8) and (2.2.6) to (2.2.14)) for each heat slab to yield a set of linear equations in two unknowns. The next to last set of equations yielded during forward elimination is

$$a_k \times T_{1k} + b_{1k} \times T_{sk} = c_k, \quad k=1, \dots, \text{NHS}_J \quad (3.1.1)$$

where NHS_J is the number of heat slabs associated with the hydraulic node J , T_{1k} is the temperature of thermal node closest to coolant surface in heat slab k (K), T_{sk} is the coolant surface temperature of heat slab k (K), and a_k , b_k and c_k are known coefficients.

The last set of equations yielded by forward elimination is

$$d_k \times T_{sk} + e_k \times q_{sk} = f_k, \quad k=1, \dots, \text{NHS}_J \quad (3.1.2)$$

where q_{sk} is the heat flux at the heat slab/coolant interface of heat slab k (W m^{-2}), and d_k , e_k and f_k are known coefficients.

All heat generated in both internally and directly heated slabs flows directly into the coolant. This may not be the case for an external heat slab which may gain or lose heat across its external boundary at a rate which is temperature dependent. This feature gives rise to two methods of solution which are described below.

Case 1: temperature independent
external boundary heat transfer

In this case, the method of solution is straightforward. The 'total' heat flux (q) to the coolant is obtained by summing the power to coolant per unit length of flowpath (PC) from each heat slab at the hydraulic node of interest (J), i.e.

$$q_J = \sum_{k=1}^{NHS_j} PC_{kJ}/p_j \quad , \quad (3.1.3)$$

The power to coolant from internally and directly heated slabs is identical to the power generated in them. In the case of an external heat slab, the power to coolant is the power generated minus the power lost across the external boundary.

The q_j are used by the hydraulic section of NAIAD to solve for the hydraulic parameters which are, in turn, used to calculate the coolant temperatures (T_c). Subsequently, the heat fluxes to the coolant from each heat slab not directly heated are used by a modified version of the subroutine FUEL to calculate the coolant surface temperatures (T_{sk}) of each heat slab. Finally, back substitution is performed on the sets of linear equations derived during forward elimination to yield the heat slab temperatures.

Case 2: temperature dependent
external boundary heat transfer

In this case, because the power across the external boundary is temperature dependent, so is the power to coolant and an iterative method of solution must be employed. An estimate is made of the power and flux (q_{ehs}^*) to coolant from the external heat slab. As in equation (3.1.3), this is combined with the power from any internal heat slabs to yield an estimate of the 'total' flux to the coolant (q_j^*), which is used by the hydraulic section of NAIAD to solve for the hydraulic parameters and calculate the coolant temperature. Subsequently, q_{ehs}^* is input to FUEL to yield the corresponding coolant surface temperature (T_{ehs}^*) of the external heat slab which, in turn, is substituted in equation (3.1.2) to yield a second estimate (q_{ehs}^{**}) for the flux to coolant from the external heat slab. An interpolation scheme, based on the derivatives of heat flux with respect to surface temperature in equations (3.1.2) and (2.1.4), is used to generate a better estimate of q_{ehs} .

and q_j . The iteration process continues until $\left| \frac{T_{ehs}^{**}}{T_{ehs}^*} - 1.0 \right| < \gamma$ (presently set at 10^{-6}) and equations (3.1.2) and (2.1.4) have been satisfied. T_{ehs}^* and T_{ehs}^{**} denote values of T_{ehs} from successive iterations. At this stage, the flux to coolant and the coolant surface temperature of the external heat slab have been determined. Finally, as in case 1, the heat fluxes to the coolant from all heat slabs are used to complete the solution.

3.2 Transient Solution

Initially, at each hydraulic node (J) not directly heated, forward elimination is performed on the set of finite difference equations (2.1.4) to (2.1.7) and (2.2.6) to (2.2.13) for each heat slab to yield the following set of equations:

$$a_k \times T_{1k}' + b_k \times T_{sk}' = c_k, \quad k=1, \dots, NHS_J \quad (3.2.1)$$

where the parameters are as defined in section 3.1. Second, the following set of equations, which is a reformulation of equations (2.1.8) and (2.2.14), is defined:

$$q_{sk}' = d_k \times T_{1k}' + e_k \times T_{sk}', \quad k=1, \dots, NHS_J \quad (3.2.2)$$

Third, the general functional relationship

$$q_{sk} = q_{sk}(T_{sk}, X),$$

where X represents the hydraulic parameters of the NAIAD code (mass flow rate, W ; pressure, P ; and flow enthalpy, H), is used to derive the Taylor expansion:

$$q_{sk}' = q_{sk} + \frac{\partial q_{sk}}{\partial X_J} (X_J' - X_J) + \frac{\partial q_{sk}}{\partial T_{sk}} (T_{sk}' - T_{sk}), \quad k=1, \dots, NHS_J \quad (3.2.3)$$

The coefficients $\partial q_{sk} / \partial X_J$ and $\partial q_{sk} / \partial T_{sk}$ are evaluated by using the NAIAD heat transfer package.

Eliminating q_{sk}' from equations (3.2.2) and (3.2.3) yields a set of equations which are linear in T_{1k}' , T_{sk}' and X_J . Eliminating T_{1k}' from this new set of equations and the set (3.2.1) yields the set of linear equations:

$$T'_{sk} = g_k + u_k \times X'_j, \quad k=1, \dots, \text{NHS}_j \quad (3.2.4)$$

where g_k and u_k are known coefficients. Substituting for T'_{sk} from equations (3.2.4) into equations (3.2.3) yields:

$$q'_{sk} = v_k + w_k \times X'_j, \quad k=1, \dots, \text{NHS}_j \quad (3.2.5)$$

where v_k and w_k are known coefficients.

The power to coolant per unit length of flowpath from each heat slab (PC'_k) may then be expressed as a linear function of X'_j :

$$PC'_k = p_k \times (v_k + w_k \times X'_j), \quad k=1, \dots, \text{NHS}_j \quad (3.2.6)$$

The 'total' power to coolant (PC'_j) per unit length of flowpath at hydraulic node J is obtained by summing the power to coolant from the individual heat slabs:

$$PC'_j = \sum_{k=1}^{\text{NHS}_j} PC'_k = \sum_{k=1}^{\text{NHS}_j} p_k \times (v_k + w_k \times X'_j) \quad (3.2.7)$$

and the 'total' heat flux to coolant is given by:

$$q'_j = PC'_j / p_j = \sum_{k=1}^{\text{NHS}_j} p_k \times (v_k + w_k \times X'_j) / p_j \quad (3.2.8)$$

Equations (3.2.8) are used to eliminate q'_j from the hydraulic energy equations. The full set of hydraulic equations is then solved in the hydraulic section of NAIAD. The solution of these equations yields the hydraulic parameters X'_j which are substituted into the set of equations (3.2.4) to yield the coolant surface temperatures of the heat slabs. Back substitution in the equations derived by forward elimination yields the nodal and surface temperatures of each heat slab. Substitution of the X'_j in equations (3.2.5) and (3.2.8) yields the heat fluxes.

It should be noted that the use of the Taylor expansion (equation (3.2.3)) has allowed all temperature variables to be eliminated and the heat flux to the coolant to be expressed as a function of the hydraulic parameters only. Thus an iterative method of solution, such as that required for the steady state (with temperature dependent external boundary heat transfer), is

not required for the transient solution.

4. INPUT DATA

For the convenience of users, a complete description of the input requirements of NAIAD is now presented.

4.1 General

The finite difference method relies on the continuity of the derivatives being approximated by finite differences. Unfortunately, some problems involve discontinuities (or, at least, large spatial derivatives) in some parameters, e.g. flowpath area, surface heat flux. Such discontinuities are best treated by placing nodes close to either side of and equidistant from the discontinuity.

Except for the title card, all data are read with the AAEC free input subroutine SCAN [Bennett and Pollard 1967]. Data may be punched anywhere on a card with numbers separated by blanks or commas. Alphabetic comments may be placed amongst the data and comment cards (* in column 1) may be used. Other features are as follows:

- . Repeat notation, e.g.
5*1.47
is equivalent to 1.47 1.47 1.47 1.47 1.47.
- . Fixed increment notation, e.g.
1. (0.5)3.
is equivalent to 1. 1.5 2. 2.5 3.
- . A decimal point is not needed for real numbers with integral values.
- . The data cards are listed in the output.

4.2 Title Card

HEAD Title card (10A8).

4.3 Controls

±NP	NP is the number of flowpaths in the network. If negative, the flowpath data interpreted by the code are printed after each set of flowpath data is read.
NC	Number of connections in the network.
GRAV	Acceleration due to gravity, g ($m\ s^{-2}$).
TOL	Tolerance in network balance (suggest 10^{-8}).
ITMAX	Maximum number of iterations in network balance (suggest 15).
SMIN	Minimum time step to be used (s).
SMAX	Maximum time step to be used (s).
CTAR	Target maximum fractional change in a time step (suggest 0.01).
CMAX	Maximum allowable fractional change in a time step (suggest 0.02).
RCMAX	Maximum allowable fractional density error in a time step involving a liquid two-phase transition (suggest 0.01).
CINC	Maximum ratio between successive time steps, e.g. 2 means that at most it will double the time step.
±TMAX	Maximum time required (s). If negative, then a restart of a previous calculation is assumed and the following pair of data items must be supplied immediately :
TIME	Time of restart (s).
DELT	Required time step (s).

Details of restart implementation and dump file specifications are presented at the end of this subsection.

- KFP Frequency of full listing, e.g. 5 means full listing every fifth time step and partial listing at other time steps. A partial listing covers only those nodes specified below in KW (section 4.4) and, if KFP is positive, details of time step change and elapsed CPU time. If no nodes are specified below and KFP is negative, no partial listing appears.
- ±TSFP A full printout will be produced at the end of every time step for which $\text{TIME} > |\text{TSFP}|$.
If $\text{TSFP} \geq 0.0$, then proceed to section 4.4 (original NAIAD input).
If $\text{TSFP} < 0.0$, then the heat slab option is assumed and the following data should appear in the input stream.
- NIHTYP Number of internal heat slab types.
- NEHTYP Number of external heat slab types.
- NHNTYP Number of hydraulic node types with heat slabs.
- NDNTYP Number of hydraulic node types with direct heating.
- IXTRAP Type of extrapolation to be used in the estimation of the surface temperatures of the solid cylindrical component of internal heat slabs:
IXTRAP=1 - linear extrapolation,
IXTRAP=2 - parabolic extrapolation.
- LGPRT An integer which specifies whether details of the geometry, thermal parameters, etc. of the heat slabs will be printed whenever flowpath geometry is printed. $\text{LGPRT} \leq 0$ suppresses printing.
- LUPRT An integer which specifies whether a printout of heat slab parameters (thermal node and surface temperatures, thermal fluxes, etc.) will accompany a full printout of the hydraulic parameters for the system during a transient calculation or a flowpath during a steady state calculation. $\text{LUPRT} \leq 0$ suppresses printing.

A dashed line is printed in the output immediately after these data have been read and printed.

Dump file specification

During execution, NAIAD writes a dump of the following data to FORTRAN unit 7 (FT07F001):

TIME, DELT	
W,P,H,TFC,TFS	- N components of each
HBS,HBF	- NP components of each
BPW,BHO,IGENRL(i,1)	- NC components of each

Such a dump from a previous calculation must be available on unit 10 (FT10F001) for a restart calculation. The actual restart will commence from the greatest dumped TIME which is less than the requested restart time. If the requested restart time step is less than or equal to zero, the code performs a perfect restart by taking the appropriate time step size from the dump.

Note: If the heat slab option is used, then TFC and TFS, each with N components, will be replaced by the array U with NEQ components. This replacement is performed automatically by NAIAD when a dump is written and is expected when a restart is made with TSFP < 0.0.

4.3.1 Specification of internal heat slab types

The following set of data is required for each internal heat slab type the user wishes to define. The different types are indexed according to their order of appearance in the input stream. The indices range from 1 to NIHTYP.

NIHNDC	Number of thermal nodes in the outer (clad) material. NIHNDC must be ≥ 1 .
REC	External radius of outer material (m).
RTHKC	Radial thickness of outer material (m).
LAMDAC	Volumetric heat capacity (>0.0) of outer material ($J m^{-3} K^{-1}$).

- HSKC Thermal conductivity (>0.0) of outer material ($\text{W m}^{-1} \text{K}^{-1}$).
- If $\text{REC-RTHKC} < 10^{-5}$, the following data for the inner (fuel) material must be bypassed; proceed to read the wetted perimeter (HPC).
- NIHNDF Number of thermal nodes in the inner material.
- LAMDAF Volumetric heat capacity (>0.0) of inner material ($\text{J m}^{-3} \text{K}^{-1}$).
- HSKF Thermal conductivity (>0.0) of inner material ($\text{W m}^{-1} \text{K}^{-1}$).
- HGAP Heat transfer coefficient for the inter-material (fuel/clad) gap ($\text{W m}^{-2} \text{K}^{-1}$).
- HPC The wetted perimeter of the internal heat slab (m).
If HPC is input as zero, it is calculated from REC, assuming a circular cross section.
- PDIH NIHNDC + NIHNDF values specifying the unnormalised radial distribution of power density (W m^{-3}) in the internal heat slab. The value for the thermal node at the largest radial distance should appear first, followed, in order, by the values representing power density at thermal nodes at smaller radial distances. The input distribution is normalised by NAIAD to calculate the volumetric power density (may be zero) corresponding to each thermal node.

A dashed line is printed in the output immediately after the data for each heat slab type have been read and printed.

4.3.2 Specification of external heat slab types

The following set of data is required for each external heat slab type the user wishes to define. The different types are indexed according to their order of appearance in the input stream. The indices range from 1 to NEHTYP.

- NEHNDE Number of thermal nodes in external heat slab.
NEHNDE must be ≥ 1 .

BH	Boundary heat transfer parameter ($W m^{-2} K^{-1}$).
BQ	Boundary heat flux parameter ($W m^{-2}$).
RIEH	Internal radius of external heat slab (m).
RTHKEH	Radial thickness of external heat slab (m).
LAMDEH	Volumetric heat capacity (>0.0) of external heat slab ($J m^{-3} K^{-1}$).
KEH	Thermal conductivity (>0.0) of external heat slab ($W m^{-1} K^{-1}$).
HPEH	Internal wetted perimeter of external heat slab (m). If HPEH is input as zero, it is calculated from RIEH assuming a circular cross section.
PDEH	NEHNDE values specifying the unnormalised radial distribution of power density ($W m^{-3}$) in the external heat slab. The value for the thermal node at the smallest radial distance should appear first, followed, in order, by the values representing power density at thermal nodes at larger radial distances. The input distribution is normalised by NAIAD to calculate the volumetric power density corresponding to each thermal node.

A dashed line is printed in the output immediately after these data have been read and printed.

4.3.3 Specification of hydraulic node types with heat slabs

The following set of data is required for each hydraulic node type with heat slabs that the user wishes to define. The different types are indexed according to their order of appearance in the input stream. The indices range from 1 to NHNTYP.

ISLIP	An integer which specifies the slip relation to be used:
	0 - homogeneous (no slip)
	1 - Jones
	2 - CISE
	3 - Beattie

- 4 - Beattie small bubble
- 5 - Fauske
- 6 - Moody
- 7 - modified CISE
- 8 - Smith
- 9 - Armand
- 10 - Bryce

- IFR An integer which specifies the friction relation to be used:
 ±1 - homogeneous
 ±2 - bubbly
 ±3 - annular
 ±4 - small bubble
 5 - constant friction factor
 If negative, the boiling wall extension will be used.
- IHTRAN An integer specifying the differencing scheme for the
 calculation of the surface heat transfer coefficients:
 0 - explicit heat transfer coefficient
 1 - implicit heat transfer coefficient
- DE The equivalent diameter, D_e (m). If DE is given as zero, it is
 calculated from A (see below), assuming a circular cross
 section.
- A The hydraulic cross sectional area, a (m^2). If A is given as
 zero, it is calculated from DE, assuming a circular cross
 section.
- ROUGH Absolute surface roughness, ϵ (m), or friction factor if IFR =
 5.
- ITYPEH Index of external heat slab type. If IYPEH is zero it is
 assumed that there is no external heat slab associated with the
 hydraulic node. In this case, proceed to MIHTYP which must be
 >0.
- FRACPE The fraction of power associated with the hydraulic node which
 is generated in the external heat slab.

Note: This fraction need not be normalised. The distribution of power among heat slabs is normalised internally to give the correct power at the corresponding hydraulic node.

MIHTYP The number of different internal heat slab types associated with the hydraulic node.

The following set of data is required for each internal heat slab type (MIHTYP of them) associated with the hydraulic node.

ITYPIH Index of internal heat slab type.

NIH Number of heat slabs of this type associated with the hydraulic node.

FRACPI The (unnormalised) fraction of power associated with the hydraulic node which is generated in each internal heat slab of the current type.

A dashed line is printed in the output immediately after the data for each type have been read and printed.

4.3.4 Specification of hydraulic node types with direct heating

The following set of data is required for each hydraulic node type with direct heating that the user wishes to define. The different types are indexed according to their order of appearance in the input stream. The indices range from 1 to NDNTYP.

ISLIP An integer in the range [0,10] which specifies the slip relation to be used (see ISLIP - subsection 4.3.3).

IFR An integer in the ranges [-4,-1],[1,5] which specifies the friction relation to be used (see IFR - subsection 4.3.3).

DE The hydraulic equivalent diameter, $D_e(m)$, as in subsection 4.3.3.

A The hydraulic cross sectional area, $a (m^2)$, as in subsection 4.3.3.

ROUGH Absolute surface roughness, ϵ (m), or friction factor if IFR = 5.

A dashed line is printed in the output immediately after the data for each type have been read and printed.

4.4 Flow Path Data

The following set of data is required for each pipe or flowpath, beginning with pipe 1. Each set must start on a new card.

NODE Number of nodes in flowpath.

KA Connection at start of flowpath.

KB Connection at end of flowpath.

PGENP Total power generated in this flowpath (W).

If the heat slab option is assumed (TSFP < 0.0), proceed to subsection 4.4.1.

ISLIP NODE integers in the range [0,10] specifying which slip relation is to be used at each node (see ISLIP - subsection 4.3.3).

IFR NODE integers in the ranges [-4,-1],[1,5] specifying which friction relation is to be used at each node (see IFR - subsection 4.3.3).

IHTRAN NODE integers specifying which differencing scheme is to be used for the calculation of surface heat transfer coefficients at each node (see IHTRAN - subsection 4.3.3).

KW NODE integers specifying which nodes are to be printed in partial listings of hydraulic data:

0 - do not print the node
1 - print it

- Z NODE values of the axial displacement (m) along the flowpath (arbitrary origin but strictly increasing).
- SINT NODE-1 values of $\Delta\text{height}/\Delta z$ for segment of flowpath between adjacent nodes.
- DE NODE values of equivalent diameter, D_e (m). If $DE(I)$ is given as zero, it is calculated from $A(I)$ assuming a round pipe.
- A NODE values of cross sectional area, a (m^2). If $A(I)$ is given as zero, it is calculated from $DE(I)$ assuming a round pipe.
- HP NODE values of heated wetted perimeters, p (m). If $HP(I)$ is given as zero, it is calculated from $DE(I)$ assuming a round pipe.
- ROUGH NODE values of absolute surface roughness, ϵ (m), or friction factor if $IFR = 5$.
- CP NODE values of fuel heat capacity ($\text{J m}^{-3} \text{K}^{-1}$). If zero, generated power passes directly to coolant.
- HF NODE values of fuel centre to fuel surface heat transfer coefficient, h ($\text{W m}^{-2} \text{K}^{-1}$). If given as zero set to 10^{10} (zero resistance).
- ORIK NODE-1 values of friction coefficient. If > 0 , then taken as K_e . If < 0 , then taken as $-K_f$.
- PD NODE values specifying an equivalent heat flux distribution (m^{-2}). The given distribution is normalised within the code so that $PD_i = Q_i/PGENP$ hence:

$$\sum_{i=1}^{\text{NODE-1}} (PD_i \times P_i + PD_{i+1} \times P_{i+1}) \times (z_{i+1} + z_i) = 2$$

If all the PD_i are zero, they are reset to unity. If the above sum is zero, normalisation is not carried out.

A dashed line is printed in the output after each set of flowpath data has been read and printed. Proceed to section 4.5.

4.4.1 Heat slab model

ITYPHN NODE values in the ranges [1,NHNTYP],[-1,-NDNTYP] specifying the hydraulic node types along the flowpath.

Z NODE values of the axial displacement (m) along the flowpath (arbitrary origin but strictly increasing).

KW NODE integers specifying which nodes are to be printed in partial listings of hydraulic data:

0 - do not print the node
1 - print it

SINT NODE-1 values of $\Delta\text{height}/\Delta z$ for segment of flowpath between adjacent nodes.

ORIK NODE-1 values of friction coefficient. If > 0 they are taken as K_e . If < 0 they are taken as $-K_f$.

EDIFF NODE-1 values of the weighting factor w ($0 \leq w \leq 1$) to be used in the hydraulic energy equation (recommend 0.0).

PDM NODE values specifying an unnormalised power distribution (m^{-1}) along the flowpath. The input distribution is normalised within the code so that:

$$\sum_{i=1}^{\text{NODE}} \text{PDM}_i \times \text{DZN}_i = 1 \quad .$$

A dashed line is printed in the output after each set of flowpath data has been read and printed.

4.5 Connection Data

The following set of data is required for all connections other than types 1 and 9. Type 1 (internal) connections are the default and type 9 connections are allocated automatically by the code. The first must start on a new card.

KC Connection number.

LC Connection type:

- 0 - explicit
- 1 - internal
- 2 - choked (burst)
- 3 - implicit
- 4 - pump
- 5 - linear
- 6 - regulator
- 7 - externally powered compressor
- 8 - compressor powered by burning hydraulic fluid
(gas powered compressor)
- 9 - output connection for gas powered compressor

If LC = 0,3 or 5

LCB Type of connection control:

- 1 - flow
- 2 - pressure

If LC = 2 A choked connection which connects to only one pipe.

PAT Pressure downstream of burst (final receiver pressure) (Pa).

TOPEN Opening time of break (s).

If LC = 4 A pump connection which connects to two pipes, the outlet of its inlet pipe and the inlet of its outlet pipe.

IQ Pump number ($1 \leq IQ \leq 5$).

PUMHR Rated head of pump (m).

PUMPQR Rated volumetric flow of pump ($\text{m}^3 \text{s}^{-1}$).

PUMPSR Rated speed of pump (rad s^{-1}).

PUMTR	Rated torque of pump (N m).
PUMDR	Rated pump density (kg m^{-3}).
PUMTF	Constant pump frictional torque (N m).
PUMMI	Pump moment of inertia (kg m^{-2}).
PUMS	Initial pump speed (rad s^{-1}).
If LC = 6	A regulator which connects to two pipes, the outlet of its inlet pipe and the inlet of its outlet pipe.
PREG	The regulator set point pressure (Pa).
If LC = 7 or 8	A compressor:
	A type 7 connection connects to two pipes, the outlet of the compressor inlet pipe and the inlet of the outlet pipe.
	A type 8 connection connects to only one pipe, the outlet of the gas powered compression inlet pipe.
	A type 9 connection connects to only one pipe, the inlet of the gas powered compressor outlet pipe.
MCOM	Mode of operation: 1 - discharge flow is controlled 2 - discharge pressure is controlled 3 - suction pressure is controlled
COMSET	Compressor setpoint (flow or pressure depending upon mode).
CPMAX	Maximum compressor power (W).
CTMAX	Maximum discharge temperature (K)
AK1,AK2,AK3	Parameters k_1, k_2 and k_3 [Turner 1981] to be used in the calculation of compressor power. AK1 and AK2 are dimensioned (J kg^{-1}); AK3 is dimensionless.

The following data must be provided if LC=8.

KOMOUT The connection number of the outlet connection. The type of this connection is set internally by the code - LC(KOMOUT) = 9.

RHCOM Mass of hydraulic fluid consumed per unit of work done by the compressor (kg J^{-1}).

A KC = 0 marks the end of the connection data. A dashed line follows the listing of the connection data in the output.

4.6 Steady State Data

The problem steady state calculation comprises a series of steady state calculations for individual flowpaths. Any number of calculations may be done on each flowpath. If a steady state calculation is not done on a flowpath, then either its steady state must be in the special routine BINITM or a restart calculation specified.

In the following specification, an asterisk as a superscript on a flow, pressure or enthalpy symbol means that it is specified by two numbers IP and Q where

IP = Pipe number or zero.

If IP \leq 0

Q = COND = the actual value of the quantity. If an enthalpy is being specified then:
 (i) if IP = 0 either an enthalpy or quality is required
 (ii) If IP < 0 a coolant temperature is required.

If IP > 0

Q = Node number, in which case the condition is set equal to its counterpart at the Qth node of pipe IP. This node number Q is the position in the flowpath containing the node, not the node number appearing in the code output. This allows extra nodes to be added with minimum impact on the input data.

The following set of data is required for each steady state calculation:

- KP Pipe number.
- IOPT Specifies which type of calculation is required:
- ±1 Conditions known at a single node.
 - ±2 Pressure known at two nodes and enthalpy at one of them.
 - ±3 Zero flow in flowpath, enthalpy known at all nodes, pressures determined from gravitational head.
 - ±4 Conditions known in all but one of the flowpaths terminating at an internal connection. The enthalpy and flow at the terminal node of the unknown flowpath are chosen to give zero net enthalpy and mass flow into the connection. The pressure is set equal to that of the other terminal nodes. This process is called a connection balance.
 - ±5 Constant gravity head pump with the head and flowpath power determined to give connection balances at both ends of the flowpath (loop balance).
 - ±6 Pump pressure drop and outlet flowpath conditions from known pump inlet conditions.
 - ±7 Conditions in pipe KP to be calculated from a given pressure at a compressor and known conditions in the pipe on the other side of the compressor.

If IOPT is negative, a listing of the calculated steady state for this flowpath will be produced before any further steady state calculations are made.

The data required for each option are given below:

IOPT = ± 1

- J Node number
- WJ* Flow at node J of flowpath KP (kg s^{-1})
- PJ* Pressure at node J of flowpath KP (Pa)

HJ* Enthalpy (J kg^{-1}) or thermodynamic quality at node J of flowpath KP

For example, to produce a steady state in pipe 1 with a mass flow of 4 kg s^{-1} , with a pressure and quality at node 2 of 8.6 MPa and -0.14 respectively

KP = 1
 IOPT = 1
 J = 2
 WJ = 0, 4.E3
 PJ = 0, 8.6D6
 HJ = 0, -0.14

The steady state finite difference equation will then be solved along flowpath KP in both directions from node J.

IOPT = ± 2

J Node number.

WJ* Estimate of flow at node J of flowpath KP (kg s^{-1}).

PJ* Pressure at node J of flowpath KP (Pa).

HJ* Enthalpy (J kg^{-1}) or thermodynamic quality at node J of flowpath KP.

K Node number.

PK* Pressure at node K in flowpath KP (Pa).

The flow will then be found by iteration and finally the steady state finite difference equations are solved along flowpath KP.

IOPT = ± 3

J Node number.

PJ* Pressure at node J of flowpath KP (Pa).

- H Enthalpies at each node of flowpath KP (J kg^{-1}).
- If the heat slab option is assumed ($\text{TSFP} < 0.0$), TFS is required; otherwise TFC is required.
- TFC Fuel temperatures at each node of flowpath KP (K), or
- TFS Heat slab wetted surface temperatures at each node of flowpath KP (K). For each node the surface temperature of the external heat slab (if specified) should appear first followed in order, by the surface temperatures of the internal heat slabs (as specified in subsection 4.3.3).

NOTE: No temperatures are required for hydraulic nodes of the directly heated type.

The steady state zero flow momentum equation will then be solved along flowpath KP. Any temperatures specified to be zero are set equal to the coolant temperature of that node.

IOPT = ± 4

KC Connection number.

Conditions at the node of flowpath KP next to connection KC will be determined by a connection balance. However, if the connection is not pressure controlled (internal) or the enthalpy is not determined because the resulting flow is zero, conditions at the node are left unchanged. The steady state finite difference equations will then be solved along flowpath KP.

IOPT = ± 5

J Segment at which a fictitious gravity head is to be inserted (between node J and node J+1).

Conditions at each end of the flowpath will be determined by connection balances. The head (Δheight) at segment J and power to coolant are then varied to achieve the required conditions. This option is used for the last pipe to complete a loop.

IOPT = ± 6 - pump calculation.

It is assumed that a steady state has already been established for the pump inlet flowpath. From the known conditions at the pump inlet, the pump head and power are determined for the given initial pump speed to yield the pump outlet conditions. The pump outlet flowpath (KP) steady state equations are then solved.

IOPT = ± 7 - compressor calculation.

KC Connection number of compressor.

PJ* Pressure at node adjoining compressor connection KC in flowpath KP.

It is assumed that the state of the other flowpath joining the compressor is known. If the given pressure cannot be attained, because of limits to the compressor power or discharge temperature, a value corresponding to the limit is substituted. No check is made that the resulting state is consistent with the compressor operating setpoint.

A KP = 0 marks the end of the steady state data.

5. MODIFICATION DETAILS

5.1 Subroutines

The subroutines COEFFM, GEOMP, MASSEQ, NAIAD, RESTRT, SETMAT, STEADM and UPDATE retain their previous functions but have been modified where necessary to facilitate the incorporation of the heat slab model. The modifications are principally concerned with program flow.

The following subroutines also retain their previous functions but have been subjected to considerable change. A brief description of the modifications is presented below.

COEFF A section of code has been added to supervise the calculation of coolant surface heat flux derivatives for the heat slabs.

- FUEL The flux to coolant has been added to the argument list of the subroutine. The steady state surface temperature corresponding to the given heat flux and the known coolant temperature at the selected hydraulic node is calculated.
- INPUT Major sections have been added. There are alternatives to older sections of code; they process the heat slab and hydraulic node type data, load information into the hydraulic and thermal node data arrays and normalise the power distributions.
- STEADY Solves the steady state hydraulic difference equations. Modifications have been made to include the heat slab model and, in particular, to control the steady state iterative solution for heat slabs.

The following subroutines have been added. A brief description of their functions follows.

- COEFFH prints a table of heat slab parameters such as thermal node and surface temperatures, heat fluxes, etc.
- EHSIT performs a single iteration on the steady state 'total' heat flux to coolant for the case of temperature-dependent external boundary heat transfer.
- FELMN performs forward elimination on the set of finite difference equations for a particular heat slab via the main entry to this routine. Back substitution is performed via the entry BSUB.
- HSCOFF is called by COEFF to calculate the heat flux derivatives for a particular heat slab.
- HSEQNS formulates the sets of finite difference equations for all heat slabs along a flowpath and supervises forward elimination. The same coding is used for both steady state and transient calculations. Time derivatives are eliminated from steady state calculations by assigning a very large value (9×10^{30}) to the time step (Δt).

- HSFLUX calculates the actual or estimated 'total' steady state heat flux to coolant at each hydraulic node along a flowpath.
- HSLABP prints a table of the geometry, thermal properties, etc. of the heat slabs along a flowpath.
- HSQX calculates the coefficients of the linear relationship between 'total' heat flux to coolant and the hydraulic parameters (X:W,P,H) for a particular hydraulic node during transient calculations.
- HSSOLN is called by UPDATE for each hydraulic node. New heat slab nodal and surface temperatures and heat fluxes are calculated from the new hydraulic parameters to complete a time step calculation.
- HSSOLV calculates all coolant surface temperatures of heat slabs along a flowpath at the end of a time step after hydraulic network convergence. Back substitution is performed on the heat slab equations.
- HSTEMP calculates the steady state coolant surface temperatures of heat slabs along a flowpath with non-zero coolant flow and performs back substitution on the heat slab equations. The total power to coolant at each hydraulic node is also calculated.
- HSTMPZ is the zero coolant flow equivalent of HSTEMP. This subroutine reads the coolant surface temperatures from the input data stream.
- IHSPOW calculates the total power generated in all internal heat slabs at a particular hydraulic node during steady state calculations.
- QTSLP is a function subprogram which calculates the derivative of heat flux to coolant from an external heat slab with respect to its surface temperature. This is required during the iterative steady state solution in the case of temperature-dependent external boundary heat transfer.

5.2 Common Areas

Three new common areas (\$HS1, \$HS2 and \$HS3) have been introduced; details of these are presented in Tables 1 to 3.

The array TYPNOD is used as a storage area for the heat slab and hydraulic node type data. The second array index (j) identifies a particular heat slab or hydraulic node type. The internal heat slab types are stored initially (j = 1 to NIHTYP) in the order in which they appear in the input stream. Next come the external heat slab types (j = NIHTYP+1 to NIHTYP + NEHTYP). Finally the hydraulic node types are stored from j = HIHTYP + HEHTYP+1 to NIHTYP + NEHTYP + NHNTYP. The first array index i identifies an item of data for a particular type j. The double word (8-byte) array is equated to a single word (4-byte) array NODTYP(40,1) to permit the storage of both single word and double word data.

Table 4 presents details of the storage arrangements. The equated arrays TYPNDH and NDHTYP are a similar storage facility for direct heating types (see Table 5).

The arrays CA, CB, CC, CK, U, HTHS, THTHS, AHS, BHS, CHS, DHS, DQDWHS, DQDPHS, DQDHHS and DQDTHS have a fixed number of elements allocated to each hydraulic node depending upon the number and type of associated heat slabs. The allocation is made up as follows:

(i) $ne + 4$ elements for an external heat slab, plus

(ii) if an inner material is defined, then

(a) $ni + no + 5$, or else

(b) $no + 2$

elements for each internal heat slab, where ne is the number of thermal nodes in an external heat slab and ni and no are the number of thermal nodes in the inner and outer materials, respectively, of the internal heat slab.

Direct heating nodes have one unused element allocated to them. Because of the different nature of the data stored in these arrays, several different forms of data arrangement within the array segments are used. For the sake of brevity these will not be presented in this report.

5.3 Problem Size Restrictions

The code now implemented allows up to fifteen heat slab and hydraulic node types to be defined, and up to a total of ten thermal nodes per heat slab. Up to five different internal plus one external heat slab types may be associated with any hydraulic node type. In addition, up to ten direct heating types may be defined. These restrictions are set quite firmly into the code and considerable checking is done within the subroutine INPUT to ensure that these restrictions are not violated. In the case of any violation, explanatory messages are printed and the program stops. Modification of these restrictions is not trivial.

In addition to the above restrictions, the following restrictions apply:

- (i) the total number of thermal nodes should not exceed 100; and
- (ii) the number of array elements required in the arrays CA, CB, etc. should not exceed 300.

These restrictions may be simply altered by changing array dimensions in the labelled common \$HS1. The code has no means of detecting the violation of such restrictions. This is not inconsistent with older sections of the code, e.g. the specification of more than the maximum number of hydraulic nodes results in no special action. For the benefit of the user, the total number of thermal nodes and the required array storage is provided in the output listing.

6. SAMPLE PROBLEM

A simple problem is presented as an example of the use of NAIAD with the heat slab option. The system (see figure 3) consists of a single horizontal pipe (length, 12 m; internal diameter 0.05 m; wall thickness 0.02 m) in which hot water is flowing. Heat is lost from the pipe wall at a rate which is a linear function of its external surface temperature. Located within the pipe and immersed in the water are two cylindrical heating elements which are of the same length as the pipe. The diameter of each is 0.02 m. One consists of a single material, the other of inner and outer materials (outer material thickness 0.004 m). This system is represented by seven hydraulic nodes. Each of these is of the same type and has one external and two internal

associated heat slabs which represent the pipe wall and the two internal heating elements respectively. The external heat slab is represented by four thermal nodes, the single material heat slab (#1) is represented by four thermal nodes and the two-material internal heat slab (#2) is represented by six thermal nodes - two for the outer material and four for the inner. The values for the thermal properties of the pipe wall and the internal heating element materials, the parameters for the pipe wall losses and the inter-material gap heat transfer coefficient may be found in Appendix A. They are reasonable values but not representative of any particular material or situation.

Initially, water enters one end of the pipe at a pressure of 10 MPa, a mass flow rate of 3 kg s^{-1} and a flow enthalpy of 10 MJ kg^{-1} (equivalent to 504.9 K). With the pressure maintained at 10 MPa at the inlet and a mass flow rate of 3 kg s^{-1} maintained at the outlet, a transient is initiated by raising, linearly with respect to time, the power generated in the internal heating elements from 0 to 60 kW over a time period of 1 s. Thirty per cent of the power is generated in the single material internal heat slab and the remainder in the other internal slab. The transient is followed for two hundred seconds, by which time the system has settled into its final state.

Parts of the listing of the sample problem output are presented as Appendix A. These include:

- (i) The FORTRAN compiler listing of the user routines. Subroutines are called to produce a dump file of problem parameters which may be processed by the moving and static graph plotting programs of Turner [1982]. The section of code in BINITM concerned with the power transient has been included to accommodate a restart of the transient calculation.
- (ii) The SCAN listing of the input data as read. The specification of a number of heat slabs and hydraulic node types and a direct heating node type which are not used in the sample problem have been included for demonstration purposes.
- (iii) The major part of the output listing of the geometry, thermal properties, etc. of the heat slabs along the flowpath produced by the subroutine HSLABP.

- (iv) The listing of the hydraulic and heat slab parameter tables for time zero produced by the subroutines CEOFFM and COEFFH. It should be noted that the parameter TFC, which appears in the hydraulic parameter table, denotes temperature at the centre of the fuel for the original NAIAD fuel model. When the heat slab model is used, this parameter is set to zero. In addition, the parameter THT, the heat transfer indicator, is set to zero in the hydraulic parameter table and values for each heat slab are included in the heat slab parameter table. The listings of these tables at subsequent times during the transient are in the same format and have not been included here.

Figures 4 through 9 show the behaviour of some of the system parameters with respect to time during the power ramp and the approach to the final steady state. These parameters exhibit good behaviour and demonstrate that the calculation proceeds smoothly from the initial to the final state. It has been verified that the final steady state is the same as that produced by a NAIAD steady state calculation for the same system, using the final values of the hydraulic parameters (W, P and H) at the inlet node with a power of 60 kW being generated along the pipe.

7. ACKNOWLEDGEMENT

The author is grateful to Mr W.J. Turner for suggesting this project.

8. REFERENCES

- Bennett, N.W. and Pollard J.P. [1967] - AAEC/TM399.
- Richtmyer, R.D. [1957] - Difference Methods for Initial-value Problems. Interscience Publishers, New York.
- Trimble, G.D. and Turner, W.J. [1974] - AAEC/E378.
- Turner, W.J. [1981] - AAEC/C11.
- Turner, W.J. [1982] - AAEC/E529.

9. NOTATION

- BH Boundary heat transfer parameter for external heat slab ($W m^{-2} K^{-1}$)
- BQ Boundary heat flux parameter for external heat slab ($W m^{-2}$)
- h heat transfer coefficient ($W m^{-2} K^{-1}$)
- k thermal conductivity ($W m^{-1} K^{-1}$)
- ne number of thermal nodes in external heat slab
- NHS number of heat slabs at a particular hydraulic node
- ni number of thermal nodes in inner material of internal heat slab
- no number of thermal nodes in outer material of internal heat slab
- p wetted perimeter (m)
- PC Power to coolant per unit length of flowpath ($W m^{-1}$)
- Q Volumetric power production ($W m^{-3}$)
- q thermal flux ($W m^{-2}$)
- r radial distance (m)
- T temperature (K)
- t time (s)
- th thickness (m)
- X hydraulic parameters of the NAIAD code (mass flow rate : W ($kg s^{-1}$),
pressure : P (Pa) and flow enthalpy : H)
- α temperature extrapolation coefficient

β temperature extrapolation coefficient

Λ volumetric heat capacity ($\text{J m}^{-3} \text{K}^{-1}$)

Subscripts

b external boundary of external heat slab

c the hydraulic fluid (coolant)

d direct heating model/node

e external heat slab

ehs external heat slab/hydraulic fluid interface

g inter-material interface (gap) of internal heat slab

i inner material of internal heat slab

ihs internal heat slab/hydraulic fluid interface

is surface of inner material of internal heat slab

J hydraulic node

j thermal node

k heat slab

o outer material of internal heat slab

oS inner surface of outer material of internal heat slab

S heat slab/hydraulic fluid interface.

Superscript

' parameter value at the end of a finite time step Δt

TABLE 1
LABELLED COMMON "\$HS1"

Variable Name and Dimension	Description	Algebraic Symbol
TYPNOD(20,15)	Heat slab and hydraulic node type data	
TYPNDH(5,8)	Direct node type data	
RAD(100)	Radial distance of thermal node (m)	r
DELR(100)	Radial thickness associated with thermal node (m)	Δr
THCON(100)	Thermal conductivity associated with thermal node ($W m^{-1} K^{-1}$)	k
VHTCAP(100)	Volumetric heat capacity associated with thermal node ($J m^{-3} K^{-1}$)	Λ
POD(100)	Volumetric power density associated with thermal node per unit power generated along flowpath ($W m^{-3} W^{-1}$)	Q
CA(300)		
CB(300)	Coefficients of finite difference	
CC(300)	equations for heat slabs	
CK(300)		
U(300)	Heat slab nodal and surface temperatures and surface and inter-material gap fluxes	T, q
HTHS(300)	Heat slab surface to coolant heat transfer coefficients ($W m^{-2} K^{-1}$)	h
THTHS(300)	Heat slab heat transfer indicators	
AHS(300)	Coefficients for linear relationships between heat slab surface to coolant fluxes and the hydraulic parameters (X:W,P,H)	
BHS(300)		
CHS(300)		
DHS(300)		
DQDWS(300)	Derivative of heat slab to coolant flux with respect to W	$\partial q / \partial w$
DQDPHS(300)	Derivative of heat slab to coolant flux with respect to P	$\partial q / \partial P$
DQDHHS(300)	Derivative of heat slab to coolant flux with respect to H	$\partial q / \partial H$
DQDTHS(300)	Derivative of heat slab to coolant flux with respect to heat slab surface temperature	$\partial q / \partial T_{sk}$
DTSDP(300)	Derivative of coolant saturation	$\partial T_s / \partial P$

temperature with respect to P

NSTN(20) Node number of first thermal node
in flowpath

NFTN(20) Node number of last thermal node
in flowpath

ITYPHN(100) Type of hydraulic node

IEQST(100) Array of indices which point to the
start of heat slab data for a particular
hydraulic node in the arrays CA, CB, CC, CK,
U, HTHS, THTHS, AHS, BHS, CHS, DHS, DQDWHS,
DQDPHS, DQDHHS, and DQDTHS

TABLE 2
LABELLED COMMON "\$HS2"

Variable Name	Description
NEHTYP	Number of external heat slab types
NHNTYP	Number of hydraulic node types with heat slabs
NDNTYP	Number of hydraulic node types with direct heating
IXTRAP	Indicator for type of heat slab temperature extrapolation
NEQ	Total number of finite difference equations for heat slabs
NTHN	Total number of thermal nodes
LGPRT	Indicator for heat slab geometry print
LUPRT	Indicator for heat slab parameter print

TABLE 3
LABELLED COMMON "\$HS3"

Variable Name	Description
SSOP	Logical which indicates whether steady state or transient calculation in progress
NODETP	Logical which indicates whether heat slab model or original fuel model specified

TABLE 4
 STORAGE ARRANGEMENT OF HEAT SLAB AND HYDRAULIC NODE
 TYPE DATA IN THE EQUIVALENCED ARRAYS TYPNOD AND NODTYP

i_{dw}^*	Internal Heat Slabs	$j \rightarrow$	External Heat Slabs	$j \rightarrow$	Hydraulic Nodes	i_{sw}^*	
1	NIHNDC		NEHNDE		ISLIP	1	
	NIHNDF				IFR	2	
2	REC		BH			IHTRAN	3
							4
3	RTHKC		BQ			DE	5
							6
4	LAMDAC		RIEH			A	7
							8
5	HSKC		RTHKEH			ROUGH	9
							10
6	LAMDAF		LAMDEH			ITYPEH	11
						MIHTYP	12
7	HSKF		KEH			FRACPE	13
							14
8	HGAP		HPEH			ITYPIH(1)	15
						NIH(1)	16
9	HPC		PDEH(r_1)			FRACPI(1)	17
							18
10	PDIH(r_1)		PDEH($r_2 > r_1$)			ITYPIH(2)	19
						NIH(2)	20

(Continued)

i_{dw}^*	Internal Heat Slabs	$j \rightarrow$	External Heat Slabs	$j \rightarrow$	Hydraulic Nodes	i_{sw}^*
11	$PDIH(r_2 < r_1)$		$PDEH(r_3)$		FRACPI(2)	21
						22
12	$PDIH(r_3)$		$PDEH(r_4)$		ITYPIH(3)	23
					NIH(3)	24
13	$PDIH(r_4)$		$PDEH(r_5)$		FRACPI(3)	25
						26
14	$PDIH(r_5)$		$PDEH(r_6)$		ITYPIH(4)	27
					NIH(4)	28
15	$PDIH(r_6)$		$PDEH(r_7)$		FRACPI(4)	29
						30
16	$PDIH(r_7)$		$PDEH(r_8)$		ITYPIH(5)	31
					NIH(5)	32
17	$PDIH(r_8)$		$PDEH(r_9)$		FRACPI(5)	33
						34
18	$PDIH(r_9)$		$PDEH(r_{10})$			35
						36
19	$PDIH(r_{10})$					37
						38
20						39
						40

- * i_{dw} : first array index of TYPNOD;
 i_{sw} : first array index of NODTYP;
 j : second array index of TYPNOD and NODTYP.

Symbols are as defined in Sections 4.3.1, 4.3.2 and 4.3.3 .

TABLE 5
 STORAGE ARRANGEMENT OF DIRECTLY HEATED NODE TYPE
 DATA IN THE EQUIVALENCED ARRAYS TYPNDH AND NDHTYP

i_{dw}^*	$j^* \rightarrow$	i_{sw}^*
1	ISLIP	1
1	IFR	2
2	DE	3
2		4
3	A	5
3		6
4	ROUGH	7
4		8

- * i_{dw} : first array index of TYPNDH;
- i_{sw} : first array index of NDHTYP;
- j : second array index of TYPNDH and NDHTYP.

Symbols are as defined in Section 4.3.4 .

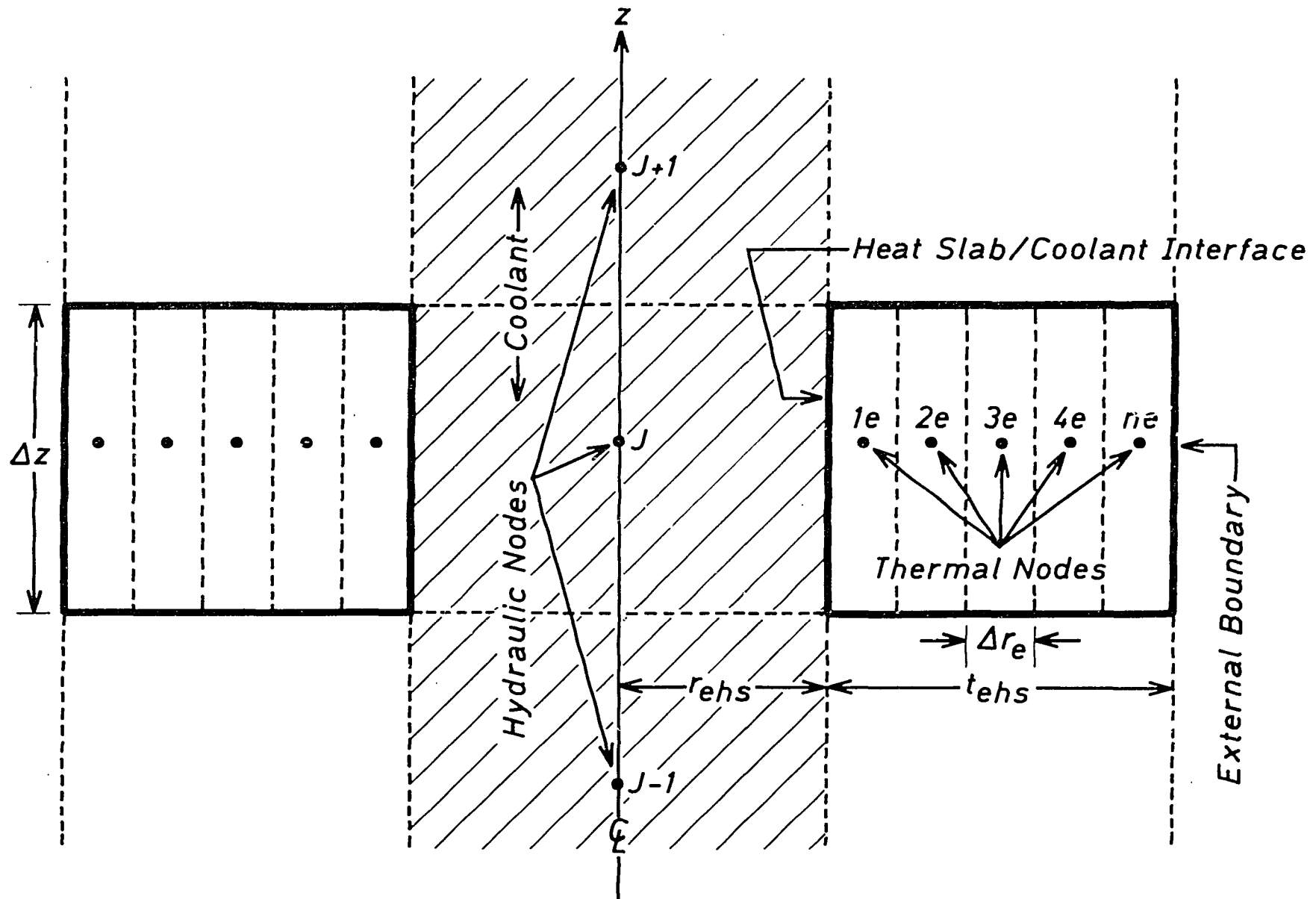


FIGURE 1. EXTERNAL HEAT SLAB MODEL

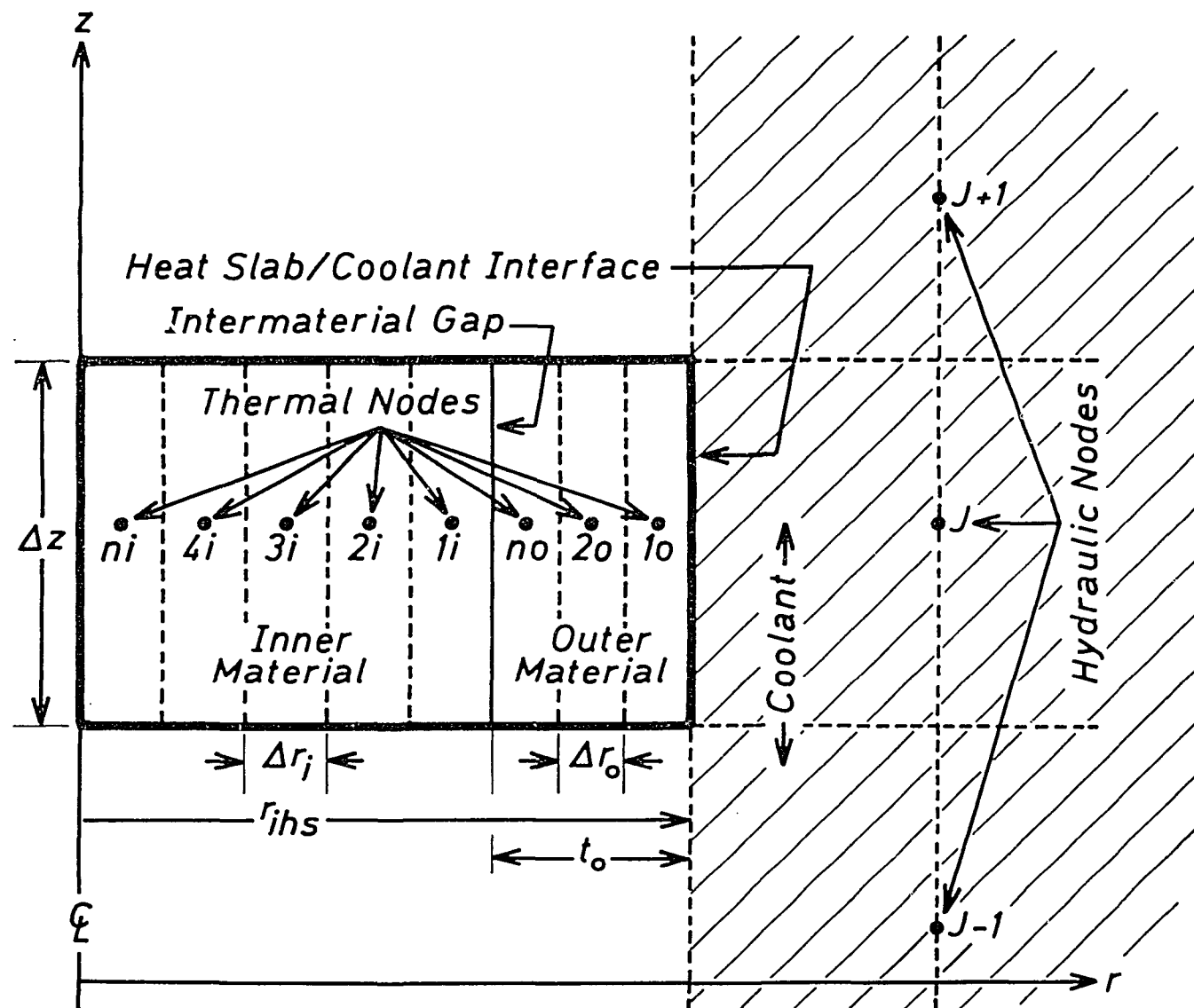
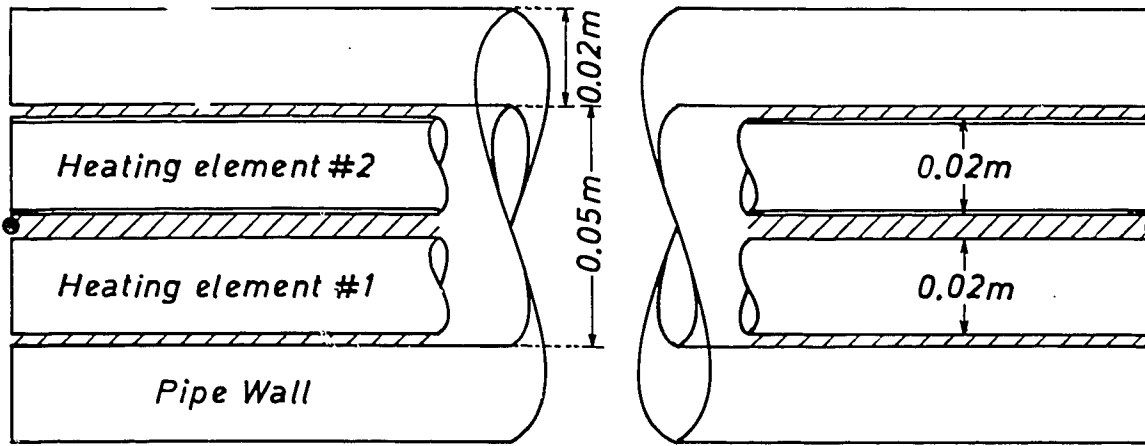
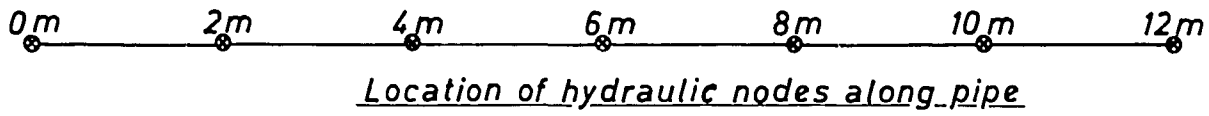


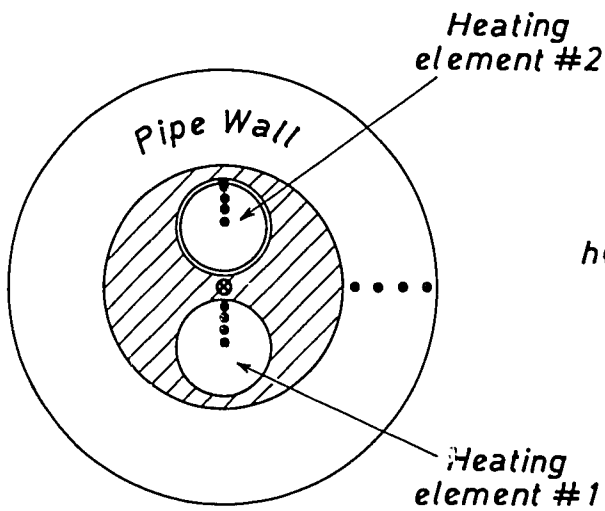
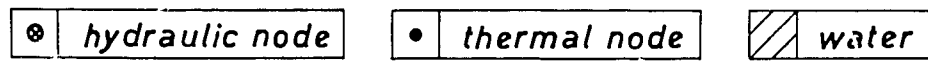
FIGURE 2. INTERNAL HEAT SLAB MODEL



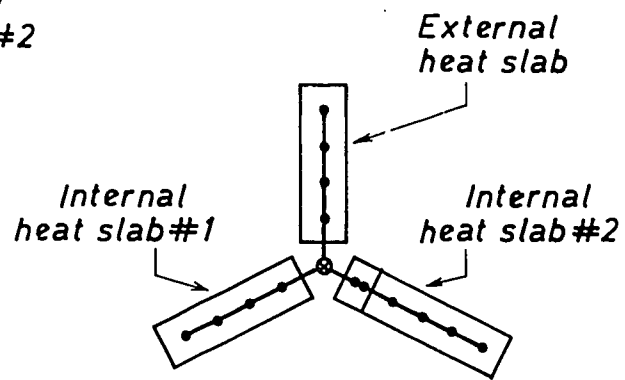
Side View - Sample Problem System



Location of hydraulic nodes along pipe



End view - Sample Problem System



Schematic arrangement of thermal nodes at each hydraulic node

FIGURE 3. SAMPLE PROBLEM SYSTEM

HEAT SLAB SAMPLE PROBLEM

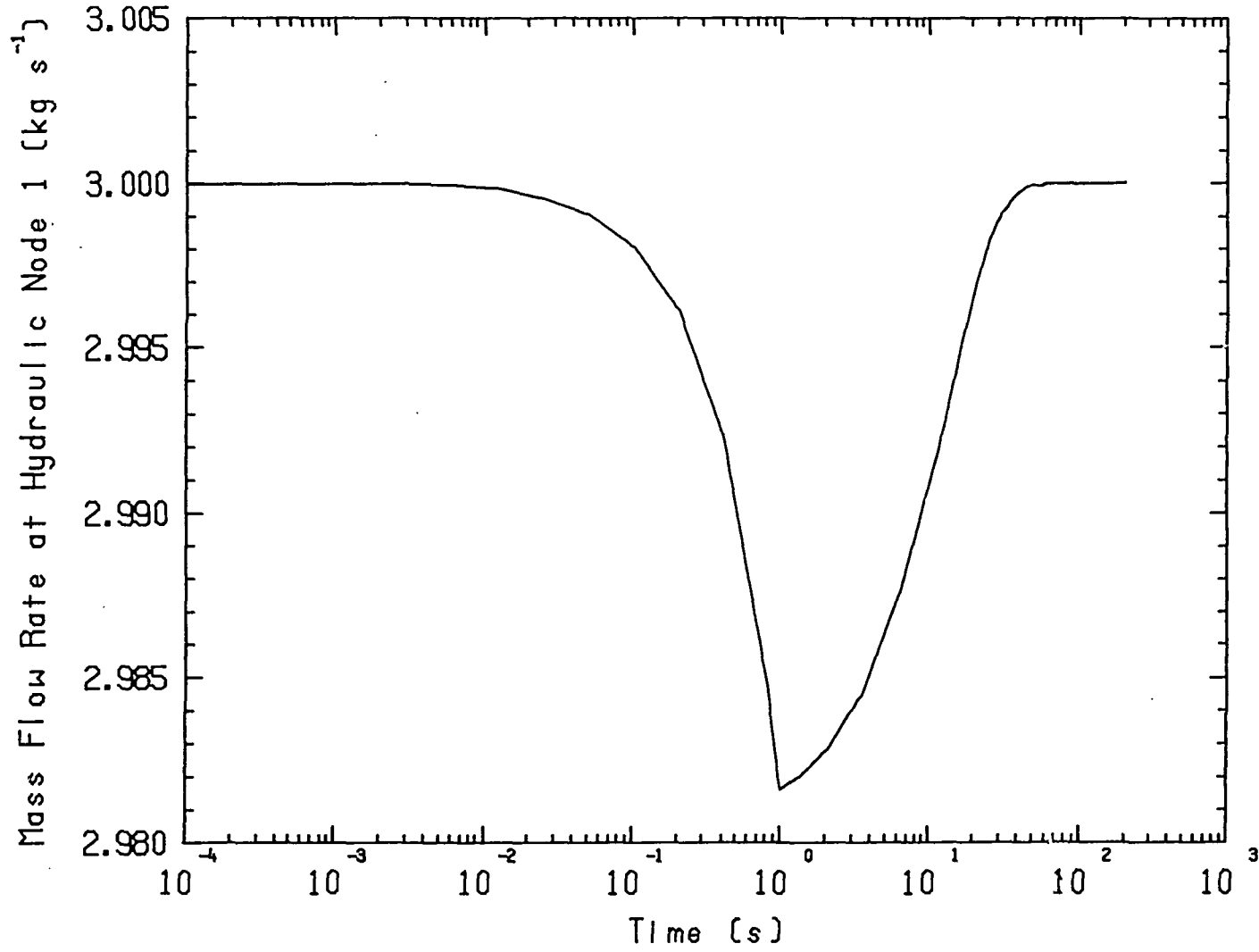


FIGURE 4. MASS FLOW RATE AT HYDRAULIC NODE 1

HEAT SLAB SAMPLE PROBLEM

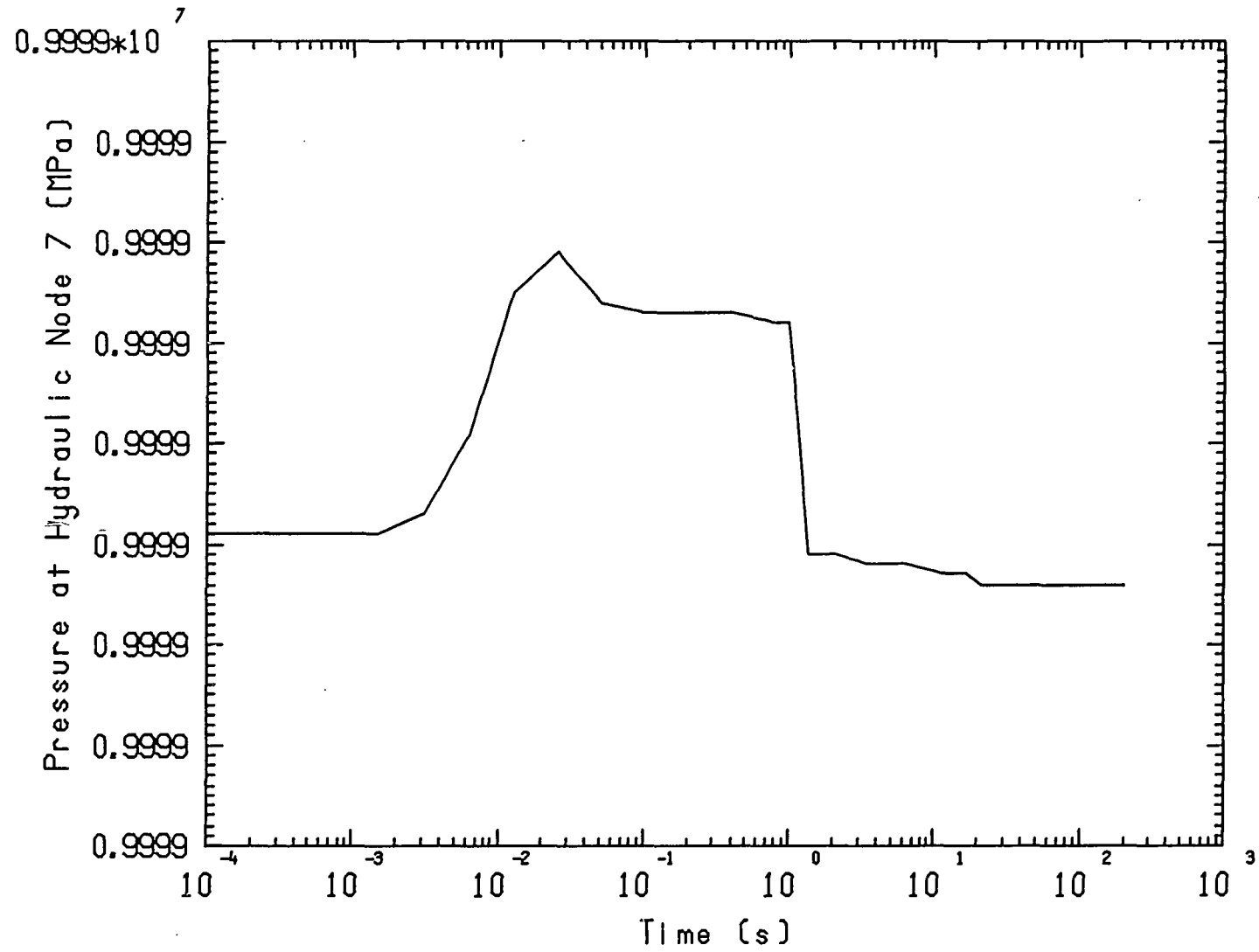


FIGURE 5. PRESSURE AT HYDRAULIC NODE 7

HEAT SLAB SAMPLE PROBLEM

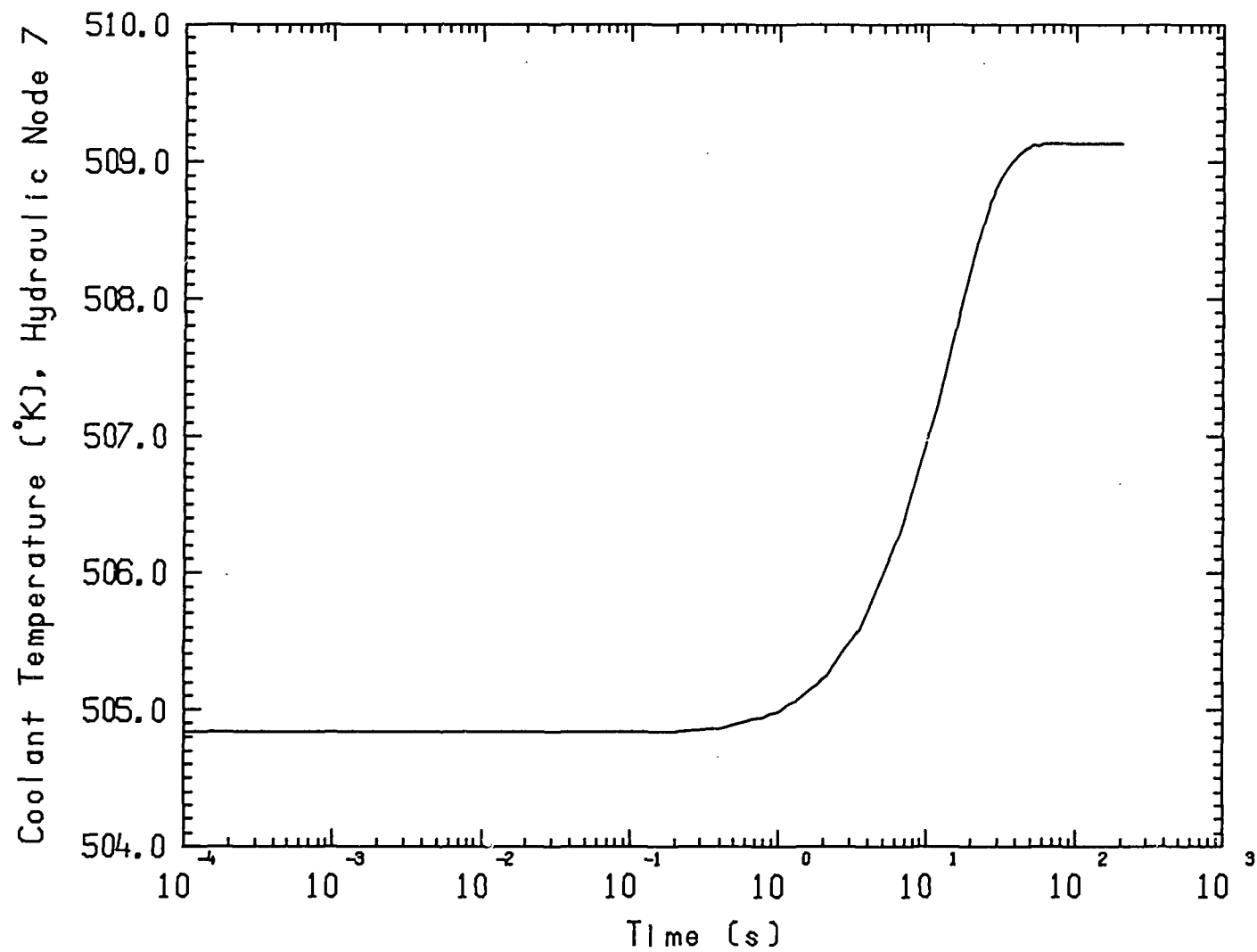


FIGURE 6. COOLANT TEMPERATURE AT HYDRAULIC NODE 7

HEAT SLAB SAMPLE PROBLEM

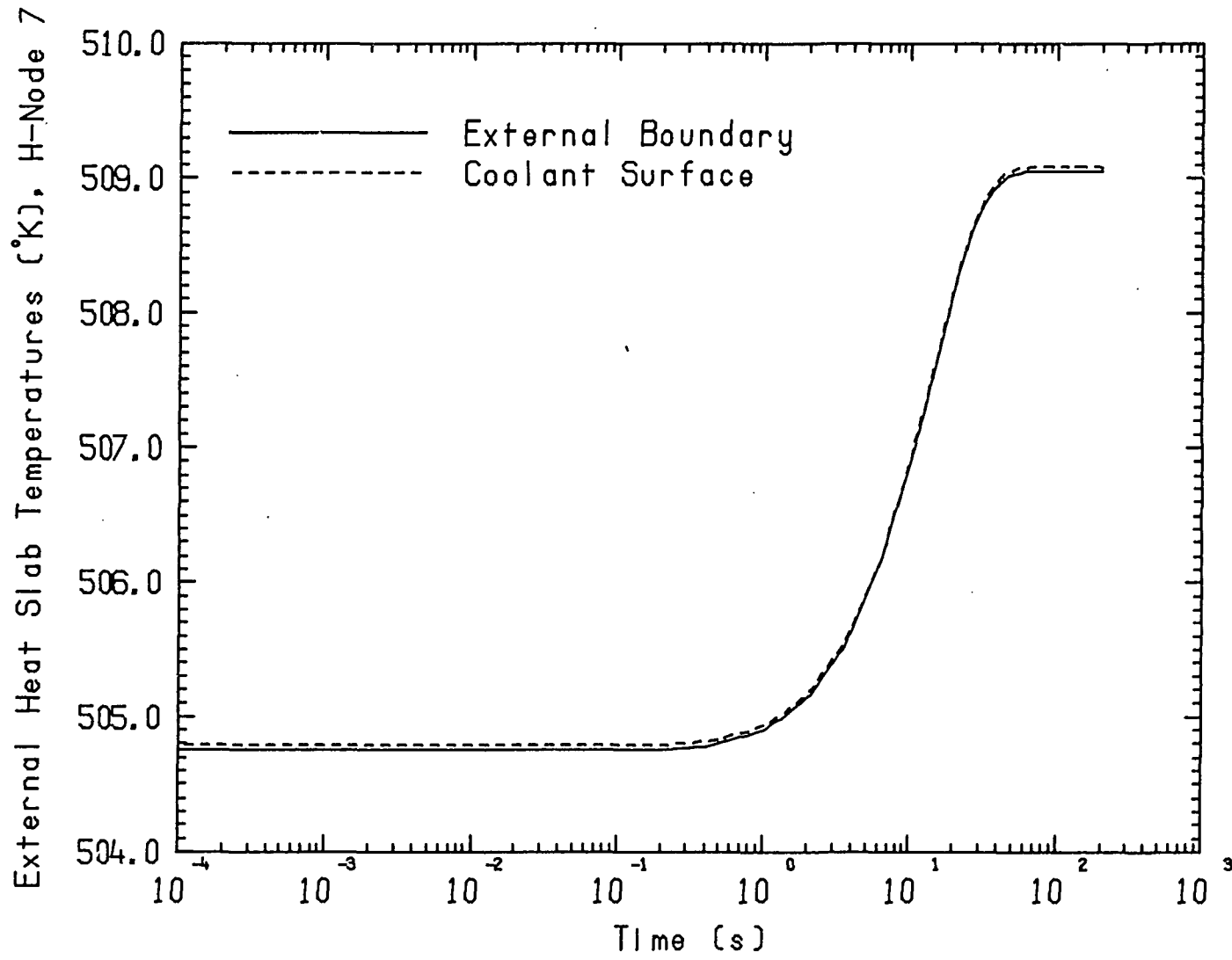


FIGURE 7. EXTERNAL HEAT SLAB TEMPERATURES AT HYDRAULIC NODE 7

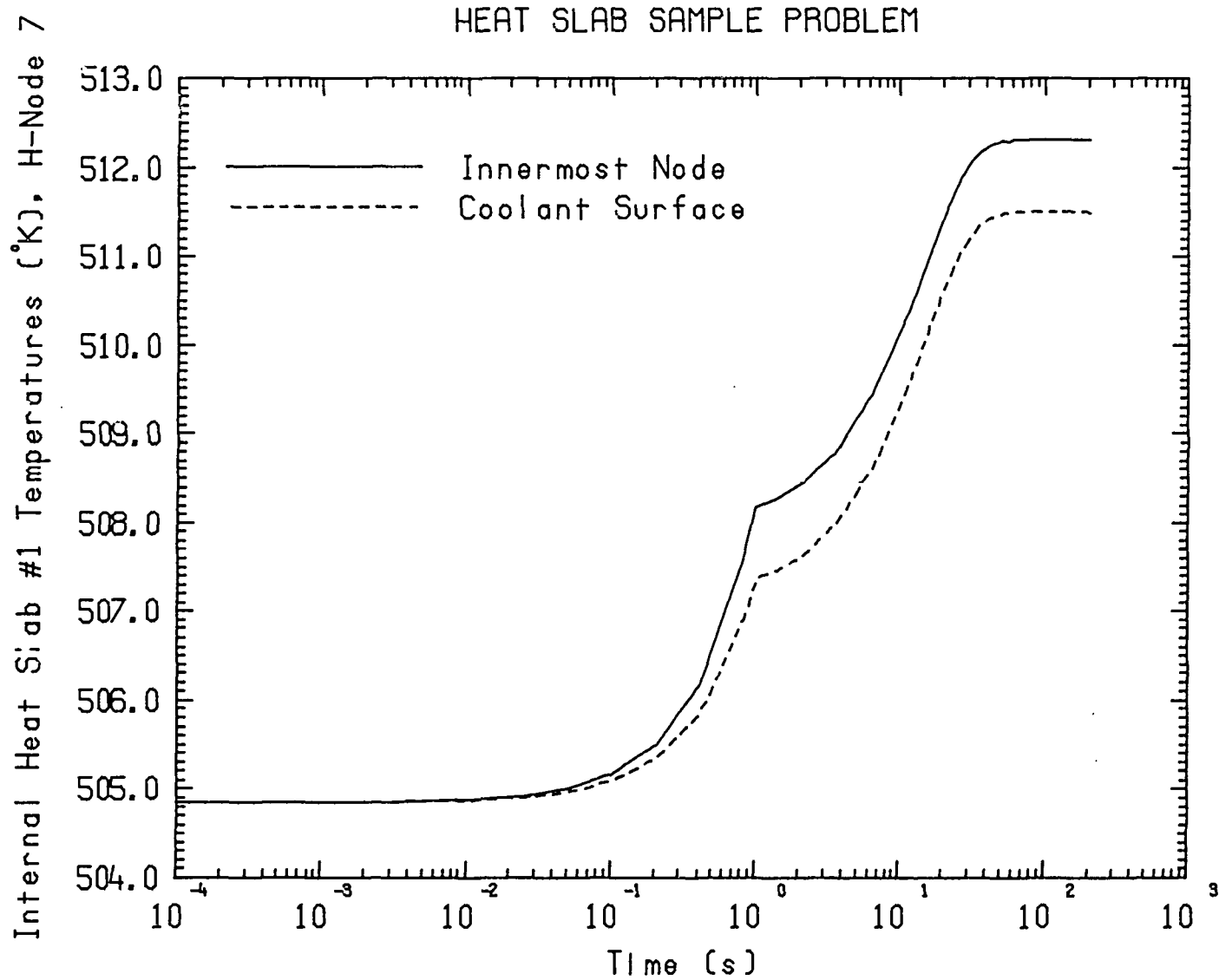


FIGURE 8. INTERNAL HEAT SLAB 1 TEMPERATURES AT HYDRAULIC NODE 7

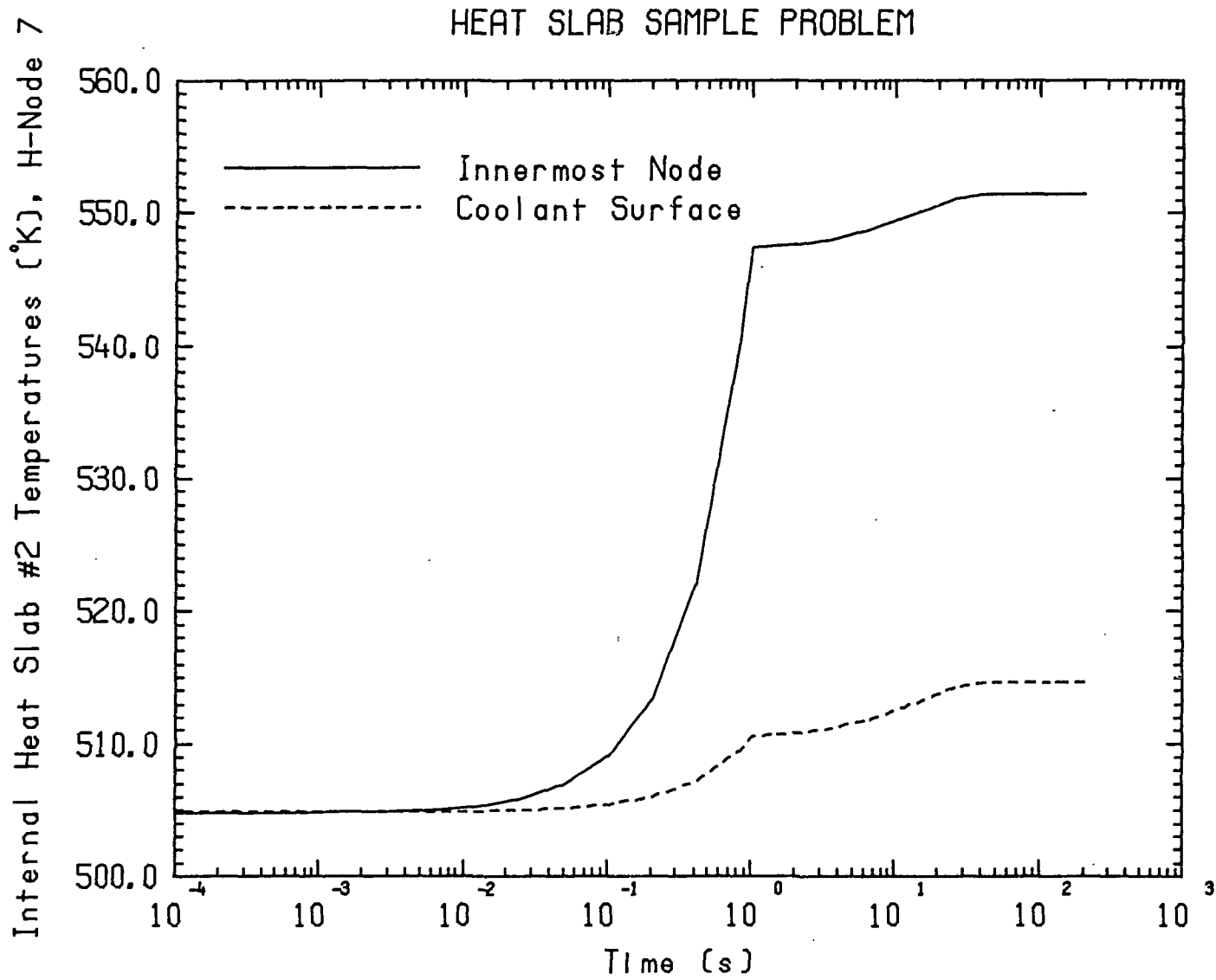


FIGURE 9. INTERNAL HEAT SLAB 2 TEMPERATURES AT HYDRAULIC NODE 7


```

ISN 0039      RETURN
ISN 0040      999 FCRMAT(20A4)
ISN 0041      ENTRY BCSETM
ISN 0042      TEND=TIME+DELT
ISN 0043      IF(TEND.GE.TTIME.AND.TIME.LT.TTIME) GO TO 5
ISN 0045      GO TO 10
ISN 0046      5 DELT=TTIME-TIME
ISN 0047      TEND=TTIME
ISN 0048      10 DPOW=DMIN1(1.00,TEND/TTIME)
ISN 0049      PGENP(1)=DPOW+DPOW*(PMAX-PCWP)
ISN 0050      RETURN
ISN 0051      ENTRY TDUMPM(IW)
ISN 0052      CALL TDUMP(8,TIME,1,DELT,1,W(1),N,P(1),N,H(1),N,
&              U(2),6,U(9),5,U(15),5,U(21),4,TFS(1),1,CT(1),1,
&              U(152),6,U(159),5,U(165),5,U(171),4,TFS(7),1,CT(7),1,
&              U(1),1,U(8),1,U(14),1,U(20),1,U(25),1,FLUX(1),1,
&              U(151),1,U(158),1,U(164),1,U(170),1,U(175),1,FLUX(7),1,
&              PGEN,1,PTCT,1)
ISN 0053      RETURN
ISN 0054      END

```

CPTICNS IN EFFECT NAME= MAIN,OPT=02,LINECNT=55,SIZE=0000K,

CPTICNS IN EFFECT SOURCE,EBCOIC,NOLIST,NGOECK,LOAD,NCMAP,NOEDIT,NOID,NOXREF

STATISTICS SOURCE STATEMENTS = 53 ,PROGRAM SIZE = 1784

STATISTICS NO DIAGNOSTICS GENERATED

***** END OF COMPILATION *****

401K BYTES OF CORE NOT USED

STATISTICS NO DIAGNOSTICS THIS STEP

NAIAD-1981. A HYDRAULIC NETWORK PROGRAM
NAIAC-1981. A HYDRAULIC NETWORK PROGRAM
NAIAC-1981. A HYDRAULIC NETWORK PROGRAM
NAIAC-1981. A HYDRAULIC NETWORK PROGRAM

***** TEST - STANDARD NAIAD (HEAT SLAB VERSION) *****

31 MAY 82 82151 12 HRS 30 MIN 1.76 SEC

INPUT DATA AS READ :-

1 PIPE 2 CONNECTIONS GRAVITY 9.8043 TOL 1.0-8
ITMAX 15 SMIN 1.0-4 SMAX 5.00 CTAR 1.0-2
CMAX 2.0-2 RCMAX 1.0-2 CINC 2.00 TMAX 200.0
KFP 10 TSFP -220.00
NIHTYP 4 NEHTYP 2 NHNTYP 9 NDNTYP 1 ITRAP 1
1 TC PRINT HEAT SLAB GEOMETRY
1 TC PRINT HEAT SLAB TEMPERATURES AND FLUXES

* DEFINING INTERNAL HEAT SLAB TYPES
* INTERNAL HEAT SLAB TYPE 1
1 CLAD NCDE
REC 0.02 RTHKC 0.02 VHTCAP 99.0 THCON 199.0
HPC 0.00 PDIH 1.0
*** SAMPLE ***
*** NOT USED ***

* INTERNAL HEAT SLAB TYPE 2
4 CLAD NCDES
REC 0.02 RTHKC 0.02 VHTCAP 99.0 THCON 199.0
HP 0.125 PDIH 1.0 1.5 2.0 3.0

* INTERNAL HEAT SLAB TYPE 3
1 CLAD NCDE
REC 0.02 RTHKC 0.005 VHTCAP 99.0 THCON 199.0
1 FUEL NCDE VHTCAP 88.0 THCON 188.0 HGAP 500.0
HP 0.0 PDIH 1.0 2.0
*** SAMPLE ***
*** NOT USED ***

* INTERNAL HEAT SLAB TYPE 4
2 CLAD NCDES
REC 0.02 RTHKC 0.004 VHTCAP 99.0 THCON 199.0
4 FUEL NCDES VHTCAP 88.0 THCON 188.0 HGAP 1000.0
HP 0.0 PDIH 0.0 0.0 1.0 1.0 1.0 1.0

* DEFINING EXTERNAL HEAT SLAB TYPES
* EXTERNAL HEAT SLAB TYPE 1
1 NCDE BH 0.0 BQ 0.0
RADIUS 0.05 RTHKEH 0.02 VHTCAP 77.0 THCON 177.0
HP 0.0 PDEH 1.0
*** SAMPLE ***
*** NOT USED ***

* EXTERNAL HEAT SLAB TYPE 2
4 NCDES BH 1.0 BQ -300.0
RADIUS 0.05 RTHKEH 0.02 VHTCAP 77.0 THCON 177.0
HP 0.0 PCEH 1.0 2.0 2.0 1.0

* DEFINING HYDRAULIC NODE TYPES
* HYDRAULIC NODE TYPE 1
ISLIP 0 IFR 1 ITRAN 0
DE 0.10 A 0.0 ROUGH 1.0-5
ITYEH 1 FRACPE 1.0
0 INTERNAL HEAT SLABS
*** SAMPLE ***
*** NOT USED ***

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(Continued)

```

-----
* HYDRAULIC NODE TYPE 2                                     *** SAMPLE ***
ISLIP 1 IFR 2 IHTRAN 1                                     *** NOT USED ***
DE 0.0 A 7.854D-3 ROUGH 2.0-5
ITYPEH 2 FRACPE 100.0
O INTERNAL HEAT SLABS
-----
* HYDRAULIC NODE TYPE 3                                     *** SAMPLE ***
ISLIP 2 IFR 3 IHTRAN 0                                     *** NOT USED ***
DE 0.09165 A 0.0 ROUGH 3.0-5
ITYPEH 0 MIHTYP 1
ITYPIH 1 NIH 1 FRACPI 50.0
-----
* HYDRAULIC NODE TYPE 4                                     *** SAMPLE ***
ISLIP 3 IFR 4 IHTRAN 1                                     *** NOT USED ***
DE 0.0 A 6.5973D-3 ROUGH 4.0-5
ITYPEH 0 MIHTYP 1
ITYPIH 2 NIH 1 FRACPE 1.0
-----
* HYDRAULIC NODE TYPE 5                                     *** SAMPLE ***
ISLIP 4 IFR 1 IHTRAN 0                                     *** NOT USED ***
DE 0.09165 A 0.0 ROUGH 5.0-5
ITYPEH 0 MIHTYP 1
ITYPIH 3 NIH 1 FRACPI 1.0
-----
* HYDRAULIC NODE TYPE 6                                     *** SAMPLE ***
ISLIP 5 IFR 2 IHTRAN 1                                     *** NOT USED ***
DE 0.0 A 6.5973D-3 ROUGH 6.0-5
ITYPEH 0 MIHTYP 1
ITYPIH 4 NIH 1 FRACPI 1.0
-----
* HYDRAULIC NODE TYPE 7                                     *** SAMPLE ***
ISLIP 6 IFR 3 IHTRAN 0                                     *** NOT USED ***
DE 0.09165 A 0.0 ROUGH 7.0-5
ITYPEH 1 FRACPE 0.1 MIHTYP 1
ITYPIH 1 NIH 1 FRACPI 0.9
-----
* HYDRAULIC NODE TYPE 8                                     *** SAMPLE ***
ISLIP 7 IFR 4 IHTRAN 1                                     *** NOT USED ***
DE 0.0 A 5.3407D-3 ROUGH 8.0-5
ITYPEH 2 FRACPE 0.0 MIHTYP 2
ITYPIH 2 NIH 1 FRACPE 3.0
ITYPIH 4 NIH 1 FRACPE 7.0
-----
* HYDRAULIC NODE TYPE 9                                     *** SAMPLE ***
ISLIP 8 IFR 1 IHTRAN 0                                     *** NOT USED ***
DE 0.08246 A 0.0 ROUGH 9.0-5
ITYPEH 2 FRACPE 0.1 MIHTYP 1
ITYPIH 4 NIH 2 FRACPE 0.45
-----
* DIRECT HEATING NODE TYPE 1                               *** SAMPLE ***
ISLIP 7 IFR 4 DE 0.0 A 5.3407D-3 ROUGH 9.0-5           *** NOT USED ***
-----
* DATA FOR THE PIPE
7 HYDRAULIC NODES START AT CONN 1 END AT CONN 2
POWER GENERATED 0.0 WATTS
HYDRAULIC NODE TYPES 7*8
Z 0.0(2.0)12.0 KW 7*0
GSINT 6*0.0 ORIK 6*0 EDIFF 6*0.00
POWER DISTRIBUTION 7*1.0
-----

```

* CONNECTIONS
 CONNECTION 1 IS EXPLICIT 0 PRESSURE CONTROLLED 2
 CONNECTION 2 IS EXPLICIT 0 FLOW CONTROLLED 1
 END CONNECTION DATA 0

*** SSTATE TABLE : STANDARD SSTATE TABLE - GENERATED USING ASTEM PACKAGE

18 NOV 81

* STEADY STATE
 PIPE 1 CPT 1 NOCE 1
 FLOW 0 3.0
 PRESSURE 0 1.007
 ENTHALPY 0 1.06
 END DATA 0
 * MY DATA
 MAXIMUM POWER 6.04 TRANSIENT DURATION 1.0 SEC
 NF -1 FOR NEW FILE

*** FILE NAME GN PSEUDO FILE 1 UNIT 8 IS
 ***** TEST - STANDARD NAIAD (HEAT SLAB VERSION) *****

31 MAY 82 12 HRS 30 MIN 11.73 SEC 82151

***** TEST - STANDARD NAIAD (HEAT SLAB VERSION) *****

31 MAY 82 82151 12 HRS 30 MIN 1.76 SEC

 *** NUMBER OF THERMAL NODES - 98 ***
 *** REQUIRED ARRAY STORAGE - 175 ELEMENTS ***

PIPE NUMBER 1 JOINS CONNECTIONS 1 AND 2
 CONNECTION 1 HAS GIVEN PRESSURE BOUNDARY CONDITION
 CONNECTION 2 HAS GIVEN MASSFLOW BOUNDARY CONDITION

NOCE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DMT	SEG	GSINT	ORIF	EDIFF	DZ
1	0.0	0.0825	0.56	5.341D-03	0.0	0.0	8.333D-02	8.00D-05	CISM	SBBL	1	1	0.0	0.0	0.0	2.00
2	2.00	0.0825	0.56	5.341D-03	0.0	0.0	1.667D-01	8.00D-05	CISM	SBBL	1	2	0.0	0.0	0.0	2.00
3	4.00	0.0825	0.56	5.341D-03	0.0	0.0	1.667D-01	8.00D-05	CISM	SBBL	1	3	0.0	0.0	0.0	2.00
4	6.00	0.0825	0.56	5.341D-03	0.0	0.0	1.667D-01	8.00D-05	CISM	SBBL	1	4	0.0	0.0	0.0	2.00
5	8.00	0.0825	0.56	5.341D-03	0.0	0.0	1.667D-01	8.00D-05	CISM	SBBL	1	5	0.0	0.0	0.0	2.00
6	10.0	0.0825	0.56	5.341D-03	0.0	0.0	1.667D-01	8.00D-05	CISM	SBBL	1	6	0.0	0.0	0.0	2.00
7	12.0	0.0825	0.56	5.341D-03	0.0	0.0	8.333D-02	8.00D-05	CISM	SBBL	1					

*** HEAT SLABS AT HYDRAULIC NOCE 1 ***

TH.NOCE	RADIUS	DELTR	TH.COND.	VOL.HEAT CAP.	PWR.DENS.	POWER	WETTED PERIMETER
EXTERNAL HEAT SLAB - TYPE 2							
1	5.25000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	3.14159D-01
2	5.75000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
3	6.25000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
4	6.75000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	H/S POWER 0.0
INTERNAL HEAT SLAB 1 - TYPE 2 - THERE ARE 1 OF THESE							
5	1.75000D-02	5.00000D-03	1.99000D+02	9.90000D+01	1.36170D+01	0.0	1.25000D-01

(Continued)

6	1.25000D-02	5.00000E-03	1.99000D+02	9.90000D+01	2.04255D+01	0.0	
7	7.50000D-03	5.00000D-03	1.99000D+02	9.90000D+01	2.72340D+01	0.0	
8	2.50000D-03	5.00000E-03	1.99000D+02	9.90000D+01	4.08511D+01	0.0	H/S POWER 0.0
INTERNAL HEAT SLAB 2 - TYPE 4 - THERE ARE 1 OF THESE							WETTED PERIMETER 1.25664D-01
CLAD							
9	1.50000D-02	2.00000D-03	1.99000D+02	9.90000D+01	0.0	0.0	
10	1.70000D-02	2.00000D-03	1.99000D+02	9.90000D+01	0.0	0.0	H/S POWER 0.0
FUEL							
11	1.40000D-02	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	
12	1.00000D-02	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	
13	6.00000D-03	4.00000E-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	
14	2.00000D-03	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	H/S POWER 0.0
*** HEAT SLABS AT HYDRAULIC NOCE 2 ***							
EXTERNAL HEAT SLAB - TYPE 2							WETTED PERIMETER 3.14159D-01
TH.NCDE	RADIUS	DELTR	TH.COND.	VOL.HEAT CAP.	PWR.DENS.	POWER	
15	5.25000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
16	5.75000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
17	6.25000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
18	6.75000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	H/S POWER 0.0
INTERNAL HEAT SLAB 1 - TYPE 2 - THERE ARE 1 OF THESE							WETTED PERIMETER 1.25000D-01
CLAD							
19	1.75000D-02	5.00000E-03	1.99000D+02	9.90000D+01	1.36170D+01	0.0	
20	1.25000D-02	5.00000D-03	1.99000D+02	9.90000D+01	2.04255D+01	0.0	
21	7.50000D-03	5.00000D-03	1.99000D+02	9.90000D+01	2.72340D+01	0.0	
22	2.50000D-03	5.00000D-03	1.99000D+02	9.90000D+01	4.08511D+01	0.0	H/S POWER 0.0
INTERNAL HEAT SLAB 2 - TYPE 4 - THERE ARE 1 OF THESE							WETTED PERIMETER 1.25664D-01
CLAD							
23	1.90000D-02	2.00000E-03	1.99000D+02	9.90000D+01	0.0	0.0	
24	1.70000D-02	2.00000D-03	1.99000D+02	9.90000D+01	0.0	0.0	H/S POWER 0.0
FUEL							
25	1.40000D-02	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	
26	1.00000D-02	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	
27	6.00000D-03	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	
28	2.00000D-03	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	H/S POWER 0.0
*** HEAT SLABS AT HYDRAULIC NODE 3 ***							
EXTERNAL HEAT SLAB - TYPE 2							WETTED PERIMETER 3.14159D-01
TH.NCDE	RADIUS	DELTR	TH.COND.	VOL.HEAT CAP.	PWR.DENS.	POWER	
29	5.25000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
30	5.75000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
31	6.25000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
32	6.75000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	H/S POWER 0.0
INTERNAL HEAT SLAB 1 - TYPE 2 - THERE ARE 1 OF THESE							WETTED PERIMETER 1.25000D-01
CLAD							
33	1.75000D-02	5.00000D-03	1.99000D+02	9.90000D+01	1.36170D+01	0.0	
34	1.25000D-02	5.00000D-03	1.99000D+02	9.90000D+01	2.04255D+01	0.0	
35	7.50000D-03	5.00000D-03	1.99000D+02	9.90000D+01	2.72340D+01	0.0	
36	2.50000D-03	5.00000D-03	1.99000D+02	9.90000D+01	4.08511D+01	0.0	H/S POWER 0.0
INTERNAL HEAT SLAB 2 - TYPE 4 - THERE ARE 1 OF THESE							WETTED PERIMETER 1.25664D-01
CLAD							
37	1.90000D-02	2.00000D-03	1.99000D+02	9.90000D+01	0.0	0.0	

*** HEAT SLABS AT HYDRAULIC NODE 6 ***

TH.NCDE	RADIUS	DELTP	TH.CCND.	VOL.HEAT CAP.	PR.DENS.	POWER	
EXTERNAL HEAT SLAB - TYPE 2							WETTED PERIMETER 3.14159D-01
71	5.25000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
72	5.75000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
73	6.25000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
74	6.75000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	H/S POWER 0.0
INTERNAL HEAT SLAB 1 - TYPE 2 - THERE ARE 1 OF THESE							WETTED PERIMETER 1.25000D-01
CLAC							
75	1.75000D-02	5.00000D-03	1.99000D+02	9.90000D+01	1.36170D+01	0.0	
76	1.25000D-02	5.00000D-03	1.99000D+02	9.90000D+01	2.04255D+01	0.0	
77	7.50000D-03	5.00000D-03	1.99000D+02	9.90000D+01	2.72340D+01	0.0	
78	2.50000D-03	5.00000D-03	1.99000D+02	9.90000D+01	4.08511D+01	0.0	H/S POWER 0.0
INTERNAL HEAT SLAB 2 - TYPE 4 - THERE ARE 1 OF THESE							WETTED PERIMETER 1.25664D-01
CLAC							
79	1.90000D-02	2.00000D-03	1.99000D+02	9.90000D+01	0.0	0.0	
80	1.70000D-02	2.00000D-03	1.99000D+02	9.90000D+01	0.0	0.0	H/S POWER 0.0
FUEL							
81	1.40000D-02	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	
82	1.00000D-02	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	
83	6.00000D-03	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	
84	2.00000D-02	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	H/S POWER 0.0

*** HEAT SLABS AT HYDRAULIC NODE 7 ***

TH.NCDE	RADIUS	DELTP	TH.CCND.	VOL.HEAT CAP.	PR.DENS.	POWER	
EXTERNAL HEAT SLAB - TYPE 2							WETTED PERIMETER 3.14159D-01
85	5.25000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
86	5.75000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
87	6.25000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	
88	6.75000D-02	5.00000D-03	1.77000D+02	7.70000D+01	0.0	0.0	H/S POWER 0.0
INTERNAL HEAT SLAB 1 - TYPE 2 - THERE ARE 1 OF THESE							WETTED PERIMETER 1.25000D-01
CLAC							
89	1.75000D-02	5.00000D-03	1.99000D+02	9.90000D+01	1.36170D+01	0.0	
90	1.25000D-02	5.00000D-03	1.99000D+02	9.90000D+01	2.04255D+01	0.0	
91	7.50000D-03	5.00000D-03	1.99000D+02	9.90000D+01	2.72340D+01	0.0	
92	2.50000D-03	5.00000D-03	1.99000D+02	9.90000D+01	4.08511D+01	0.0	H/S POWER 0.0
INTERNAL HEAT SLAB 2 - TYPE 4 - THERE ARE 1 OF THESE							WETTED PERIMETER 1.25664D-01
CLAC							
93	1.90000D-02	2.00000D-03	1.99000D+02	9.90000D+01	0.0	0.0	
94	1.70000D-02	2.00000D-03	1.99000D+02	9.90000D+01	0.0	0.0	H/S POWER 0.0
FUEL							
95	1.40000D-02	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	
96	1.00000D-02	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	
97	6.00000D-03	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	
98	2.00000D-03	4.00000D-03	1.88000D+02	8.80000D+01	7.25315D+01	0.0	H/S POWER 0.0

*** TOTAL POWER ALONG FLOW PATH - 0.0 WATTS ***

***** TEST - STANDARD NAIAD (HEAT SLAB VERSION) *****

31 MAY 82 82151 12 HRS 30 MIN 1.76 SEC

DATA FOR RESTART WRITTEN ON DUMP FILE 1 UNIT 7

*** FILE NAME ON PSEUDO FILE 1 UNIT 7 IS

(Continued)

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*** HEAT SLAB TEMPERATURES AT HYDRAULIC NODE 3 ***

	EHS	IHS1	IHS2
BOUNDARY	504.805	504.889	504.889
	504.808	504.889	504.889
	504.814	504.889	504.889
	504.821	504.889	504.889
	504.828	504.889	504.889
SURFACE	504.832	SURFACE 504.889	SURFACE 504.889
			504.889
			504.889
			504.889
			504.889

COOLANT TEMP 504.889
 HT 5.05859D+03 5.05859D+03 5.05859D+03
 THT 1.0 1.0 1.0

EXTERNAL HEAT SLAB FLUXES: COOLANT SURFACE -2.86727D+02 BOUNDARY 2.04805D+02
 INTERNAL HEAT SLAB #1 FLUXES: COOLANT SURFACE 0.0
 INTERNAL HEAT SLAB #2 FLUXES: COOLANT SURFACE 0.0 FUEL/CLAD GAP -3.41061D-09

*** HEAT SLAB TEMPERATURES AT HYDRAULIC NODE 4 ***

	EHS	IHS1	IHS2
BOUNDARY	504.792	504.876	504.876
	504.795	504.876	504.876
	504.801	504.876	504.876
	504.808	504.876	504.876
	504.815	504.876	504.876
SURFACE	504.819	SURFACE 504.876	SURFACE 504.876
			504.876
			504.876
			504.876
			504.876

COOLANT TEMP 504.876
 HT 5.05851D+03 5.05851D+03 5.05851D+03
 THT 1.0 1.0 1.0

EXTERNAL HEAT SLAB FLUXES: COOLANT SURFACE -2.86709D+02 BOUNDARY 2.04792D+02
 INTERNAL HEAT SLAB #1 FLUXES: COOLANT SURFACE 0.0
 INTERNAL HEAT SLAB #2 FLUXES: COOLANT SURFACE 0.0 FUEL/CLAD GAP -3.41061D-09

*** HEAT SLAB TEMPERATURES AT HYDRAULIC NODE 5 ***

	EHS	IHS1	IHS2
BOUNDARY	504.779	504.863	504.863
	504.782	504.863	504.863
	504.788	504.863	504.863
	504.795	504.863	504.863
	504.802	504.863	504.863
SURFACE	504.806	SURFACE 504.863	SURFACE 504.863
			504.863
			504.863
			504.863
			504.863

COOLANT TEMP 504.863
 HT 5.05842D+03 5.05842D+03 5.05842D+03
 THT 1.0 1.0 1.0

EXTERNAL HEAT SLAB FLUXES: COOLANT SURFACE -2.86691D+02 BOUNDARY 2.04779D+02

(Continued)

INTERNAL HEAT SLAB #1 FLUXES: COOLANT SURFACE 0.0
 INTERNAL HEAT SLAB #2 FLUXES: COOLANT SURFACE 0.0 FUEL/CLAD GAP-3.41061D-09

*** HEAT SLAB TEMPERATURES AT HYDRAULIC NODE 6 ***
 EHS IFS1 IHS2
 BOUNDARY 504.766 504.850 504.850
 504.769 504.850 504.850
 504.775 504.850 504.850
 504.782 504.850 504.850
 504.789 SURFACE 504.850 SURFACE 504.850
 SURFACE 504.793 SURFACE 504.850
 SURFACE 504.850
 SURFACE 504.850

COOLANT TEMP 504.850
 HT 5.05834D+03 5.05834D+03 5.05834D+03
 THT 1.0 1.0 1.0

EXTERNAL HEAT SLAB FLUXES: COOLANT SURFACE-2.86672D+02 BOUNDARY 2.04766D+02
 INTERNAL HEAT SLAB #1 FLUXES: COOLANT SURFACE 0.0
 INTERNAL HEAT SLAB #2 FLUXES: COOLANT SURFACE 0.0 FUEL/CLAD GAP-3.41061D-09

*** HEAT SLAB TEMPERATURES AT HYDRAULIC NODE 7 ***
 EHS IFS1 IHS2
 BOUNDARY 504.753 504.837 504.837
 504.756 504.837 504.837
 504.762 504.837 504.837
 504.769 504.837 504.837
 504.776 SURFACE 504.837 SURFACE 504.837
 SURFACE 504.780 SURFACE 504.837
 SURFACE 504.837
 SURFACE 504.837

COOLANT TEMP 504.837
 HT 5.05825D+03 5.05825D+03 5.05825D+03
 THT 1.0 1.0 1.0

EXTERNAL HEAT SLAB FLUXES: COOLANT SURFACE-2.86654D+02 BOUNDARY 2.04753D+02
 INTERNAL HEAT SLAB #1 FLUXES: COOLANT SURFACE 0.0
 INTERNAL HEAT SLAB #2 FLUXES: COOLANT SURFACE 0.0 FUEL/CLAD GAP-3.41061D-09

CHANGE 0.0 AT NODE 0 - NEW TIME STEP 1.00000D-04
 TIME 1.00000D-04 ELAPSED CPU TIME 0.02 MINUTES AFTER 1 TIME STEPS
 CHANGE 2.82657D-10 AT NODE 7 - NEW TIME STEP 2.00000D-04
 TIME 3.00000D-04 ELAPSED CPU TIME 0.02 MINUTES AFTER 2 TIME STEPS
 CHANGE 1.14831D-09 AT NODE 7 - NEW TIME STEP 4.00000D-04
 TIME 7.00000D-04 ELAPSED CPU TIME 0.02 MINUTES AFTER 3 TIME STEPS
 CHANGE 6.91454D-09 AT NODE 3 - NEW TIME STEP 8.00000D-04
 TIME 1.50000D-03 ELAPSED CPU TIME 0.02 MINUTES AFTER 4 TIME STEPS