TECHNICAL REPORT

NASA CONTRACT NAS9-2772

EXPLICIT FINITE DIFFERENCE HEAT TRANSFER PROGRAM LVVM 25

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Submitted By

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to

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FOREWORD

This report presents the description of a computer routine capable of transient or steady state analysis of heat transfer problems involving conduction, internal flow with convection, and radiation. The computer routine is an extension of the routines described in LTV Astronautics Reports 00.391 and 00.716. Mr. J. L. Gaddis formulated and checked out the new routine capabilities which were programmed by Miss M. S. Thornton. Miss P. A. Davis also assisted in the final check-out to get the routine operational on the NASA-MSC UNIVAC 1108. The program was developed under NASA-MSC Crew Systems Division Contract NAS9-2772. Mr. D. W Morris is the Contract Technical Monitor.

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A	matrix of simultaneous equation coefficients, coefficient of flow rate
A_c	inside area of tube (cross-section)
A_e	tube lump external radiation area
A_{ec}	effective conduction area between lumps
A_f, A_{HT}	area for fluid convective heat transfer to tube
A_{LC}	tube lump longitudinal conduction area
A_s	area for structure lump external radiation
A_t	tube lump external radiating area
a_o, a_1	coefficients
b	coefficients
c	specific heat
c_p	constant pressure specific heat
c_s	specific heat of structure lumps
c_t	specific heat of tube lump
D_h	hydraulic diameter
F1,F2,F3	data input factors which multiply h_f and ΔP
f	friction factor
H	enthalpy
h_f	fluid heat transfer coefficient
$\mathcal{K}$	pressure loss factor
K	thermal conductivity and $\Delta P/\dot{w}$
K_f	fluid conductivity
K_j	thermal conductivity of adjacent lump j
K_t	thermal conductivity of tube lump t

LIST OF SYMBOLS (Continued)

L	Length from tube entrance
ℓ	tube lump length
ℓ'	fluid lump length
WP	wetted perimeter of tube
$\mathcal{P}$	pumping power
Pr	Prandtl Number
Q	fluid heat rejection
Q_E	heat absorbed from surrounding environment
Q_i	incident heat flux
Q_{io}	Incident heat flux for which surface absorptance is directionally sensitive
Q_R	radiated heat flux
Q_S	heat stored in structure element
Q_t	incident heat flux on tube lumps
Re	Reynolds Number
St	Stanton Number
T	absolute temperature
T'	temperature at time $\tau + \Delta\tau$
T_f	temperature of fluid at time τ
$T_{f_{in}}$	temperature of fluid at radiator inlet
$T_{f_{out}}$	temperature of fluid at radiator outlet
T_f'	temperature of fluid at time $\tau + \Delta\tau$
T_{fu}	upstream fluid temperature
T_s	temperature of structure lump at time τ
T_s'	temperature of structure lump at time $\tau + \Delta\tau$
T_t	temperature of tube lump at time τ
T_t'	temperature of tube lump at time $\tau + \Delta\tau$

LIST OF SYMBOLS (Continued)

U_{sj}	heat transfer conductance between structure lump, s, and adjacent structure lumps, j
U_{tj}	heat transfer conductance between tube lump, t, and adjacent structure lump, j
V	fluid velocity
w	mass of finite difference lumps
$\dot{w}$	fluid mass flow rate
w_s	structure lump weight
w_t	tube lump weight
$\dot{w}'$	intermediate flow rate for balancing of pressure drop
$\dot{w}''$	flow rate for next iteration during balancing of pressure drop
χ	fraction of flow bypassed
x	valve position
Δx	fluid lump length
X	distance from tube entrance
Y_j	is the portion of the conductance path between lump s and j which lies in lump j
Y_t	that portion of the conductance path length between lump t and s which lies in lump t
α_s	absorptivity of structure lump for incident heat flux
α_t	absorptivity of tube lump for incident heat flux
β	matrix
δ	structure lump thickness
$\Delta\tau$	time increment for next calculation
ΔP	pressure loss between inlet and outlet of tube
$(\Delta P)_{avg}$	average pressure loss
ϵ_s	emissivity of structure lump

LIST OF SYMBOLS (Continued)

α_t	emissivity of tube lump
θ	convergence factor
μ_b	viscosity evaluated at fluid bulk temperature
μ_w	viscosity evaluated at tube wall temperature
ρ	density
$(\rho f)_{avg}$	average density
σ	Stefan-Boltzmann constant
τ	time variable
Υ	directional absorptance correction factor

1.0 SUMMARY

This report describes analytical methods, user's instructions and data preparation guide, and a sample problem for a generalized heat transfer computer routine. The routine is capable of analysis of conduction, radiation to space, and convection from internal flow. It is particularly suited for the analysis of space radiators and general thermal control fluid loops.

Transient thermal analysis is performed using an explicit finite difference method. Flow analysis of internal flow in general fluid networks is performed in accordance with pressure drop phenomena. The flow may either (1) be balanced to give equal pressure drop in parallel portions of a circuit with or without the total flow determined for a specific pump or (2) be prescribed in individual tubes to aid in post-test correlation.

Several program options are available. Six different types of valves are included along with a general heat exchanger option to provide capability for analysis of interloop heat exchange and regenerative systems. Fluid is allowed to be "frozen" or stagnant in portions of the flow network. The program may be interrupted and restarted at a later time, and a detailed printout of intermediate calculations is available for checkout purposes. An option is available to account for directionally-sensitive surface absorptance of an incident flux.

The inputs to the routine are made in the form of equivalent rectangular dimensions for solids and equivalent round-tube dimensions for fluids. Properties of the materials are input and quantities such as nodal thermal capacity, conductances, heat transfer coefficients, etc. are computed by the routine. Incident heat fluxes are permitted to be different for each subdivision of the model.

The specific additional options incorporated since publication of the last comprehensive documentation in November 1965 are tabulated in the Introduction.

2.0 INTRODUCTION

During the past three years LTV Astronautics has developed a generalized explicit finite-difference computer routine for heat transfer analysis under NASA-MSC Crew Systems Division Contracts NAS9-1751, NAS9-2772, and NAS9-4776. The basic routine has also been expanded into several versions, each of which is tailored for a group of problems having a requirement for a specific type of calculation.

The routine described herein is a basic version capable of handling a wide range of problems. Specific capabilities which have been added in accordance with contract requirements since publication of the last report (Reference 18) describing the basic routine include:

1) The capability to analyze flow problems having "off-axis" flow paths,

2) The incorporation of an input pressure-balance tolerance,

3) Generalized valves including a real tube bypass valve, a polynomial bypass valve, shut-off valves, switching valves, and a proportioning valve,

4) A generalized heat exchanger option capable of analysis of inter-loop heat exchange and regenerator deployment,

5) A closed loop option,

6) An option providing for surfaces which absorb incident radiation based on the angle of incidence,

7) A temperature card-punch option, and

8) Fortran IV operation on the UNIVAC 1107/1108 system.

Certain options were eliminated from the routine in the interest of attaining maximum data space. In addition to the previously eliminated superposition option, the known heat load and gradient methods were deleted.

3.0 ANALYTICAL METHODS

This section presents the methods employed in the computer routine for (1) thermal analysis, (2) convergence and accuracy of the analysis, (3) fluid heat transfer and (4) fluid flow analysis. Each of these will be described fully in the paragraphs which follow.

3.1 THERMAL ANALYSIS

The method used to determine the temperature field provides for accurate transient or steady state analysis of any object characterized by isothermal "lumps". The capabilities and underlying assumptions are developed, followed by a development of the fluid heat balance equations.

3.1.1 Nodal Method - With this very accurate method of steady-state or transient thermal analysis, the differential equations which describe convective, conductive, and radiative heat transfer throughout an object are solved by a commonly used explicit finite difference approximation (Reference 1). The object is divided into many individual lumps for the following significant conditions which may occur in spacecraft applications:

1. Different incident heat quantities for every tube and external surface lump.
2. Three dimensional conduction in spacecraft external surfaces, tubes, and structure.
3. Dissimilar materials and surface coatings.
4. Temperature dependent material properties including surface emissivity and absorptivity.
5. Temperature dependent fluid thermodynamic properties.

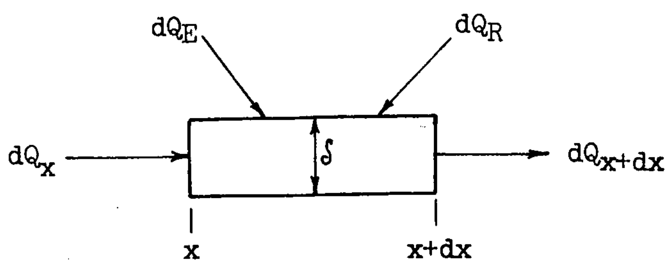
The following simplifying assumptions have been made for the nodal method of analysis:

1. The fluid thermodynamic porperties are considered constant within each finite fluid element, but may vary between elements.
2. Cylindrical surfaces are approximated by small rectangular segments.
3. Radiant interchange is not considered.

Assumptions 1 and 2 are judged to have too small an effect in most spacecraft applications to justify the added complexity of the analytical description required to include them. A separate computer routine version (Reference 17) has been assembled to analyze situations involving radiant interchange.

The development of the equations used with the nodal method of analysis will first be illustrated by a one-dimensional heat balance on a typical external surface element. The resulting finite difference equation is easily extended to include two or three-dimensional conduction into the radiating element. A typical tube element heat balance will also be shown together with the governing temperature equations.

The heat balance of a radiating element of differential length and unit width shown below can be written as:



$$dQ_s = dQ_x + dQ_E - dQ_{x+dx} \tag{1}$$

where:

Q_s = heat stored in the element

Q_R = radiated heat flux

Q_E = heat absorbed from surrounding environment

δ = element thickness

By use of the Fourier heat conduction law,

$$dQ_x - dQ_{x+dx} = \frac{\partial}{\partial x}\left(K \frac{\partial T}{\partial x}\right) \delta \, dx \tag{2}$$

where:

K = material thermal conductivity

Since K is a function of T only, $\frac{\partial K}{\partial x} = \frac{\partial K}{\partial T}\frac{\partial T}{\partial x} = \frac{dK}{dT} \cdot \frac{\partial T}{\partial x}$, thus

$$dQ_x - dQ_{x+dx} = K \delta \frac{\partial^2 T}{\partial x^2} \, dx + \delta \left(\frac{\partial T}{\partial x}\right)^2 \frac{dK}{dT} \, dx \tag{3}$$

Combining (3) and (1),

$$c \delta dx \frac{\partial T}{\partial \tau} = \delta K \frac{\partial^2 T}{\partial x^2} \, dx + \delta \left(\frac{\partial T}{\partial x}\right)^2 \frac{dK}{dT} \, dx + \alpha Q_i dx - \epsilon \sigma T^4 dx \tag{4}$$

where:

c = material specific heat

τ = time

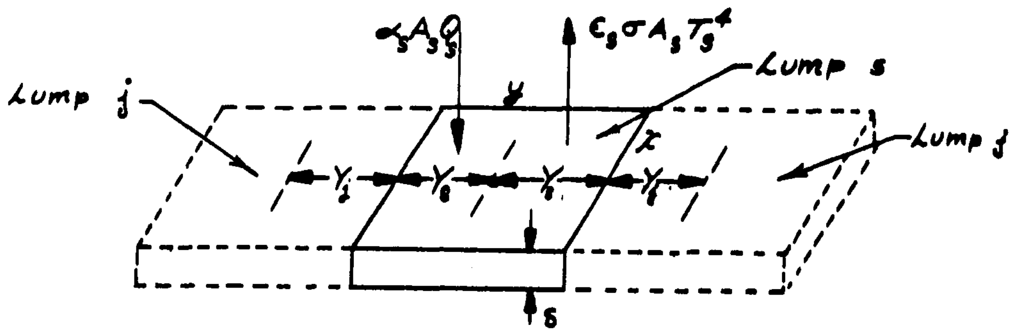
α = surface absorptivity for incident heat flux

Q_i = incident heat flux

ϵ = surface emissivity

σ = Stefan-Boltzmann constant

Since closed form solutions of equation (4) with the appropriate boundary conditions have not been obtained, numerical solutions using finite difference approximations are generally employed. The external structure is divided into lumps which are considered to be isothermal for heat capacitance effects, and which are considered to have temperatures located at their geometric centers (nodes) for conduction effects. The one-dimensional heat balance for a typical external surface lump, s, shown below, may be written in finite difference form as:



$$w_s\, c_s\, \frac{T_s' - T_s}{\Delta\tau} = \sum_j U_{sj}\,(T_j - T_s) + \alpha_s\, A_s\, Q_s - \epsilon_s \sigma A_s\, T_s^4 \quad (5)$$

Rearranging:

$$T_s' = T_s + \frac{\Delta\tau}{w_s\, c_s}\left[\sum_j U_{sj}(T_j - T_s) + \alpha_s\, A_s\, Q_s - \epsilon_s \sigma A_s\, T_s^4\right] \quad (6)$$

where:

$w_s = x \cdot y \cdot \delta \cdot \rho$ = weight of lump (ρ is the density of the fin lump material)

c_s = specific heat of lump s

T_s = temperature of lump s at time τ

T_s' = temperature of lump s at time $\tau + \Delta\tau$

$\Delta\tau$ = time increment for next step in calculation as determined by convergence criteria (Paragraph 3.2)

U_{sj} = the conductance between structure lump s and adjacent structure lumps, j

$$U_{sj} = A_{ec}\left[\frac{1}{\dfrac{Y_s}{K_s} + \dfrac{Y_j}{K_j}}\right]$$

where:

Y_s is that portion of the conduction path length between lump s and j which lies in lump s

Y_j is that portion of the conduction path length between lump s and j which lies in lump j

A_{ec} is the effective conduction area between lumps s and j (i.e., $x \cdot \delta$ in figure above)

K_s is the thermal conductivity of lump s

K_j is the thermal conductivity of lump j

T_j = temperature of adjacent lumps at time τ

Q_s = incident heat flux on lump s

A_s = area of lump s (i.e., x, y in the figure above)

α_s = absorptivity of lump s for incident heat flux

ϵ_s = emissivity of lump s

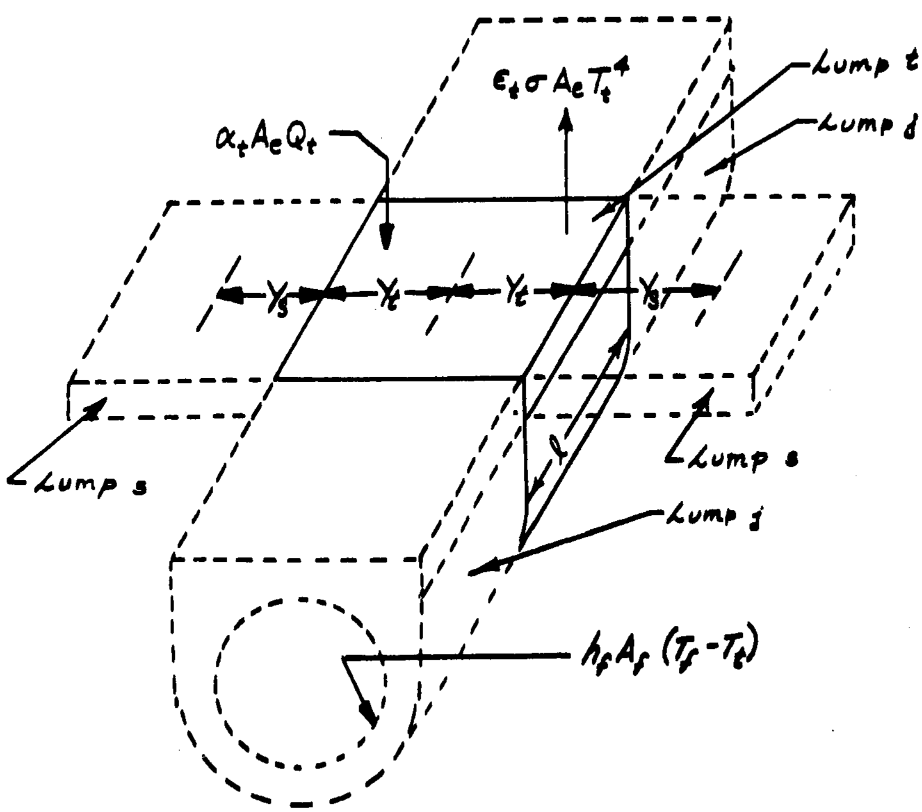
The finite difference heat balance of equation (5) is basically a "forward difference" heat balance (Reference 1) chosen because it yields an explicit solution for the future temperature of lumps. The form of the thermal conductance, U_{sj}, with separate conduction distances and conductivities for adjacent lumps, serves a multiple purpose. First, since the conduction distances are separate, the size of adjacent lumps may be varied. Secondly, for comprehensive thermal analyses which may include low conductivity supporting structure, the conduction paths in the different materials of adjacent lumps can be accurately described. Finally, the evaluation of conductivities at the different temperatures of adjacent lumps approximates the effect of the term $\delta \left(\frac{\partial T}{\partial x}\right)^2 \frac{dK}{dT}$ in equation (4). This approximate method of accounting for variable conductivity is judged to be as good as other methods where a single conductivity based on the average temperature of adjacent lumps is employed (Reference 1).

The inclusion of variable material properties is not intended to remove large errors from steady-state external surface analyses. A previous investigation (Reference 2) can be used to show that the error in heat rejection incurred by use of constant material properties is less than 2% for the steady-state analysis of typical environmental control system radiating fin elements for instance.

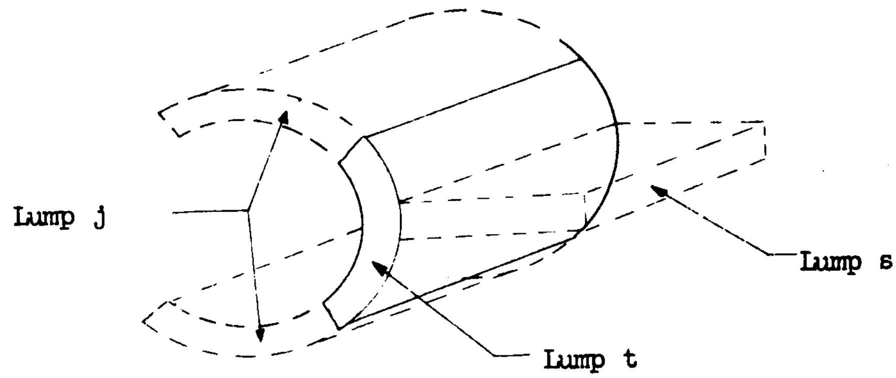
A somewhat larger error may be removed, however, by use of variable properties for transient operating conditions.

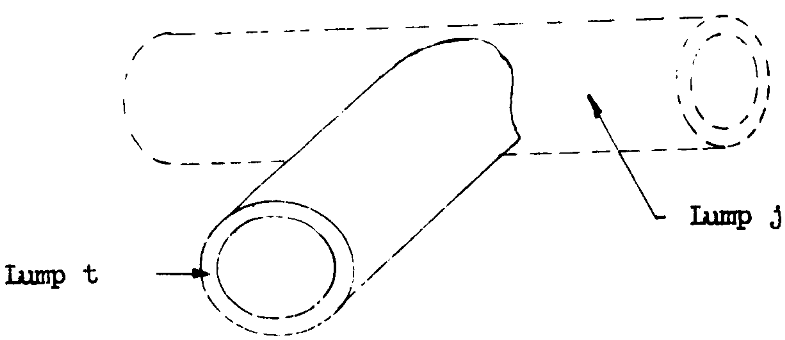
Although the heat balance of equation (5) is only for one-dimensional heat transfer, one, two, and even three-dimensional heat balances may be used in the routine. To do this, the numbers of adjacent lumps and appropriate conduction distances (Y_S and Y_j) must be specified. Lump type numbers are used to describe each lump. Lumps having the same dimensions, conduction data, external radiation area and of the same material may be designated as a single "type". This format reduces the required data input for many problems. Completely different adjacent structure may be included in a thermal analysis by adding another type of lump or by specifying a constant temperature for those lumps representing boundaries on a problem.

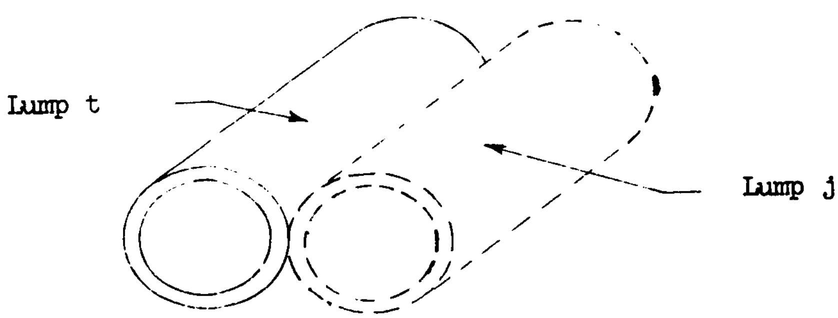
A typical tube lump is shown below.



Other types of tube lumps, in addition to isothermal lumps which completely enclose fluid lumps or lumps which only conduct longitudinally, can be accommodated in the computer routine. The three sketches below illustrate tube lumps used in peripheral subdivisions, tube junctions, and juxtapositioned tubes.







The finite difference heat balance for these lumps is:

$$w_t\, c_t\, \frac{T_t' - T_t'}{\Delta \tau} = \sum_j U_{tj}(T_j - T_t) + \sum_s U_{ts}(T_s - T_t) + \alpha_t\, A_e\, Q_t - \epsilon_t \sigma A_e\, T_t^4 + h_f\, A_f\, (T_f - T_t) \qquad (7)$$

Rearranging:

$$T_t' = T_t + \frac{\Delta\tau}{w_t c_t}\left[\sum_j U_{tj}(T_j - T_t) + \sum_s U_{ts}(T_s - T_t) + \alpha_t\, A_e\, Q_t - \epsilon_t \sigma A_e T_t^4 + h_f\, A_f (T_f - T_t)\right] \qquad (8)$$

Where:

$w_t = A_{LC} \cdot \ell \cdot \rho =$ tube lump weight, where:

A_{LC} = tube lump longitudinal conduction area (i.e., tube lump cross-sectional area)

ℓ = tube lump length

ρ = density of tube lump material

c_t = tube lump specific heat

T_t = temperature of tube lump at time τ

T_t' = temperature of tube lump at time $\tau + \Delta\tau$

$\Delta\tau$ = time increment for next step in calculation as determined by convergence criteria (Paragraph 3.2)

U_{tj}= the conductance between tube lump t and adjacent tube lumps j

$$= A_{ec}\left[\frac{1}{\frac{Y_t}{K_t} + \frac{Y_j}{K_j}}\right]$$

A_{ec} is the effective conduction area between tube lumps t and j
Y_t is that portion of the conduction path length between lump t and j which lies in lump t
Y_j is that portion of the conduction path length between lump t and j which lies in lump j
K_t is the thermal conductivity of tube lump t
K_j is the thermal conductivity of tube lump j

U_{ts}= the conductance between tube lump t, and adjacent fin or structure lumps, s

$$U_{ts} = A_{ec}\left[\frac{1}{\frac{Y_t}{K_t} + \frac{Y_s}{K_s}}\right]$$, where:

Y_t is that portion of the conduction path length between lump t and s which lies in lump t

Y_s is that portion of the conduction path length between lump t and s which lies in lump s

T_s = temperature of adjacent fin or structure lump s at time τ

Q_t = incident heat on tube lump, t

A_e = tube lump external area

α_t = absorptivity of lump t for incident heat flux

ϵ_t = emissivity of tube lump, t

h_f = fluid convective heat transfer coefficient

A_f = area for fluid convective heat transfer

T_f = fluid lump temperature at time τ

For the case where tube lump-to-tube conduction involves only upstream and downstream tube lumps, the term $\Sigma U_{tj}(T_j - T_t)$ in equation (7) was further expanded in terms of upstream and downstream tube lump values for use in the computer routine. The subscript tu refers to the upstream tube lump and td refers to the downstream tube lump.

$$\sum U_{tj}(T_j - T_t) = A_{LC}\left[\frac{1}{\frac{\ell/2}{K_{tu}} + \frac{\ell/2}{K_t}}\right](T_{tu} - T_t) + A_{LC}\left[\frac{1}{\frac{\ell/2}{K_{td}} + \frac{\ell/2}{K_t}}\right](T_{td} - T_t)$$

$$= \frac{2A_{LC}}{\ell}\left[\frac{(T_{tu} - T_t)K_{tu}K_t}{K_{tu} + K_t} - \frac{(T_t - T_{td})K_{td}K_t}{K_{td} + K_t}\right]$$

$$= \frac{2A_{LC}K_t}{\ell}\left[\frac{T_{tu}K_{tu}}{K_{tu} + K_t} + \frac{T_{td}K_{td}}{K_{td} + K_t} - T_t\left(\frac{K_{tu}}{K_{tu} + K_t} + \frac{K_{td}}{K_{td} + K_t}\right)\right] \quad (9)$$

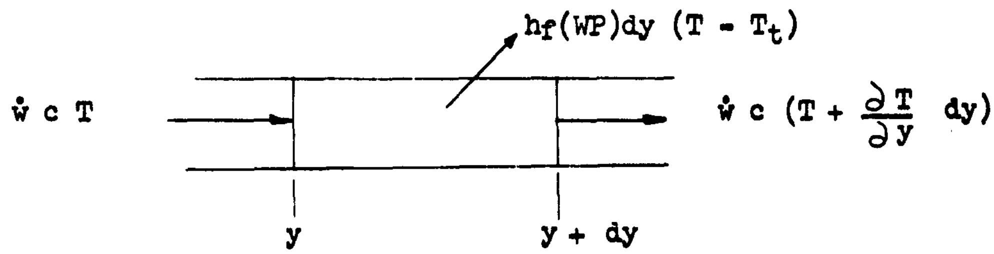
The inclusion or omission of tube lump to tube lump longitudinal conduction was left as a program input option.

The tube lump characterization is completely general as a result of specifying a tube type number for each lump. Different lumps, having the same dimensions, conduction data, external radiation areas, and of the same material may be classed as a single "type" which is specified separately from the lump number.

A discussion of the convergence and accuracy criteria which determine the size of the time step that can be used for transient calculations and the size of the lumps into which an object must be divided is presented in Paragraph 3.2.

3.1.2 Fluid Heat Balance

The energy balance on the fluid is given by equation (10) for the differential fluid element shown below:



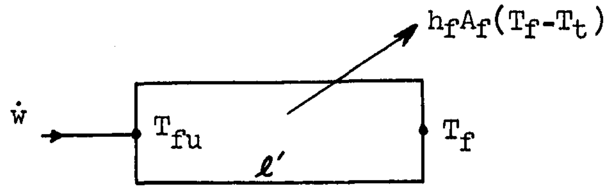
$$\rho c\ A_c\ dy \frac{\partial T}{\partial \tau} = \dot{w}\ c\ T - \dot{w}\ c\ (T + \frac{\partial T}{\partial y}\ dy) - h_f(WP)\ dy\ (T - T_t) \quad (10)$$

where:

- ρ = fluid density
- A_c = fluid cross-section area
- τ = time
- $\dot{w}$ = mass flow rate
- c = fluid specific heat
- h_f = fluid convective heat transfer coefficient
- WP = tube wetted perimeter
- T_t = tube temperature

The fluid temperature is taken as the mixed mean temperature, the fluid specific heat and density are assumed to be constant, and the fluid conduction in the y direction is neglected in equation (10).

The finite difference fluid energy balance is given in equation (11).



$$w_f c_f \frac{T_f' - T_f}{\Delta \tau} = \dot{w}\, c_f\, (T_{fu} - T_f) - h_f\, A_f\, (T_f - T_t) \qquad (11)$$

thus
$$T_f' = T_f + \frac{\Delta \tau}{w_f c_f} \left[\dot{w}\, c_f\, (T_{fu} - T_f) - h_f\, A_f\, (T_f - T_t) \right] \qquad (12)$$

where:

- w_f = weight of fluid in lump f = $A_c\, (\ell')\, (\rho)$ where ρ is the fluid density and ℓ' is the fluid lump length
- c_f = specific heat of fluid in lump f
- T_f = temperature of fluid at time τ
- T_f' = temperature of fluid at time $\tau + \Delta\tau$
- $\Delta\tau$ = time increment for next calculation step as determined from convergence criteria (Paragraph 3.2)
- $\dot{w}$ = fluid flow rate
- T_{fu} = upstream fluid lump temperature
- h_f = fluid convective heat transfer coefficient
- A_f = area for convective heat transfer
- T_t = temperature of tube lump which encloses fluid lump

Equation (11) is a frequently used approximate equation (Reference 1) which yields an explicit solution for T_f'. It involves the approximation that the fluid capacitance effect is based on the outlet fluid temperature of the tube length ℓ'. In writing equation (11), an isothermal tube wall is also assumed so the temperature T_t is not located as a node at a finite depth in the tube lump.

The fluid temperature, T_f, in the term $h_f\, A_f\, (T_f - T_t)$ of equations (7) and (11) can be more accurately represented by $(T_{fu} + T_f)/2$. However, use of this latter form in equation (11) also imposes an additional convergence criteria (see Paragraph 3.2) which restricts A_f of the fluid lump. Since this size limitation is not a practical requirement for all analyses, because A_f will have to be very small for low flow rates, the use of either $(T_{fu} + T_f)/2$ of T_f was left as a routine option.

The variation of the fluid properties with temperature is approximated by using properties in equation (11) which correspond to the temperatures of the different fluid lumps.

3.1.3 Calculation of Heat Rejection

The total heat rejection between the inlet and outlet of a general flow system is computed from:

$$Q = \dot{w} (H_{in} - H_{out}) \tag{13}$$

where:

Q = fluid heat rejection
H_{in} = enthalpy of fluid at system inlet
H_{out} = enthalpy of fluid at system outlet

The program user supplies a curve of fluid specific heat versus temperature. This data is integrated by a trapezoidal integration method within the routine to provide an enthalpy versus temperature curve.

3.2 CONVERGENCE AND ACCURACY CRITERIA

The heat transfer equations used in the computer routine described herein are based on an explicit method of finite difference solution. With this method, the future temperatures of any fluid, tube or structural lump are evaluated from the present temperature of surrounding lumps and the thermal environment. The validity of this type of solution depends on satisfying criteria for stability, oscillation, and truncation error minimization. A discussion of these criteria and a review of the literature are presented by Clark (Reference 5). Chu (Reference 6) also discusses convergence criteria in the report on the basic routine from which this thermal analysis routine was derived. The pertinent points from both references are outlined below.

3.2.1 Stability

The term stability usually refers to errors in equation solution that progressively increase or accumulate as the calculations proceed. After a review of the literature, Clark concludes any explicit forward difference equation will yield stable results for the future temperatures of any lump if the coefficients of the present lump temperature are at least zero or have the same sign as the other coefficients of known temperatures. Chu (Reference 6) also bases his convergence proof on the condition that the coefficient of the present lump temperature be of the same sign as other coefficients of other known temperatures. This stability criterion defines the size of the time step to be used with the basic equations. The equations used in the routine for both techniques are rearranged below to show the development of the stability requirement.

Nodal Technique - Equation (5) for Structure Lumps

$$w_s c_s \frac{(T_s' - T_s)}{\Delta\tau} = \sum_j U_{sj}(T_j - T_s) + \alpha_s A_s Q_s - \epsilon_s \sigma T_s^4 A_s$$

Rearranging,

$$T_s' = \frac{\Delta\tau}{w_s c_s}\left[\sum_j U_{sj} T_j + \alpha_s A_s Q_s\right] + T_s\left[1 - \frac{\Delta\tau}{w_s c_s}\left(\sum_j U_{sj} + \epsilon_s \sigma T_s^3 A_s\right)\right]$$

For the coefficient of T_s to be positive,

$$\Delta\tau = \frac{\theta\, w_s c_s}{\sum_j U_{sj} + \epsilon_s \sigma T_s^3 A_s} \qquad \text{where } \theta = \text{convergence factor} \le 1.0 \qquad (14)$$

Nodal Technique - Equation (7) for Tube Lumps

$$w_t\ c_t\ \frac{(T_t' - T_t)}{\Delta\tau} = \sum_j U_{tj}(T_j - T_t) + \sum_s U_{ts}(T_s - T_t) + \alpha_t\ A_e\ Q_t - \epsilon_t\ \sigma\ A_e\ T_t^4 + h_f\ A_f(T_f - T_t)$$

Rearranging,

$$T_t' = \frac{\Delta\tau}{w_t\ c_t}\left[\sum_s U_{ts}T_s + \alpha_t\ A_e\ Q_t + h_f\ A_f\ T_f + \sum_j U_{tj}\ T_j\right] + T_t\left[1 - \frac{\Delta\tau}{w_t\ c_t}\left(\sum_j U_{tj} + \sum_s U_{ts} + \epsilon_t\ \sigma\ A_e\ T_t^3 + h_f\ A_f\right)\right]$$

For the coefficient of T_t to be positive,

$$\Delta\tau = \frac{\Theta\ w_t\ c_t}{\sum_j U_{tj} + \sum_s U_{ts} + \epsilon_t\ \sigma\ A_e\ T_t^3 + h_f\ A_f} \quad \text{where } \Theta \leq 1.0 \qquad (15)$$

From the development above, it is evident that the use of $(T_{fu} + T_f)/2$ instead of T_f in the convective heat transfer term will not affect the convergence expression for $\Delta\tau$ because the coefficient of T_t is unchanged.

Fluid Lump - Equation (11)

$$w_f\ c_f\ \frac{(T_f' - T_f)}{\Delta\tau} = \dot{w}\ c_f\ (T_{fu} - T_f) - h_f\ A_f\ (T_f - T_t)$$

Rearranging,

$$T_f' = \frac{\Delta\tau}{w_f\ c_f}\left[\dot{w}\ c_f\ T_{fu} + h_f\ A_f\ T_t\right] + T_f\left[1 - \frac{\Delta\tau}{w_f\ c_f}(\dot{w}\ c_f + h_f\ A_f)\right]$$

For the coefficient of the T_f to be positive,

$$\Delta\tau = \frac{\Theta\ w_f\ c_f}{\dot{w}\ c_f + h_f\ A_f} \quad \text{where } \Theta \leq 1.0 \qquad (16)$$

If T_f is replaced by $(T_{fu} + T_f)/2$ in the convective heat transfer term for greater solution accuracy, the convergence criteria for $\Delta\tau$ changes, and another limitation on the size of the fluid lump is required, as shown below.

$$w_f \, c_f \frac{(T_f' - T_f)}{\Delta\tau} = \dot{w} \, c_f \, (T_{fu} - T_f) - h_f \, A_f \left[\frac{T_{fu} + T_f}{2} - T_t \right]$$

Rearranging,

$$T_f' = \frac{\Delta\tau \, T_t}{w_f \, c_f} (h_f \, A_f) + T_{fu} \frac{\Delta\tau}{w_f \, c_f} \left(\dot{w} \, c_f - \frac{h_f \, A_f}{2}\right) + T_f \left[1 - \frac{\Delta\tau}{w_f \, c_f} \left(\dot{w} \, c_f + \frac{h_f \, A_f}{2}\right) \right]$$

For the coefficient of T_f to be positive,

$$\Delta\tau = \frac{\Theta \, w_f \, c_f}{\dot{w} \, c_f + \frac{h_f \, A_f}{2}} \quad \text{where } \Theta \leq 1.0 \tag{17}$$

Furthermore, for the coefficient of T_{fu} to be positive,

$$\frac{h_f \, A_f}{2} \leq \dot{w} \, c_f$$

or

$$A_f \leq \frac{2 \, \dot{w} \, c_f}{h_f} \tag{18}$$

This places a restriction on the size of the fluid lump to be used in the routine. Since it may not be practical to meet this restriction for all problems, the use of averaged fluid temperatures if left as a program option.

3.2.2 Oscillation

Even though a solution is stable, it may oscillate around a correct mean value. To eliminate this undesirable oscillation, Clark (Reference 5) recommends that the calculation time increment based on the stability criterion be further reduced by a factor of 1.5. It should be noted that this reduction may not suffice for all cases since the oscillation depends strongly on the size of space increment and the problem boundary conditions. In setting up the basic routine from which this thermal analysis routine was derived, Chu used a factor 1.11. The routine described herein will also employ this factor (Θ = .9) unless otherwise specified by the program user.

3.2.3 Truncation Error

The truncation error in the routine solution results from replacing derivatives with finite differences. In order to provide a measure of the accumulated truncation error, results for smaller time and space increments (subject to stability and oscillation criteria) should be compared. Chu recommends halving the space increment and quartering the time increment to obtain an estimate of the error in a numerical result. In general, an investigation of truncation error must be made by changing lump sizes for each type of problem to determine the maximum size of isothermal lumps that can be used for a valid solution.

The truncation error has been shown to be of the form A + B, (Reference 5) where A is proportional to the time increment and B is proportional to the square of the lump linear dimension. LTV experience indicates that time truncation error (A) is relatively small ($\approx$ 3 percent) if the time increment satisfies the stability criteria. The spatial truncation error (B) can be evaluated at steady state. In the case of radiators and segments of radiators for instance, changing the number of lumps along the length of the tube from 20 to 10 causes less than 0.2 percent difference in heat rejection (Reference 7). Further reduction to 5 lumps along the tube in the analysis of large radiators also appears to have only a slight effect, but no direct comparison is available. A comparison of two and four fin lumps between tubes in the analysis of large radiators with high fin effectiveness shows about a 2 percent difference in heat rejection, even though the fin temperatures are considerably different. These sample results are subject to variation due to the application.

3.2.4 Steady State Shutdown and Jump Ahead

Since the computer routine uses a transient approach to steady state conditions, a shutdown criteria indicating that steady state has been reached must be specified to terminate a run. Experience gained during the program showed that most problem solutions have reached steady state when the temperature change of every lump between successive calculations for T' was less than .0001 to .001 percent of the lump absolute temperature. However, since the temperature change between successive calculations is a function of the minimum time step for convergence, which is in turn a function of lump size, it was decided to allow the program user to specify the steady state shutdown as part of the routine data input.

When transient problems are being considered, equilibrium conditions may also be achieved at intermittant points (such as on the dark side of the moon in a lunar orbit analysis). To conserve transient analysis computer time the criteria for steady state conditions is considered at every iteration. When every temperature satisfies the input criteria a transient problem will be considered at steady state. In such an event the iteration process is terminated and problem time is jumped ahead to the next point at which any time-dependent curve change occurs whereupon iterations are continued. This option permits exclusion of long periods of calculation in mission analysis where the system is at steady state, thus shortening calculation time. The option can also be utilized to analyze several successive steady state conditions in one submission of transient data since the problem will jump ahead after reaching equilibrium at each intermittant condition.

3.3 FLUID HEAT TRANSFER COEFFICIENT

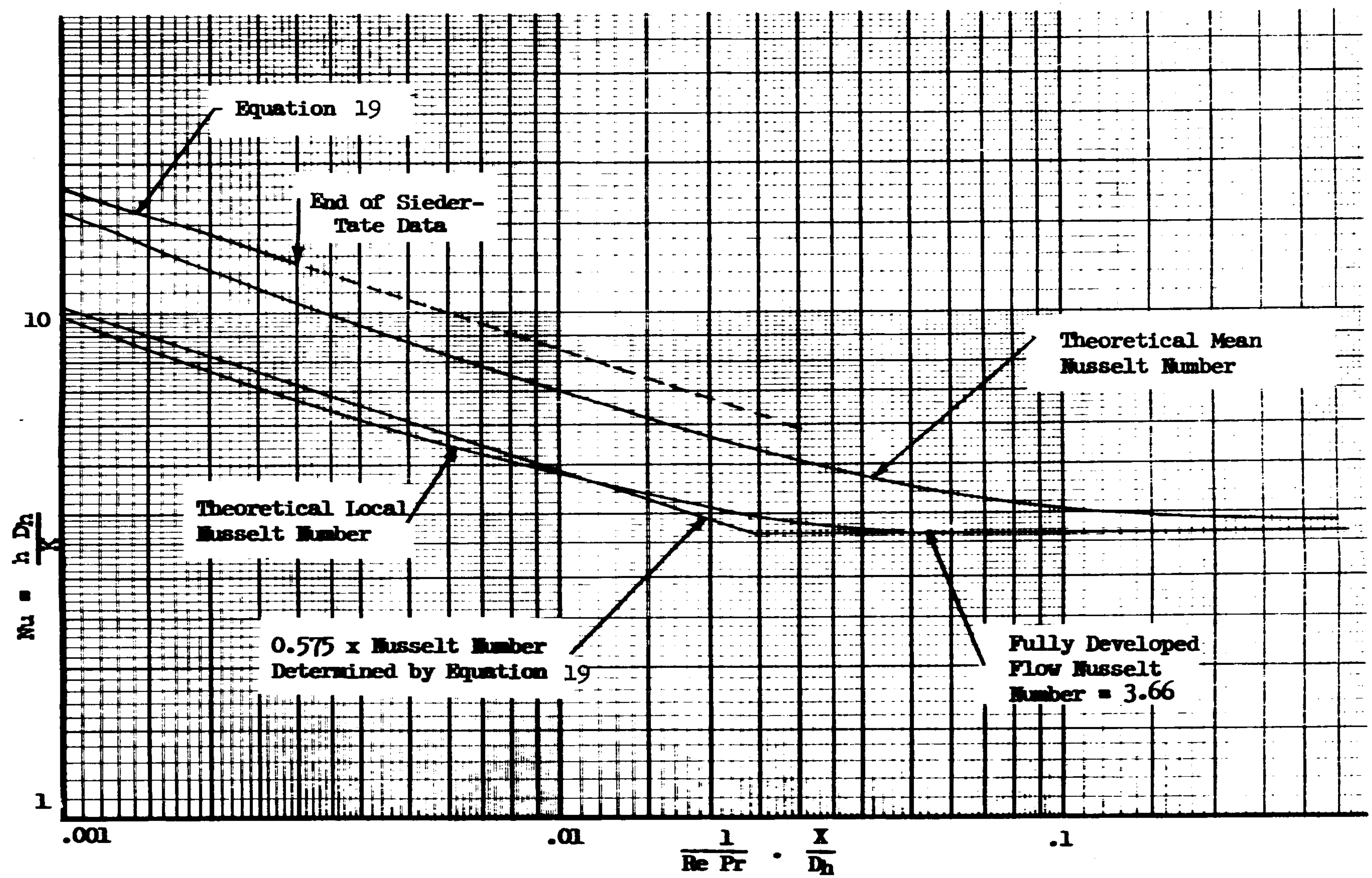
Commonly used equations for determining both laminar and turbulent flow heat transfer coefficients were programmed in the computer routine. An investigation of the basis for laminar flow heat transfer coefficient equations was undertaken since a majority of Apollo spacecraft flow conditions are in the laminar regime. It was found that both experimental correlations and theoretical equations for laminar flow heat transfer coefficients can only be applied with considerable approximation to the flow conditions on external spacecraft surfaces. It was decided therefore to let the program user specify a factor in the data input which modifies the heat transfer coefficients de-determined by the equations within the routine. This provision not only permits studies of the effect of heat transfer coefficient variations, but also provides a method for specifying non-circular duct coefficients. The performance of space radiators for instance, is not directly proportional to changes of fluid heat transfer coefficient. In general, if the path between a radiator fluid temperature and an equivalent temperature of space is characterized by the resistance of an internal heat transfer coefficient and the resistance of a radiating fin, the former will be found to be quite small compared to the latter. Thus, appreciable changes in fluid heat transfer coefficient may affect the net radiator heat rejection by only a small degree. This fact, however, does not permit gross errors in heat transfer coefficients if accurate radiator and cold plate cooling loop performance predictions are expected.

3.3.1 Laminar Flow

Both the thermal entry length and the fully developed flow regimes must be considered to properly evaluate a laminar flow heat transfer coefficient. The thermal entry length region is usually considered to include those values of $(1/\text{Re Pr})(X/D_h)$ below .050. The portion of total tube length in the thermal entry region may vary from the entire tube length for higher fluid flow rates and higher fluid temperatures to only a small percentage of the total length for tubes with low flow rates and low fluid temperatures.

The theoretical solutions which have been obtained for thermal entry lengths are frequently based on boundary conditions of either constant tube wall surface temperature or constant heat rate per unit of tube length. These solutions are also formulated under the assumptions of constant fluid properties and symmetrical heat transfer around the tube periphery. In addition, many of the solutions only apply rigorously if a hydrodynamic starting length is provided because the flow is considered to be isothermal with a fully established velocity profile at the tube entrance. Results are shown in Figure 1 for both local and mean Nusselt Numbers obtained by the Graetz solution for circular tubes with uniform surface temperature under the assumptions outlined above (Reference 8).

The solutions exhibit an asymptotic approach to a fully developed flow Nusselt Number of 3.66. The local Nusselt Number has reached the fully developed flow value for $(\text{Re Pr})(D_h/X) < 20$. The local Nusselt Number is employed to arrive at local heat transfer coefficients for the tube lump heat balances in the computer routine, whereas mean Nusselt Numbers are commonly used for overall heat exchanger calculations.



COMPARISON OF CIRCULAR TUBE LAMINAR FLOW NUSSELT NUMBERS
FOR CONSTANT WALL TEMPERATURE

FIGURE 1

The use of theoretical solutions based on the assumptions of constant fluid properties can introduce errors for fluids where viscosity is a strong function of temperature. Yang (reference 9) and Deissler (reference 10), among others, have considered the effects of variable properties on fully developed and thermal entry length solutions. The Nusselt Numbers, in general, fall below the constant property solutions for cooling and above the constant property solutions for heating. The effects of variable viscosity reported by Yang for uniform wall temperature can be approximated by multiplying the constant property Nusselt Number by $(\mu_b/\mu_w)^{0.11}$ (where μ_b is fluid viscosity evaluated at fluid bulk temperature and μ_w is fluid viscosity evaluated at tube wall temperature) for both heating and cooling conditions. Deissler (reference 10) recommends use of the empirical correction of $(\mu_b/\mu_w)^{.14}$ for fully developed constant heat rate solutions.

The analyses of references 9 and 10, like most other theoretical solutions, were derived for conditions of symmetrical heating or cooling (i.e., the derivative of temperature with respect to tube radius is zero at the tube centerline). Reynolds (reference 11) has shown the type of variations in Nusselt Number which can be encountered for non-uniform peripheral heat flux. For thin walled tubes attached to the backside of radiating surfaces, theoretical equations derived for symmetrical heating must be regarded as approximate for predicting heat transfer coefficients.

The basic equation which was programmed in the computer routine for thermal entry length heat transfer coefficients was the widely used (references 12, 13, 14, and 15) Sieder-Tate correlation:

$$h_f = 1.86\ K_f/D_h(\mu_b/\mu_w)^{.14}\left[\frac{Re\ Pr}{L/D_h}\right]^{1/3} \quad (F_1) \qquad (19)$$

where:

h_f = convective heat transfer coefficient

K_f = fluid conductivity

L = length from tube entrance

D_h = tube hydraulic diameter = 4 Ac/WP

μ_b = fluid viscosity evaluated at fluid bulk temperature

μ_w = fluid viscosity evaluated at tube wall temperature

Re = Reynolds Number

Pr = Prandtl Number

F_1 = Entry length heat transfer coefficient factor (data input)

Equation (19) represents an experimental correlation of test data for $[\text{Re Pr D/X}]^{-1}$ of .003 and below. As shown in Figure 1, it does not yield an asymptotic approach to a fully developed Nusselt Number when extended to higher values of (1/Re Pr) · (X/D). Although equation (19) is used as the basis of thermal entry length heat transfer coefficients in the computer routine, the values calculated with it are compared with values calculated by

$$h_f = 3.66\ K_f/D_h \left[\frac{\mu_b}{\mu_w}\right]^{.14} (F_2) \qquad (20)$$

F_2 = Developed flow heat transfer coefficient factor (data input)

and the higher value is used in the heat balance equations. Since both equations (19) and (20) apply to fluid flow on external spacecraft surfaces only with considerable approximation, the routine user may input separate factors to modify coefficients calculated by these equations.

The following considerations are involved in selecting the proper factor (F_1) for modifying the heat transfer coefficient calculated with the basic thermal entry length equation.

1. The Sieder-Tate equation represents an experimental correlation for the heating of oils in horizontal tubes with constant wall temperature.

2. The Sieder-Tate equation yields overall heat transfer coefficients, whereas a local coefficient is required for the tube lump heat balance in the computer routine.

3. The equation applies only for circular tubes.

A plot of the Sieder-Tate equation with a viscosity ratio term of 1.0 is shown in Figure 1. A curve for a factor of (.575) x the coefficient evaluated by equation (14) is shown to fit the greater portion of the theoretical heat transfer coefficient curve in the thermal entry length region. Although use of this factor causes the minimum limiting Nusselt Number to be reached at a value of $(\text{RePr})^{-1}$=.025 D/X, the deviation from the theoretical heat transfer coefficient will be less than 10% near the minimum limiting value of the Nusselt Number. The actual heat transfer coefficient used in space radiator calculations for instance will be below the .575 factor curve because the term $(\mu_b/\mu_w)^{.14}$ in equation (19) will be less than one for the cooling of the radiator fluid.

In selecting the heat transfer coefficient factor (F_2) it should be remembered that a Nusselt Number of 3.66 applies for

1. Constant wall temperature boundary condition

2. Circular ducts

The constant wall temperature value is pessimistic since the actual radiator Nusselt Number **may lie between the constant wall temperature** solution of 3.66 and the constant heat rate value of 4.36. The circular duct value of 3.66 should be appropriately modified by (F_2) for non-circular tube configurations.

3.3.2 Turbulent Flow

A commonly used equation for turbulent heat transfer coefficients was programmed directly without a detailed investigation of the underlying assumptions. The correlation of equation (21), recommended in reference 12, is used to determine heat transfer coefficients at Reynolds Numbers greater than 2000.

$$h_f = .027 \frac{K_f}{D_h} \left[\frac{\mu_b}{\mu_w} \right]^{.14} (Re)^{.8} (Pr)^{1/3} \qquad (21)$$

h_f = convective heat transfer coefficient

K_f = fluid conductivity

D_h = tube diameter

μ_b = fluid viscosity evaluated at fluid bulk temperature

μ_w = fluid viscosity evaluated at tube wall temperature

Re = Reynolds Number

Pr = Prandtl Number

In turbulent flow the undeveloped region of heat transfer is short ($\approx$ 4 diameters) such that for most cases it will constitute only a small portion of the total internal heat transfer region.

3.4 FLOW SYSTEM ANALYSIS

This section includes a description of the methods used for (1) computing incompressible fluid pressure losses, (2) analyzing simple flow systems with tubes in parallel, (3) analyzing complex parallel/series systems with manifolding, (4) analyzing flow rate as a function of pressure loss, and (5) computing pumping power. For all systems involving parallel flow paths, the flow rates which give balanced system pressures are determined after each temperature iteration and these flow rate values are used in the thermal calculations for the next temperature iteration.

3.4.1 Fluid Pressure Loss

The flow system pressure loss under the assumption of a system involving single phase incompressible fluids is calculated by the usual Fanning equation with a dynamic head loss factor ($\mathcal{K}$) added. The pressure loss for each fluid lump is calculated by:

$$\Delta P = 4 f \frac{\ell'}{D_h} \frac{\rho V^2}{2} + \mathcal{K} \frac{\rho V^2}{2} = \frac{\dot{w}^2}{2 \rho A_c^2} \left[\frac{f(WP)\ell'}{A_c} + \mathcal{K} \right] \quad (22)$$

where:

- f = friction factor = 16/Re for Reynolds Numbers less than 2000 and is read from input data for Reynolds Numbers greater than 2000
- ℓ' = fluid lump length
- $\mathcal{K}$ = number of fluid dynamic head losses
- $\dot{w}$ = tube fluid flow rate
- WP = wetted perimenter
- AC = fluid cross-section area
- D_h = tube hydraulic diameter = 4 A_c/WP
- ρ = fluid density
- V = fluid velocity

Two additional terms F_3 and $(\mu b/\mu w)^{.14}$ were added to equation (22) to account for non-circular ducts and non-isothermal flow:

$$\Delta P = \frac{\dot{w}^2}{2 A_c^2 \rho} \left[\frac{f(WP)\, \ell' \, F_3 (\mu b/\mu w)^{.14}}{A_c} + \mathcal{K} \right] \quad (23)$$

where:

F_3 = pressure loss factor for non-circular ducts, is 1.0 for circular ducts

μ_b = fluid viscosity evaluated at fluid bulk temperature

μ_w = fluid viscosity evaluated at tube wall temperature

The fluid lump type cards provide for inputs of ($\mathcal{K}$) which can be different for each fluid lump type. The term is used to account for pressure losses in tube entrance regions, bends, contractions, and expansions. Entrance pressure losses for varying duct geometries (Reference 16) may also be specified by ($\mathcal{K}$).

3.4.2 Parallel Flow

The term parallel flow is used herein to refer to systems with simple sets of tubes arranged in parallel as shown in Figure 2. The tubes do not have to be the same diameter or length. The tube manifolds are not included in the analysis; the system inlet temperature and pressure are supplied to the entrance of each parallel flow tube. The flow rates which give equal pressure losses do not involve any fluid outlet manifolding. A mixed fluid outlet temperature is computed by using flow rates and enthalpies of each parallel fluid stream.

The pressure balancing subroutine is called after initial flow rates are read from the data input before the first temperature iteration is made and after each successive temperature iteration. The individual tube pressure losses are calculated and compared. If the pressure losses differ by more than an input fraction of the average pressure drop in all tubes, the individual tube fluid flows are adjusted by the equations shown below, and the comparison is repeated. No advance in time is made until a pressure balance is obtained.

$$\dot{w}_1' = \frac{\Delta P_{avg}}{\Delta P_1} (\dot{w}_1) ,$$

$$\dot{w}_2' = \frac{\Delta P_{avg}}{\Delta P_2} (\dot{w}_2) \quad \text{etc. to}$$

$$\dot{w}_n' = \frac{\Delta P_{avg}}{\Delta P_n} (\dot{w}_n) \qquad n = \text{number of radiator tube}$$

$$\dot{w}_t = \sum_{i=1}^{n} \dot{w}_i \; ; \quad \dot{w}_t' = \sum_{i=1}^{n} \dot{w}_i'$$

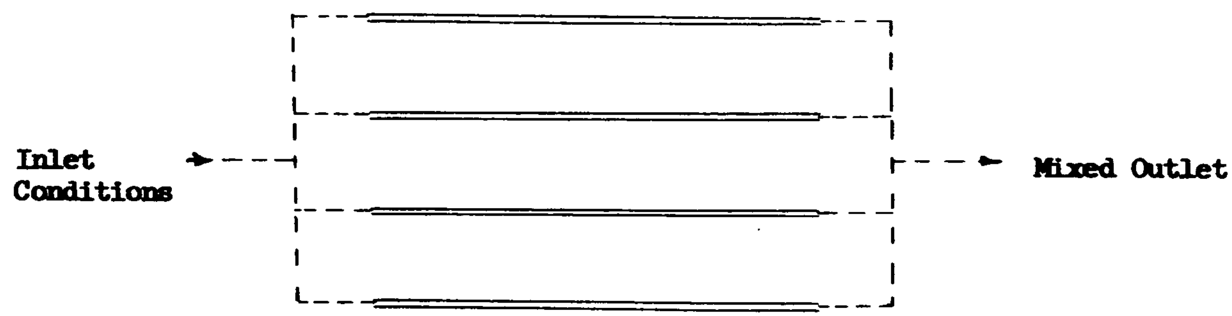


FIGURE 2

PARALLEL FLOW SYSTEM

$$\dot{w}_1'' = \frac{\dot{w}_t}{\dot{w}_t'}(\dot{w}_1') \quad , \quad \dot{w}_2'' = \frac{\dot{w}_t}{\dot{w}_t'}(\dot{w}_2') \text{ , etc. to}$$

$$\dot{w}_n'' = \frac{\dot{w}_t}{\dot{w}_t'}(\dot{w}_n') \qquad n = \text{number of radiator tube}$$

where:

$\dot{w}$ = individual tube fluid flow rates. Prime values are intermediate calculation numbers and double prime values are the assigned flow rates for the next pressure drop calculation.

ΔP_{avg} = the arithmetic average of all individual tube pressure drops.

subscripts 1 through n denote parallel flow tube numbers for flow rate and pressure drop.

3.4.3 Banks and Headers Flow

The banks and headers option permits analysis of combinations of parallel and series flow in general networks. The name is derived from "banks" of parallel flow paths and "headers" or manifold arrangements. To aid in discussing the use of the option certain terms require definition. First a "feeder" (referring to Figure 3) is the single inlet or exhaust tube of a manifold. A "bank" of pipes is the portion of flow network between the inlet and outlet manifold. A "manifold" is the system of tubes separating or joining the flow from or into a feeder. For analysis, manifolds are subdivided into tubes. A "tube" or "segment" is the largest subdivision in a network in which the flow is the same; hence, is the portion of a flow path between two tube junctures. The tubes are subdivided into lumps to provide for thermal considerations of fluid flow. When the banks and headers option is used, there must be two tubes per bank minimum and at least four tubes per system. Two portions of a flow line cannot be called two tubes in series due to the definition of a tube.

The present routine permits tubes of a bank to connect into the manifold of another bank which is arranged in series with the first bank. Figure 3 shows schematically the arrangement which has been included. This capability is new and was not included in earlier versions of the program.

The flow rates in a general network must be determined so as to (1) preserve flow continuity and (2) balance pressure drop in the various parallel sections of the network. The flow rates which satisfy these requirements are determined by solving a set of simultaneous equations. The

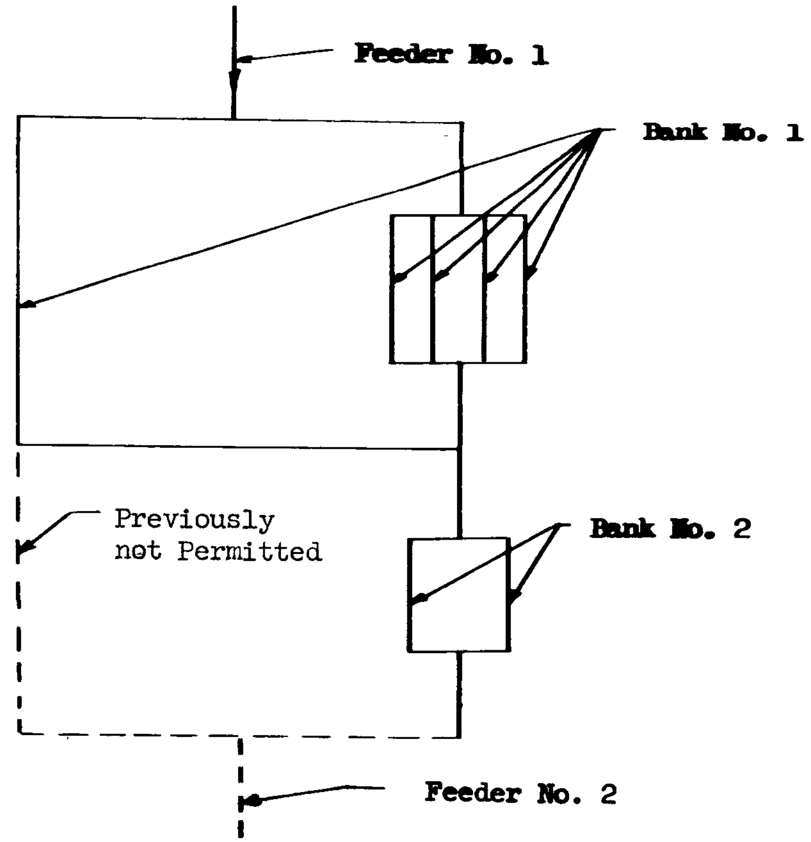


FIGURE 3

HEADERS AND BANKS FLOW SYSTEM

pressure drop is linearized to be proportional to the flow rate of the previous iteration, or problem input flow rates, and the equations are set up and solved for new flow rates. Using this set of flow rates the pressure balance is checked. If the pressures are not balanced within an input tolerance of the pressure drop in the flow path a new pressure drop per flow rate is used to resolve the simultaneous equations until a pressure balance is achieved.

For problems with laminar flow and no ($\mathcal{K}$) losses, only one solution of the simultaneous equation at each iteration is required. If the flow is turbulent, or if $\mathcal{K}$ losses are high, successive solutions of the equations will be required. The new flows are adjusted to the average of two successive equation solutions to provide for rapid convergence. Any problem will be terminated by the routine if a pressure balance is not obtained after solving the simultaneous equations twenty times at any one iteration.

The pressure drop per tube is computed from the sum of the pressure drops of the lumps in the tube. The equations for flow rates are set up as shown below for the flow system in Figure 4. Only three tubes may join at any one point. When several tubes are manifolded together, "dummy" short tubes must be inserted. There are seven flow rates for the system in Figure 4 requiring seven equations. These are:

(1) $\dot{w}_1$ = known value

$$\dot{w}_1 = \dot{w}_2 + \dot{w}_3$$

$$\dot{w}_3 = \dot{w}_4 + \dot{w}_5$$

$$\dot{w}_6 = \dot{w}_2 + \dot{w}_5$$

(2) $\dot{w}_7 = \dot{w}_4 + \dot{w}_6$

$$\Delta P_2 = \Delta P_3 + \Delta P_5$$

$$\Delta P_4 = \Delta P_5 + \Delta P_6$$

The last two equations are linearized by dividing the ΔP of the tube by the flow rate to give the coefficient of flow rate, A.

$$A_2 \dot{w}_2 = A_3 \dot{w}_3 + A_5 \dot{w}_5$$

$$A_4 \dot{w}_4 = A_5 \dot{w}_5 + A_6 \dot{w}_6$$

The first equation of the set (1) and the equation for the flow continuity into the last tube (2) are not considered in the solution because they are known. The others are written in the form:

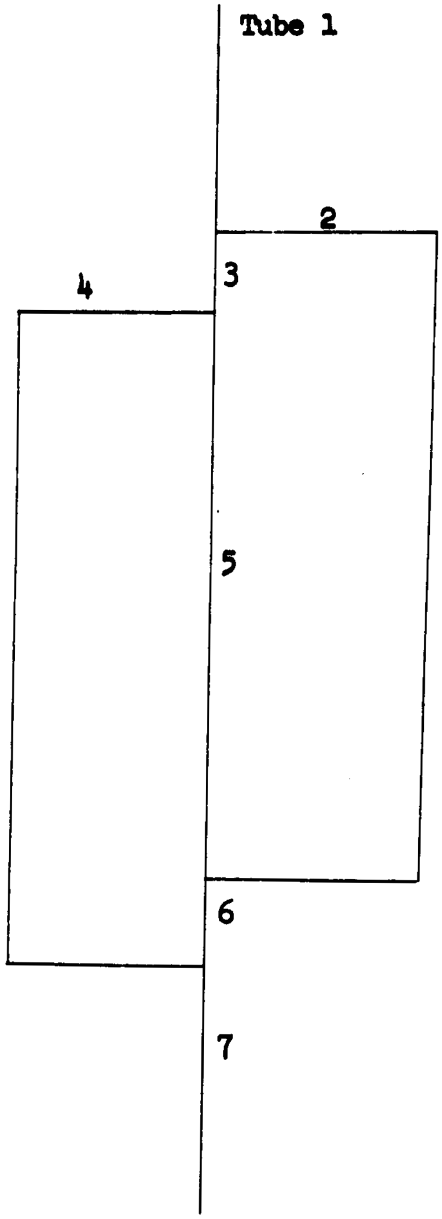


FIGURE 4

HEADERS AND BANK FLOW SYSTEM

$$
\begin{aligned}
\dot{w}_2 + \dot{w}_3 &= \dot{w}_1 \\
\dot{w}_3 - \dot{w}_4 - \dot{w}_5 &= 0 \\
-\dot{w}_2 - \dot{w}_5 + \dot{w}_6 &= 0 \\
A_2\dot{w}_2 - A_3\dot{w}_3 - A_5\dot{w}_5 &= 0 \\
A_4\dot{w}_4 - A_5\dot{w}_5 - A_6\dot{w}_6 &= 0
\end{aligned}
$$

The matrix of coefficients β is written from these equations as:

$$
\beta = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & -1 & 0 \\ -1 & 0 & 0 & -1 & 1 \\ A_2 & -A_3 & 0 & -A_5 & 0 \\ 0 & 0 & A_4 & -A_5 & -A_6 \end{bmatrix}
$$

The equation $\beta \dot{w} = C$ is solved by determining β^{-1} and results in:

$$\dot{w} = \beta^{-1} C$$

3.4.4 Flow Rate Versus Pressure Loss

For many flow systems pump characteristics determine system flow rate as a function of pressure loss. The routine provides for data input of pump ΔP versus $\dot{w}$ characteristics. If this option is used, after each solution for pressure balance a flow rate for the total system pressure loss is determined from the pump characteristic curve. If the flow rate is within 0.1 percent of the flow rate used for the pressure balance the next temperature iteration is made. If the flow rate is out of tolerance, the average flow between iterations is used for successive iterations until a match point is achieved.

3.4.5 Pumping Power

For radiators with a series flow arrangement, the total fluid pressure loss will be the summation of fluid lump ΔP's for a single tube. For parallel flow arrangements, a flow balancing procedure shown in paragraph 3.2.2 is employed to insure equal pressure drops in all radiator tubes.

The fluid pumping power requirement is based on the frictional and dynamic head pressure loss of the fluid. The pumping power is calculated for each tube separately and totaled for parallel flow radiators. The following equation is used to calculate pumping power.

$$\mathcal{P} = \frac{\dot{w}}{(\rho_f)_{avg}} \Delta P \quad , \quad (\rho_f)_{avg} = \frac{\sum_j \rho_j}{\text{Number of fluid lumps per radiator tube}}$$

$\mathcal{P}$ = pumping power

$\dot{w}$ = fluid flow rate

$(\rho_f)_{avg}$ = average fluid density

ΔP = pressure loss between inlet and outlet of radiator tube

4.0 SPECIAL ROUTINE OPTIONS

4.1 FLOW CONTROL VALVES

A generalized capability is provided for analyzing systems with four types of control valves. Each of the valves, rate-limited bypass, polynomial bypass, proportioning, and shut-off is described in this section. Figures 6 and 7 show a typical deployment of the valves described together with the data input nomenclature for "from" and "to" tubes. In each case the valves are set in position at the end of a time increment by the sensor lump temperatures at that time.

For both the bypass and shut-off valves the equations (Section 3.4.3) generated for the determination of flow rate are changed by deleting the pressure drop equation and adding in its place the flow proportion caused by the valve. As an example consider a bypass valve in the system schematic of Figure 6. The equations which normally determine flow rate would contain the equation

$$\Delta P_3 = \Delta P_2 + \Delta P_6 + \Delta P_7$$

With the valve in operation this equation would be replaced simply by $\dot{w}_3 = \chi \dot{w}_1$, and the pressure drop would not necessarily be balanced.

A pressure balance is maintained across the proportioning valves as described below in paragraph 4.1.4.

Any of these valves may be unused for a particular problem or part of a problem as determined by the program user. This feature enables the assessment of the system performance characteristics with and without the valves for a minimum of data input.

4.1.1 Rate-Limited Bypass Valve

This valve is designed to proportion the flow branching from a single tube in such a way that the temperature at a designated sensor tube lump is constrained to a specified temperature if obtaining the temperature at the end of each time increment is within the valve response capability. The valve's position (fraction bypassed) is determined by integration of its velocity. The velocity is determined according to the difference between the sensor lump temperature after each iteration and the desired temperature of the sensor lump. The model for this velocity dependance is shown in Figure 5. This model was designed to represent an electromechanical bypass valve used for the Apollo ECS radiators. Since the valve is rate sensitive, a value for the time increment must be used for steady state solution even though it is physically meaningless.

4.1.2 Polynomial Bypass Valve

The polynomial bypass valve distributes the flow at a branch dependent on a specified temperature in the problem. The fraction bypassed

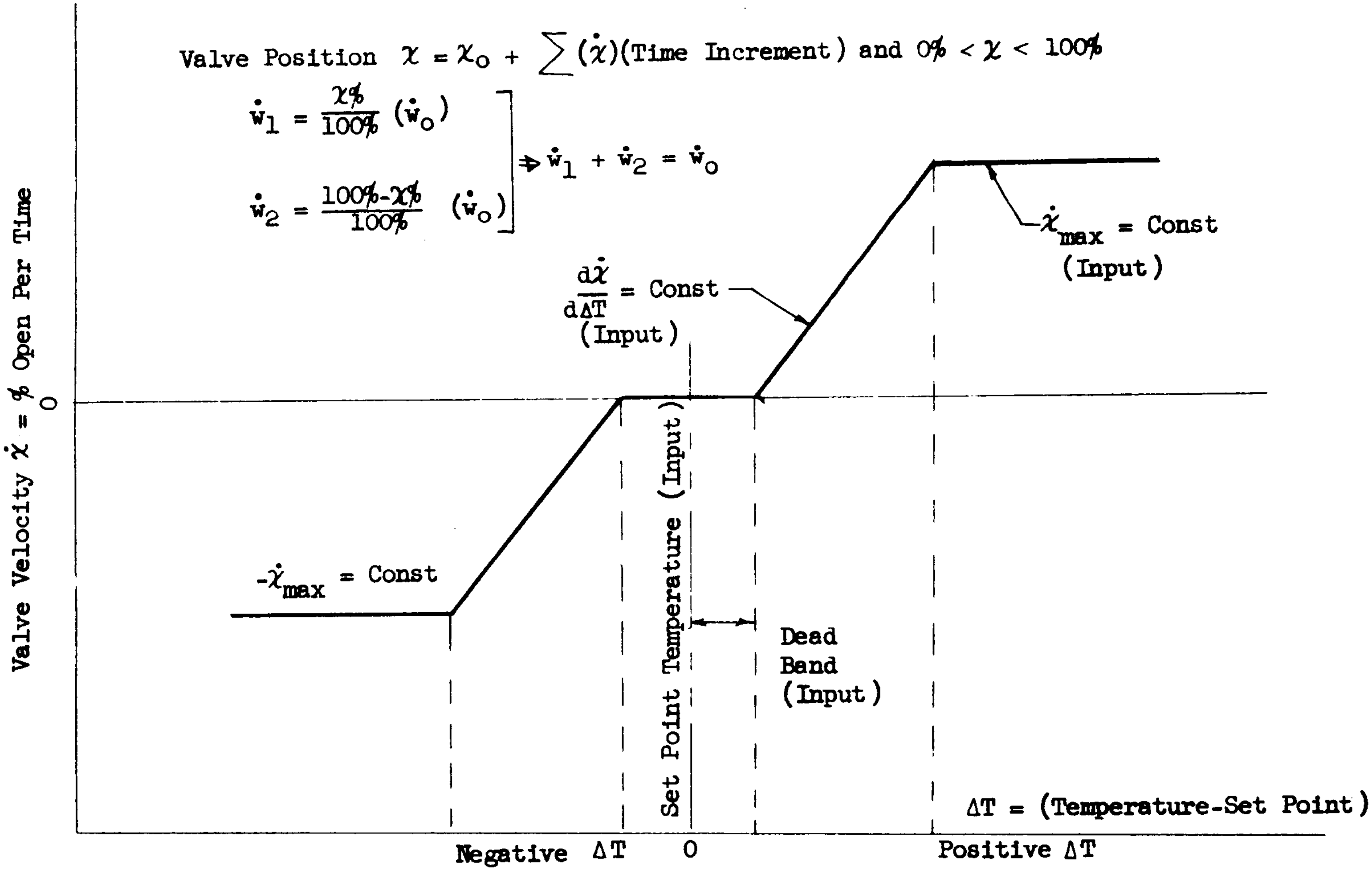
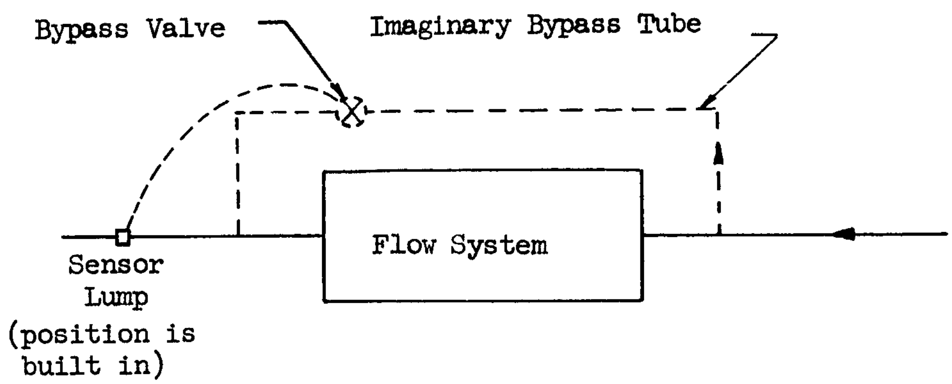
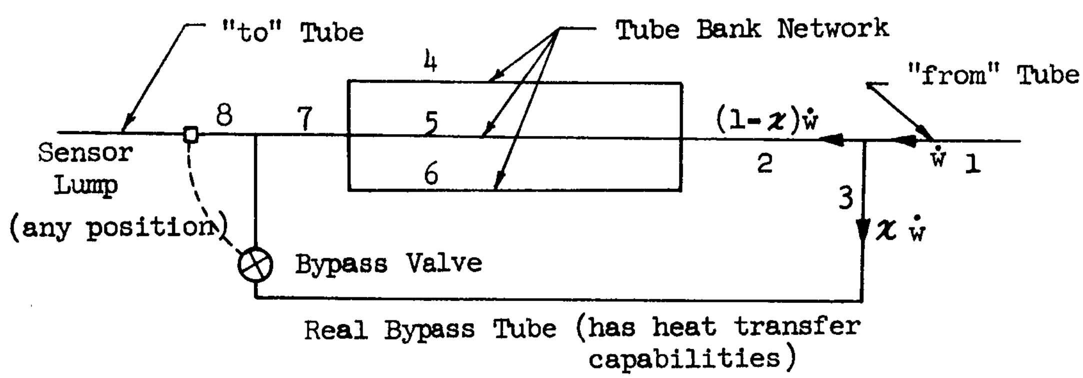


FIGURE 5

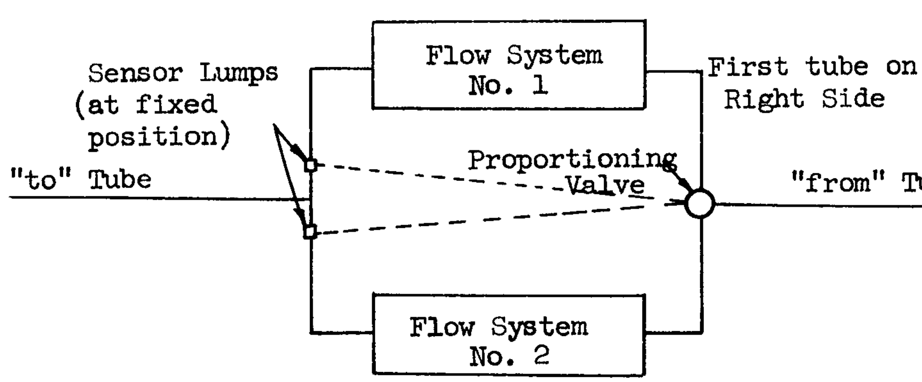
BYPASS VALVE OPERATION



IMAGINARY BYPASS VALVE

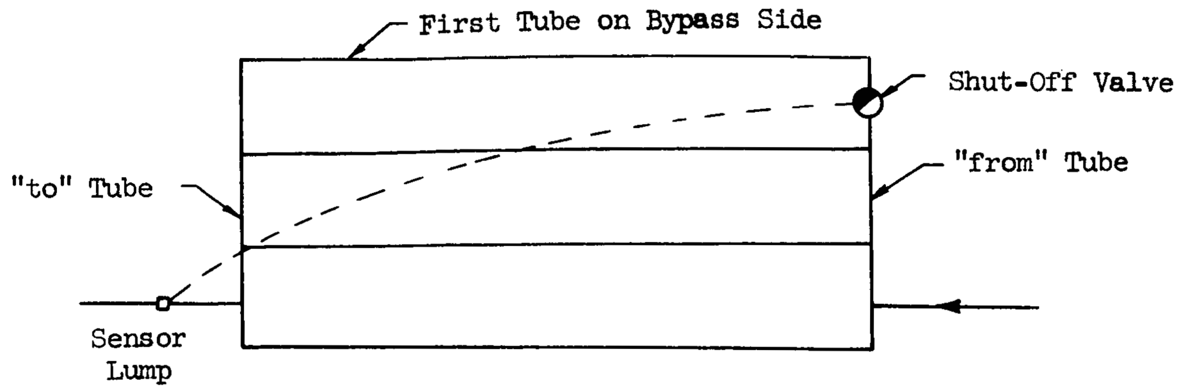


BYPASS VALVE WITH REAL TUBE

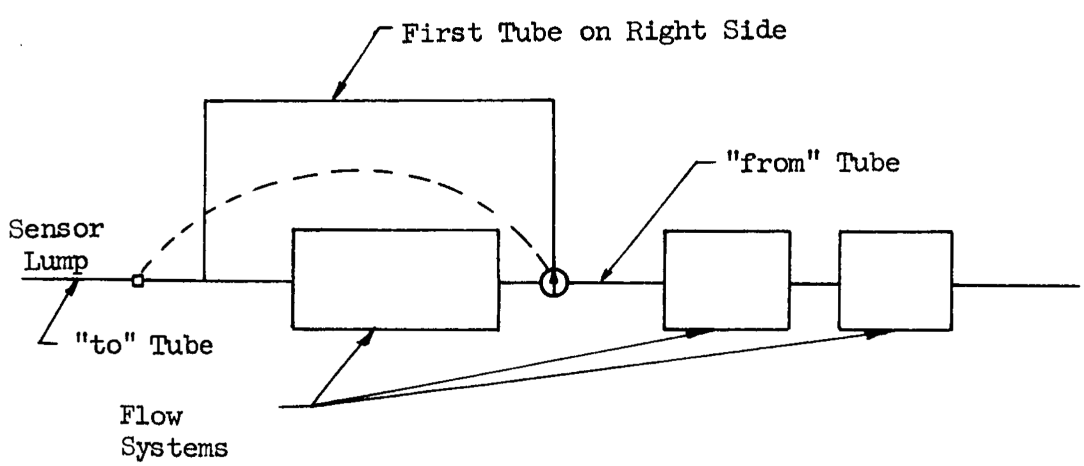


TYPICAL PROPORTIONING VALVE DEPLOYMENT

FIGURE 6 - SCHEMATICS SHOWING TYPICAL VALVE DEPLOYMENT



TPYICAL SHUT-OFF VALVE DEPLOYMENT



TYPICAL SWITCHING VALVE DEPLOYMENT

FIGURE 7 - SCHEMATICS SHOWING VALVE DEPLOYMENT

is determined by a fourth order polynomial (χ versus temperature) for which the coefficients are data inputs.

4.1.3 Shut-Off Valves

Three types of shut-off valves are available for use. The first and second merely are open or shut depending on a temperature in the system. The first closes when the selected temperature drops below a pre-arranged value and re-opens when that temperature exceeds a separate higher value. The second opens as the temperature falls below a first value and closes when a second value is exceeded. The third valve combines the first and second valve such that it switches the flow between two branches as a function of the two temperatures chosen.

4.1.4 Proportioning Valve

The proportioning valve is designed to respond in the direction of causing the flow in two parallel paths to exhaust at the same temperature. This arrangement may be utilized to provide maximum heat rejection when two sides of a radiator system operate in a significantly different incident heat environment. The valve operates in a manner designed to reproduce characteristics of an actual valve used during Apollo Block II ECS radiator tests. The equation describing the operation of the valve is:

$$\chi = \chi_{previous} + \Delta\tau \left[(\chi_i - \chi_{previous}) + \text{valve gain } (T_{RT} - T_{LT}) \right]$$

where:

Valve gain is allowed as an input constant in the data.

$\Delta\tau$ = time increment

χ_i = initial valve position

χ = present valve position

T_{RT}, T_{LT} = temperature of sensors in right and left hand tubes

After the position χ is determined, it is used to define the pressure drops in each side of the valve through the relation:

$$\Delta P_{RT} = E \left[\frac{\dot{w}_{RT}}{\chi_2} \right]^2$$

$$\Delta P_{LT} = E \left[\frac{\dot{w}_{LT}}{\chi_1} \right]^2$$

E = proportionality factor ($= \frac{PPARA}{2\ GFACT}$ see Parameter Card 22 of data preparation)

$\dot{w}_{RT}, \dot{w}_{LT}$ = right and left flow rates

χ_1 = valve position from left

χ_2 = valve position from right

The valve pressure drops are considered together with the pressure drops in the remainder of the right and left hand flow paths to determine flow rates which give a pressure balance for both sides of the system. Considering the pressure drop of the radiator to be a linear function of flow rate, such that $\Delta P = K\dot{w}$, the pressure balance in the radiator and valve can be written as:

$$K_{RT}\dot{w}_{RT} + E\left[\frac{\dot{w}_{RT}}{\chi_2}\right]^2 = K_{LT}\dot{w}_{LT} + E\left[\frac{\dot{w}_{LT}}{\chi_1}\right]^2$$

where:

K_{RT} = ΔP of radiator right branch/right side flow rate

K_{LT} = ΔP of radiator left branch/left side flow rate

$\dot{w}_{RT}, \dot{w}_{LT}$ = right and left flow rates

The pressure drop equation may be solved for the left side flow rate by substituting $\dot{w}_{RT} = \dot{w}_{TOT} - \dot{w}_{LT}$.

$$E\left[\frac{1}{\chi_1^2} - \frac{1}{\chi_2^2}\right](\dot{w}_{LT})^2 + \left[K_{LT} + K_{RT} + \frac{2E\,\dot{w}_{TOT}}{\chi_2^2}\right]\dot{w}_{LT} = K_{RT}\dot{w}_{TOT} + \frac{E(\dot{w}_{TOT})^2}{\chi_2^2}$$

Denoting the coefficient of $\dot{w}_{LT}^2$ by (a), of $\dot{w}_{LT}$ by (b), and the constant term by (c), the $\dot{w}_{LT}$ may be put into the standard quadratic form.

$$\dot{w}_{LT} = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

When χ_1 and χ_2 are different by less than a specified tolerance (VLVTOL, Card 22, Columns 31-40), the value of (a) will be small and the approximation $\dot{w}_{LT} = c/b$ is used.

4.2 HEAT EXCHANGERS

A heat exchanger option is provided in the program which will allow transient analysis of systems containing a heat exchanger. The heat transfer process is calculated in the following manner. First the data input designates certain lumps to be heat exchanger lumps and indicates whether they are on the cold side of the exchanger and if so, the numbers of the adjacent hot side lumps. For lumps in the heat exchanger, the heat transfer calculations are performed as if the hot side tube lump exchanges heat with both hot and cold side fluid lumps. The cold side tube lump does not participate in the thermal exchange except to provide necessary information, such as heat transfer area to cold side fluid lump. Given the following information, the heat transfer rates may be calculated.

Denoting the position by subscript and time by superscript, the energy balance equation for the hot side tube lump is

$$w_{Tj}c_{Tj}\ \frac{T_j^{i+1} - T_j^{i}}{\Delta\tau} = (h_f A_{HT})_{cold}(T_{f_{cold}j} - T_j^{i}) + (h_f A_{HT})_{hot}(T^{i}_{f_{hot}j} - T_j^{i}) + U_+(T^{i}_{j+1} - T_j^{i}) + U_-(T^{i}_{j-1} - T^{i}_j) + \sum_K U_{jK}(T^{i}_K - T^{i}_j)$$

h_{cold}	- cold side heat transfer coefficient
h_{hot}	- hot side heat transfer coefficient
$A_{HT_{cold}}$	- cold side area for heat transfer
$A_{HT_{hot}}$	- hot side area for heat transfer
$w_t\ c_t$	- weight of hot side tube lump x specific heat
U_+	- conductance of hot side tube lump to downstream lump
U_-	- conductance of hot side tube lump to upstream lump
U_{jK}	- conductance to any other tube or structure lumps

This equation is used to solve for T_j^{i+1}. The cold tube temperature merely follows the cold fluid temperature and has no meaning. Each of the fluid temperatures, hot and cold, is determined in the same manner as for other lumps except that the cold fluid lump transfer is from the hot tube temperature rather than the cold tube temperature.

The solution thus determined is quite general in application potential, allowing either counterflow or parallel flow and unmixed cross flow. However, certain precautions should be observed. (1) The mass and longitudinal conduction area of the entire exchanger should be input for the hot side tube lump alone. The mass of cold side tube lump does not enter the problem. (2) The area for heat transfer to the enclosed fluid lump must be entered properly for the cold tube lump. (3) No conduction data for conduction between hot and cold tube lumps should be used. Essentially the cold tube lumps do not participate in the heat exchange, since the heat exchanger characterization is one in which one tube lump transfers heat with two fluid lumps. The second tube lump (cold side, by convention) is retained to enable independent specification of parameters determining pressure drop in and heat transfer from the cold fluid lump.

Three options are available to the user to determine the heat transfer coefficient in heat exchanger lumps, (1) the coefficient may be determined as per the normal flow-in-tube equations used for all other lumps, (2) a curve of heat transfer coefficient versus flow rate may be input as curve data, (3) a curve of Stanton number x (Prandtl number)$^{2/3}$ versus Reynold's number may be input from which the heat transfer coefficient may be determined. These data options permit a maximum of variety for the user's convenience.

4.3 RESTART

Provisions for problems requiring extended computer time have been made in that a dump tape is written from which the run may be continued if all conditions of the problem are not satisfied (i.e., transient time not achieved). The problem may also be dumped by the user even if specified conditions are satisfied, and then restarted from the dump tape at a later date. This latter option is particularly useful for examining the output of a long problem after a short initial period to determine whether the data has been input properly. The detail instructions on the use of the restart option are given in paragraph 5.3 of the data preparation.

4.4 TIME INCREMENT SELECTION

Several options were programmed into the routine to provide alternate methods for computing the problem time increment. These options can increase the speed of the problem solution without loss of accuracy when properly used. The use of the time increment in the finite difference equations is shown and the various computing options are described.

The basic finite difference equations (paragraph 3.1) may be written in a general form as:

$$T_j^{i+1} = T_j^{i} + \frac{\Delta\tau}{w_j c_j}\left[\sum_{K} U_{jK}(T_K^{i} - T_j^{i}) + Q - B_j (T_j^{i})^4 \right].$$

The subscript denotes lump number, the superscript time.

$\Delta\tau$ = time increment
w_j = weight of lump j
c_j = specific heat of lump j
U_{jK} = coefficient of energy transfer between j and K
Q = heat added to lump
B_j = radiation coefficient

Further, in Section 3.2 it was demonstrated that the maximum time increment for which iterations of the equation above would remain stable is:

$$\Delta\tau = \frac{\theta\, w\, c}{\sum_K U_{jK} + B_j (T_j^i)^3} \qquad \theta \text{ (convergence factor)} \leq 1.0$$

If T_j^i is set to T_j^{i+1}, the temperature of lump j may be solved for its steady state value. The finite difference equation may be written:

$$\sum_K U_{jK} (T_K^i - T_j^{i+1}) + Q - B_j (T_j^{i+1})^4 = 0$$

$$T_j^{i+1} = \frac{\sum_K U_{jK} T_K^i + Q}{\sum_K U_{jK} + B_j \left[T_j^{i+1}\right]^3}$$

Substitution of the $\Delta\tau$ from the convergence criterion into the finite difference equation yields:

$$T_j^{i+1} = T_j^i + \frac{\theta}{\sum_K U_{jK} + B_j (T_j^i)^3} \left[\sum_K U_{jK} (T_K^i - T_j^i) + Q - B_j (T_j^i)^4 \right]$$

$$T_j^{i+1} = T_j^i (1 - \theta) + \theta \; \frac{\sum_K U_{jK} T_K^i + Q}{\sum_K U_{jK} + B_j (T_j^i)^3}$$

The term on the right is by inspection exactly θ times the steady state value of temperature except that T_j^i instead of T_j^{i+1} is in the denominator. For most cases, these two are not greatly different, such that T_j^{i+1} will be approximately $(1 - \theta)$ of the previous temperature and θ of the steady state value at time i. For cases, such as fluid lumps, where radiation is non-existent, this relation is exact.

For lumps in a problem with very short time increments the time increment may be substituted into the respective difference equation and that particular lump will assume steady state with respect to its surroundings at each iteration. The value of θ is retained in the calculation to insure that the non-linearity will not cause instability. The "floating" or steady state lump may be employed in several manners in the routine:

(1) No lump's time increment will be overridden, such that the shortest of all the time increments will be used for each node.
(2) All lumps whose time increments are shorter than a specified minimum time increment will be "floating" and will assume steady state as described above at every time increment. Lumps with longer time increments will use the minimum time increment in the finite difference equation.
(3) All fluid and tube lumps will be considered "floating" using the steady state approximation, and all structure lumps will be surveyed to determine the smallest time increment, which is then used in all structure lump finite difference equations. This option is attractive only when the mass of fluid and tube lumps is very small as is the case in many radiator problems.
(4) All lumps will use the "floating" steady state approximation and the equations will be iterated without regard to time. In this iterative option the solution is only steady state but a time increment must be input to control the operation of the rate sensitive bypass valve.

4.5 CHECKOUT PRINT

The routine user may select the checkout print option which will give a detailed print at each iteration. The checkout print provides a direct, relatively simple check of the data input consistency, and indicates the time increments calculated for each lump. The check of data consistency may be performed by examining values of weight, conductance, and other quantities which are known to have recognizable symmetries and variations in the problem. One may survey the time increments and pick the value of a minimum time increment which will accurately characterize the transient and only override those lumps which realistically can be considered at steady state compared to their neighbors. An explanation of the terms of the check out print is included in paragraph 6.3.

4.6 FLUID FREEZING

An option is provided to analyze stagnant or frozen fluid lumps. The option operates in the following manner. The flow in each radiator tube is tested against a minimum flow rate which is specified in the data input. If the flow drops below this minimum flow rate, the fluid is considered to be stagnant in the tubes. Conduction data which was previously input is then used to compute fluid lump to fluid lump conduction and fluid to tube conduction. The change of phase of a fluid is accounted for in an input curve of specific heat versus fluid temperature.

In order to judge when a tube should be considered flowing after the fluid begins to thaw, a flow rate is computed at every iteration based on the fluid lump temperatures in each tube. If the calculated flow is higher than the specified minimum flow, the tube is considered to be flowing again.

4.7 FLOW BALANCE OPTIONS

Several methods of specifying the fluid flow have been found to be of use. Normally one will specify the total flow of a system and require that the flow will be such that a pressure balance is maintained in all parallel flow paths. This option is designated NFD = 0 (page 54) and is suitable for any flow network (i.e., banks and headers and parallel flow, steady state or transient).

In certain instances it may be desirable to use predetermined flow rates in parallel flow systems and not balance pressure drops. This can be useful when attempting to establish thermal verification of test results. Two such options are available. With NFD = 1, the flow rates of each tube are input as functions of time and with NFD = 2, the flow rates of each tube are specified independently as constant percentages. The total of the flows remains the total flow with NFD = 2, but flow is allowed to bypass the radiator, thus reducing proportionately the flow in each tube.

In many systems, the total system flow is not independent of the thermal solution but is dependent on the operation characteristics of a pump. This option (described in paragraph 3.4.4) is available for the user's choice as NFD = 3 (page 54). If multi-system problems are run each system will require its own pump curve. Except for the selection of total flow rate, NFD = 0 and NFD = 3 operate identically.

4.8 DIRECTIONAL ABSORPTANCE

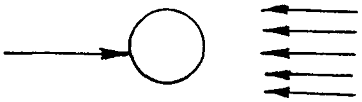
The routine provides for analysis of surfaces which absorb incident radiation in a directionally sensitive manner. Any or all tube or structure lumps may use this option. Lumps not using the option will have inputs of α , A_{ER}, and Q_i such that the rate of heat addition is $\alpha A_{ER} Q_i$. A code is provided to designate certain lumps as directionally sensitive. For these lumps an additional input is accepted such that the heat addition rate is the sum of a non-directional and a directional absorptance. The additional inputs are (1) heat flux (Q_{io}) as a function of time, (2) a directional absorptance correction factor (Υ) as a function of the cosine of the angle between the normal to the surface and the incident flux, and (3) a curve of the cosine of the angle (cosine ψ) between the normal to the surface and the incident flux as a function of time. This dual input will accommodate the absorption of energy from two sources of different wavelength, one of which the surface can absorb in a directional manner. The equation for the heat addition for such a case is:

$$\text{heat added} = \alpha A_{ER} \left[(Q_i(\tau) + \mathcal{T} Q_{io} \text{ cosine } \measuredangle) \right]$$

where:

$$\begin{aligned} \alpha &= f(T) \text{ all surfaces} \\ Q_i &= f(\tau) \text{ non-directional surfaces} \\ \left.\begin{aligned} \mathcal{T} &= f(\cos \measuredangle) \\ Q_{io} &= f(\tau) \\ \text{cosine} \measuredangle &= f(\tau) \end{aligned}\right\} & \text{ directional surface} \end{aligned}$$

The heat flux which is to be absorbed in a directionally sensitive manner (Q_{io}) is assumed to be the same function of time for all lumps. The curve number for Q_{io} is specified on Parameter Card 4, page 54. A typical application would involve specification of solar $Q_{io} = f(\tau)$ for interplanetary flight.

Spacecraft Thermal Model  $Q_{io} = f(\tau)$

The directional absorptance correction factor may be different for each lump, but since it is expected that many external surface lumps will have the same coating, the input for $\mathcal{T}$ has been provided on the tube and structure type cards, pages 71 and 74 respectively. Since the variation of cosine $\measuredangle$ with time may be different for many lumps of the same type on the spacecraft external surface it is input on tube and structure lump cards, pages 73 and 75 respectively.

The program user may utilize the directionally dependent absorptance option for separate pickup of non-directionally sensitive infrared and solar heating by specifying data input values for the above variables corresponding to:

$$\text{heat added} = \epsilon A_{ER} \left[Q_{infrared}(\tau) + (\alpha/\epsilon)(1.0)\, Q_{solar}(\tau) \right]$$

Thus parametric studies of solar absorptance coating degradation (with ϵ unchanged) can be accomplished with the same time varying incident heat curves and a simple type card change of $\mathcal{T}$, (i.e., α/ϵ).

4.9 CLOSED LOOP OPERATION

A closed loop code is input for each system (Parameter Card 10) which provides for analysis of closed fluid loops. When employed, the inlet temperature table is overridden and the outlet temperature of the system at time τ is the inlet temperature to the system at time $\tau + \Delta\tau$.

4.10 TEMPERATURE PUNCH OPTION

Often it is desirable to change data during the course of a run to analyze the effect of changing some configuration or parameter at a point in the mission. On normal restart operation this is not possible. Provision has been made to output all temperatures in punched card form in the same (five temperatures per line) format as is normally printed. These punched cards are then loaded with a NASA routine which repunches them onto the lump cards as initial temperatures. The deck is then reloaded with whatever data changes were desired. The run thus initiated begins at the same point in time with TIME (Parameter Card 4, page 53) input as the initial time.

5.0 DESCRIPTION AND USE OF COMPUTER ROUTINE

5.1 DESCRIPTION

This computer routine was written in Fortran II for an IBM 7090 computer and converted to Fortran IV for Univac 1107/1108. These machines have core storage capacities of 32,768 words and 65,536 words, respectively, and the minimum requirement of eight magnetic tape units. To use certain options of the routine requires as many as three additional tape units. The program makes use of the chain feature of Fortran II and the overlay provision of Fortran IV to minimize the amount of core storage required and still provide a large data block. The first four chain links (or Fortran IV subroutine counterparts) read, process, and store the data in a packed data block, and the fifth chain executes the main program. The operations performed by each chain and its corresponding subroutines are outlined briefly in the following paragraphs.

5.1.1 Chain 1

1. Reads the first three data cards and stores all of the first card and the first six columns of the second card for a heading to be printed at the top of every page of output. Stores the parameters on the second and third cards and begins writing a description of the problem.

2. Tests the re-start code. If it is zero, the data processing will be continued by Chain 1 as described in the following paragraphs. If it is not zero, this indicates that all data is from the dump of a previous problem. Chain 1 reads tape NDPT and Chain 5 is called to begin calculations.

3. Reads the fourth card, stores the parameters, and continues writing the description of the problem, listing the options indicated on this card.

4. If fluid flow is indicated, reads the fifth card and stores and writes the heat transfer coefficient factors.

5. If the tubes are arranged in parallel and if more than one system is to be analyzed, reads the sixth card and as many additional cards as needed to supply the number of tubes in each system.

6. If the tubes are arranged in the banks and headers form, reads the seventh, eighth, and ninth cards giving the description of fluid flow paths and writes the flow path list.

7. Reads the tenth card(s) to provide a closed loop code for every system.

8. If a steady state solution involving parallel fluid flow is indicated, reads the eleventh card and as many other cards as necessary to supply an inlet temperature for every tube in every system.

If a steady state solution involving banks and headers fluid flow is indicated, reads the twelfth card and as many other cards as needed to furnish an inlet temperature for the first tube in each system.

If a transient solution involving parallel fluid flow is indicated, reads the thirteenth card and as many additional cards as needed to supply table numbers for the inlet temperature of each tube in each system.

If a transient solution involving banks and headers fluid flow is indicated, reads the fourteenth card and as many additional cards as necessary to furnish a table number for the inlet temperature of the first tube in each system.

9. Reads the fifteenth, sixteenth, seventeenth, or eighteenth card according to the flow control option indicated.

10. Reads the nineteenth card if the flow control option indicates it is needed.

11. If there are any valves, reads the twentieth and twenty-first cards, and the twenty-second card if it is required, to specify the parameters for each valve.

12. Calls subroutine SUBP to write the page heading, count lines, skip pages, and increment the page count. Assumes 60 lines/page minimum.

13. Calls subroutine RESET, CLOCK, and WCLCK to read the computer clock and accumulate the time usage in the chain link. WCLCK reads the printer clock; RESET calls WCLCK and initializes computer time while CLOCK calls WCLCK and computes the elapsed time in the particular chain link. Dummy subroutines may be used if desired, or a single NASA-MSC clock routine may be used for Fortran II operation. For operation on the Univac 1108, no clock routine is needed.

5.1.2 Chain 2

1. Calls subroutine SUBA to read, write, and store all of the fluid lump data.

2. Calls subroutine SUBB to read, write, and store all of the tube lump data.

3. Calls subroutine SUBP to write the page heading, count lines, skip pages, and increment the page count.

4. Calls subroutines RESET, CLOCK, and WCLCK to read the computer clock and accumulate the time usage in the chain link.

5. Writes the amount of data space used by the parameter data and the fluid data.

6. Writes the amount of data space used by the parameter data, fluid data, and tube data combined.

7. Calls Chain 3.

5.1.3 Chain 3

1. Reads, stores, and writes the structure lump data.

2. Calls subroutine SUBP to write the page heading, count lines, skip pages, and increment the page count.

3. Calls subroutines RESET, CLOCK, and WCLCK to read the computer clock and accumulate the time usage in the chain link.

4. Writes the amount of data space used including the structure lump data.

5. Calls Chain 4.

5.1.4 Chain 4

1. Reads, writes, and stores all curve data.

2. Checks to see that all required curves are given.

3. Calls subroutine SUBP to write the page heading, count lines, skip pages, and increment the page count.

4. Calls subroutines RESET, CLOCK, and WCLCK to read the computer clock and accumulate the time usage in the chain link.

5. Writes the amount of data space used including the curve data.

6. Calls Chain 5.

5.1.5 Chain 5

1. Evaluates the heat balance equations for the various types of lumps.

2. Calls the following subroutines as needed:

(a) Subroutine SUBP to write the page heading, count lines, skip pages, and increment the page count.

(b) Subroutines RESET, CLOCK, and WCLCK to read the computer clock and accumulate the time usage in the chain link.

(c) Subroutine START which calls Chain 1 and a new problem if the data exceeds the allowable data space.

(d) Subroutine POL which does table look-up and straight line interpolation.

(e) Subroutine SUBWT which converts a block of temperatures from absolute Rankine to Fahrenheit and back to absolute Rankine.

(f) Subroutine SUBEND which writes the flow rates and pressure drops and computes and writes the power requirement, total heat rejected, and the radiator structure and fluid weight.

(g) Subroutines CHECK and SURVEY find and search all time-dependent tables, so in a transient problem, time can be up-dated to the minimum point at which any table value changes.

(h) Subroutine SUBDP initializes flow rate and inlet temperature arrays for certain flow control options. SUBDP computes the pressure drop for each tube, tests the flow control code and adjusts the flow rate as required. Tests for freezing and re-computes the pressure drops and flow rates when freezing occurs. SUBDP analyzes flow control valves for applicable problems.

(i) Subroutine REVPOL does a reverse table look-up and interpolation.

3. Tests the temperature change for every lump. If a steady-state solution is indicated and the change for all lumps is less than the value of SSTEST multiplied by the lump absolute temperature, the steady-state condition has been reached and the solution is ended. If a transient solution is indicated, the time is tested and the solution is ended when the total time for transient is reached.

4. Tests the computer time usage and end the solution if the requested time is exceeded.

5. If the solution is ended before completion of if the dump option is used, writes the entire data block and the variable block on tape IDPT so that the problem can be restarted.

5.2 DATA PREPARATION

An explanation of the input data is presented in this section of the report. Where applicable, the inputs are referenced to page numbers in the analytical methods portion of the report.

The data input is described in terms of five sets of cards (1) Parameter Cards, (2) Fluid Data Cards, (3) Tube Data Cards, (4) Structure Data Cards, and (5) Curve Data Cards. The preparation of these cards is described in paragraphs 5.2.1 through 5.2.5, respectively.

Although the twenty-two parameter cards determine almost all of the computing options, many are not required for any one particular problem. A flow chart in Figure 8 shows which parameter cards are required for the basic routine options and is intended to supplement paragraph 5.2.1.

The thermal conduction data which is read in as part of the fluid, tube, and structure cards is explained on pages 65 through 66 which have been inserted between the parameter card description and the fluid, tube, and structure card description.

A five column field is used for all data unless otherwise specified. Integers should be right adjusted within the field. The option codes are one digit, usually "0" or "1". An "0" need not be punched as blanks are read as zero. The integer format is designated simply as "I".

Unless otherwise stated, the fixed point format specification is F5.2. That is, if the decimal point is not written, it is assumed to be between the third and fourth columns of the five column field. A decimal point may be written in any column of the field and its position will override the indicated position in the format specification. The fixed point format is designated simply as "FP".

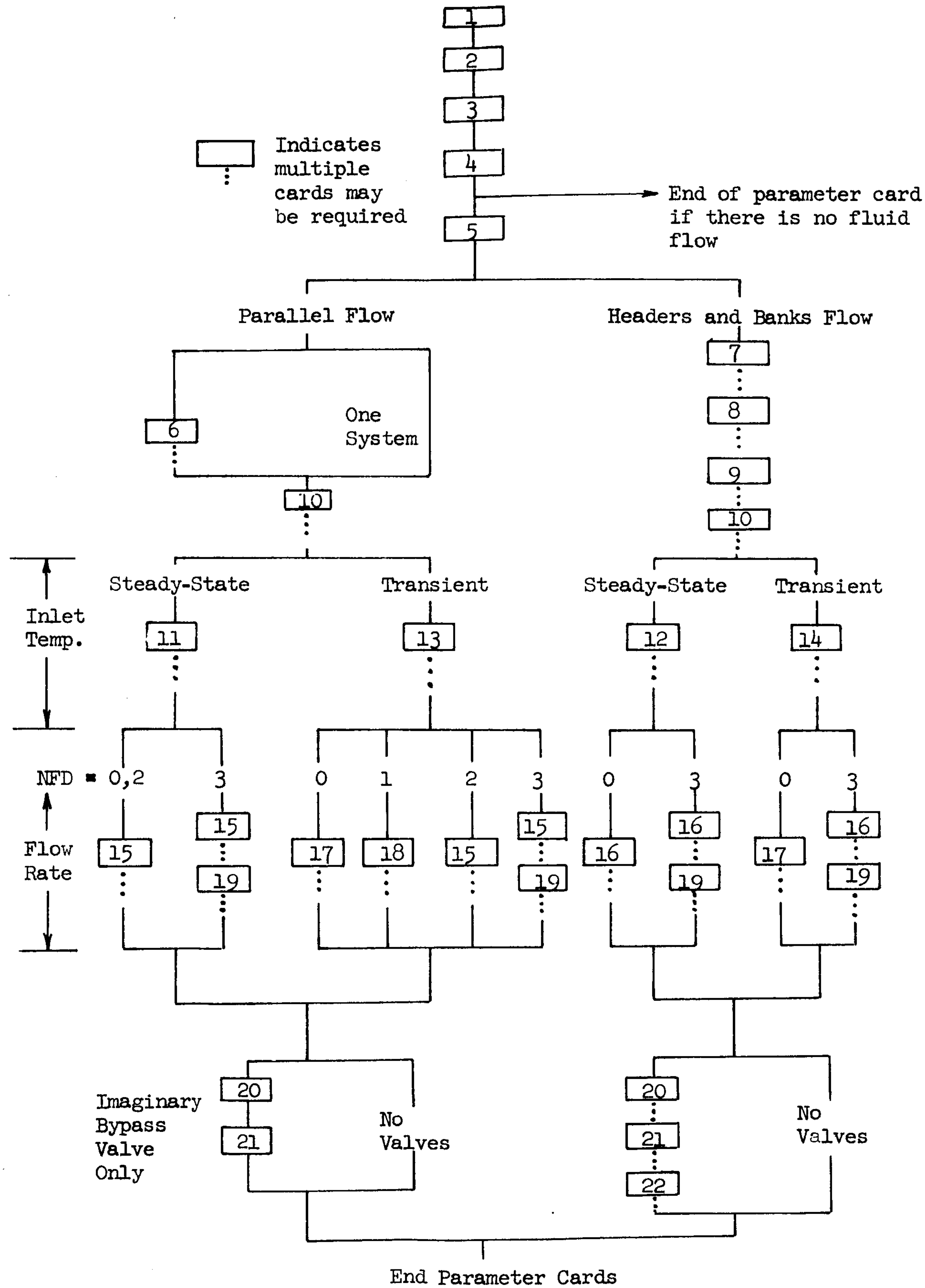


FIGURE 8 - PARAMETER CARD REQUIREMENTS

5.2.1 Parameter Cards

Card 1

Any 72 alphanumeric characters which are desired can be printed at the top of every page of output. Columns 1 through 72 will be read and printed. Any part or all of the card may be blank.

Card 2

Columns	Nomenclature	Form	Description	Analysis Page Reference
1-6			Any 6 alphanumeric characters.	
7-20	TINCMN	FP F14.14	Minimum time increment if NCC = 1 (Column 37). Time increment for valve operation if NCC = 3.	40 33
21-23	NVLVRS	I	The number of valves having parameters to be changed on restart.	
24-25			Blank	
26-30	ISET	I	Data set number. May be any number except for the first set which must be 00001 (or 1 in column 30).	
31-35	RTIME	FP	Requested computer time (minutes) for this set of data. The problem will be written on a dump tape for re-starting if this time is exceeded.	
36			Punch option. Punches out temperatures. = 0, No punch = 1, For steady state. Will punch if MAXI (Columns 51-55) is exceeded. = 2, For transient. Will punch if TAU (Columns 41-45) is exceeded. = 3, Punch every iteration	44
37	NCC	I	= 0, Survey all lumps to determine the smallest time increment which will then be used as the transient time step for all lumps. = 1, Minimum time increment supplied (Col. 20). Lumps with time increments smaller than minimum time increment will be considered steady state. All other lumps use the minimum time increment.	40

Columns	Nomenclature	Form	Description	Analysis Page Reference
			= 2, Each fluid and tube lump will be considered steady state. The smallest structure lump time increment will be used for the transient time interval. = 3, Each fluid, tube, and structure lump will be considered steady state. Equations are iterated to determine steady state answer. Do not use for a transient problem.	
38	ISTART	I	0, This problem has not been run before. New data follows. 1, The data for this problem is to be read from the dump tape. 2, Skip over this problem on the dump tape. It is not to be re-started.	40
39			Blank	
40	IDUMP	I	0, Dump this problem for re-starting only if TAU (Col. 45) or SSTEST (Col. 70) is not satisfied. 1, Dump this problem even if conditions are satisfied.	
41-45	TAU	FP	= 0, A steady state solution is desired. ≠ 0, The total time for a transient solution (hours).	
46-50	DELTAU	FP	= 0, Print only at end or every hour if problem time is greater than one hour. ≠ 0, Print interval (hours).	
51-55	MAXI	I	Maximum number of iterations for a steady state solution. Routine sets to 10,000 if left blank.	
56-60	THETA	FP	Convergence factor. Routine sets to .9 if left blank.	40

Columns	Nomenclature	Form	Description	Analysis Page Reference
61-70	SSTEST	FP F10.5	Steady state testing factor. Routine sets to .000001 if left blank.	17
71	NCKOUT	I	0, Print under control of print interval. 1, Provide checkout printing during every iteration and regular print at end of each time interval.	42
72	NREG	I	Heat exchanger code. 0, Not heat exchanger problem. ≠ 0, Heat exchanger problem.	39
Card 3				
1-10	DELP	F10.5	Pressure drop tolerance.	25,29
Card 4				
1-5	NTUBE	I	Total number of tubes in all systems.	25,27
6-10	NTFL	I	Total number of all fluid lumps.	12
11-15	NTML	I	Total number of all tube lumps.	7
16-20	NSL	I	Number of structure lumps for a nodal solution. Must be > 0.	3
21-25	NSYS	I	Number of systems. Routine sets to one if left blank.	
26-30	MAXTB	I	Number of tubes in system that has greatest number of tubes of any system. Maximum value is 102.	
31-35	TIME	FP F5.4	Time in hours. Usually will be left blank but may be input for beginning a transient problem at some particular point on the time dependent tables. Do not set greater than TAU (Card 2, Col. 41).	
36-40	NVLV	I	Number of valves (requires parameter cards (20), (21) and possibly (22).	33
41-42	NAVTC	I	= 0, Use $(T_{fu} + T_f)/2$ for equation (12). Check stability criteria for A_f (equation 18) before using this option. = 1, Use T_f in equation (12).	12 16 12

Columns	Nomenclature	Form	Description	Analysis Page Reference
43-44	NRMIHC		Directional coating code. = 0, Normal incident heat flux for all lumps. > 0, Curve number of incident heat flux (Q_{io}) to be used with directional coatings.	43
45-46			Blank	
47-48	NPFC	I	= 0, Parallel flow. ≠ 0, Banks and headers flow.	25 27
49-50	NFC	I	= 0, Do not consider freezing. ≠ 0, Consider a tube to be frozen if the flow rate is less than FMIN (Col. 70).	 42
51-52	NFD	I	= 0, The flow rates are adjusted in subroutine SUBDP to maintain equal pressure drops in parallel flow paths. If a transient problem, the total flow is read in as a function of time (Card 17). At each time interval, the total flow is found from the $\dot{w}$ versus time curve. If a steady state problem, parallel flow, the flow rate of each tube is input (Card 15) and summed for total flow. If a steady state problem, banks and headers flow, the total flow in each system is input (Card 16). = 1, Use only for transient parallel flow. The flow rate of each tube is a function of time (Card 18). The pressure drops in the tubes are computed for the print-out but the flow rates are not adjusted. Use of bypass valve not allowed.	43

Columns	Nomenclature	Form	Description	Analysis Page Reference
51-52	NFD	I	= 2, The flow rates of each tube are read in (Card 15) and remain proportional. The pressure drops will be computed for print-out. Each flow rate is bypassed proportionally when a bypass valve is used(parallel flow only).	43
			= 3, Pressure drop is computed and the total flow as a function of pressure drop is found from the $\dot{w}$ versus ΔP curve (Card 19)	
			For either steady state or transient problems.	
			If parallel flow, the initial flow rate of each tube is read in (Card 15) and summed for total initial flow.	
			If banks and headers flow, the flow in each system (card 16) is read as total initial flow.	
53-60			Blank	
61-70	FMIN	FP F10.9	Minimum flow, lb/hr, of a tube before freezing. If NFC $\neq$ 0 (Col. 50) any tube will be considered frozen if the flow rate drops below FMIN.	42

Card 5 (Heat transfer coefficients for fluid flow)

1-5	HI1	FP F5.4	Entry length heat transfer coefficient factor. Recommended value for circular tubes .575.	22
6-10	HI2	FP F5.4	Fully developed heat transfer coefficient factor. Recommended value for circular tubes 1.0.	22

Card 6 (For parallel flow, if NSYS > 1)

1-5	NTB1	I	Number of tubes in system 1.
6-10	NTB2	I	Number of tubes in system 2.

Etc. through Column 70.

Repeat this card as many times as needed to supply NTB for every system. If NSYS = 1, omit this card and NTB1 will be set to NTUBE.

Columns	Nomenclature	Form	Description	Analysis Page Reference
Card 7 (For banks and headers)				
1-5	NFLO1	I	Number of flow paths in system 1.	58
6-10	NFLO2	I	Number of flow paths in system 2.	

Etc. through Column 70.

Repeat this card as many times as needed to supply NFLO for each system.

Columns	Nomenclature	Form	Description	Analysis Page Reference
Card 8 (For banks and headers)				
1-5	NFDRS	I	Number of feeders in system 1. (A feeder is a tube containing the total flow.)	28
6-10	NFDR1	I	Number of first feeder (first tube).	
11-15	NFDR2	I	Number of second feeder.	

Repeat until all feeders have been listed. The last feeder will always be the last tube in the system. Continue in the next five-column field with the number of feeders in System 2, without any blank fields. Begin a new card after Columns 65-70 have been filled.

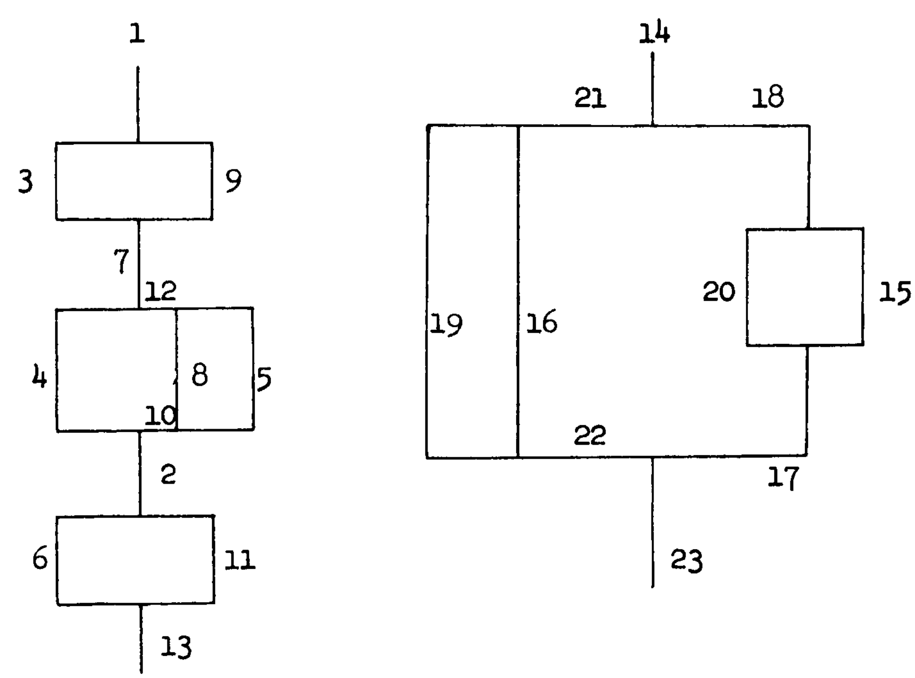
Columns	Nomenclature	Form	Description	Analysis Page Reference
Card 9 (For banks and headers)				
1-5	ISEG 1,1,1	I	Number of first tube in first flow path (see example on next page for definition of a flow path) in first system.	
6-10	ISEG 1,1,2	I	Number of second tube in first flow path in first system.	
11-15	ISEG 1,1,3	I	Number of third tube in first flow path in first system.	
Etc.				
	ISEG 1,1,n	I	Number of last tube in first flow path in first system.	
	Blank		Leave 5 columns blank to indicate the end of a flow path.	

Columns	Nomenclature	Form	Description	Analysis Page Reference
	ISEG 1,2,1	I	Number of first tube in second flow path in first system.	
	ISEG 1,2,2	I	Number of second tube in second flow path in first system.	
	ISEG 1,2,3	I	Number of third tube in second flow path in first system.	
Etc.				
	ISEG 1,2,n	I	Number of last tube in second flow path in first system.	
	Blank		Leave 5 columns blank to indicate the end of a flow path.	

Etc. through Column 70.

Repeat this card as many times as needed until all flow paths in all systems have been listed. No blank is required after the last tube in the last flow path in the last system.

For example:



Flow path 1 consists of tubes 1, 3, 7
Flow path 2 consists of tubes 1, 9, 7
Flow path 3 consists of tubes 7,4,2
Flow path 4 consists of tubes 7, 12, 8, 10, 2
Flow path 5 consists of tubes 7, 12, 5, 10, 2
Flow path 6 consists of tubes 2, 6, 13
Flow path 7 consists of tubes 2, 11, 13
Flow path 8 consists of tubes 14, 21, 19, 22, 23
Flow path 9 consists of tubes 14, 21, 16, 22, 23
Flow path 10 consists of tubes 14, 18, 20, 17, 23
Flow path 11 consists of tubes 14, 18, 15, 17, 23

Restrictions:

(a) Two and only two tubes must branch from or flow into another tube.
(b) Tubes must be numbered one through NTUBE.
(c) The first tube in a system must have the smallest number of any tube in that system, the first tube in system 1 being numbered 1.
(d) Each system must have at least four tubes.
(e) The last tube in a system must have the largest number of any tube in that system, the last tube in the last system being numbered NTUBE.

Card 10 (Closed Loop Card)

Columns	Nomenclature	Form	Description	Analysis Page Reference
1-5	CLS1	I	Closed loop code for system 1.	44
6-10	CLS2	I	Closed loop code for system 2.	

etc.

Repeat in five-column fields until a closed loop code has been specified. A new card is required after columns 65-70 have been filled. A zero will provide an open system, a "one" will cause the inlet temperature of the last lump in the system to be input to the system at each iteration.

Card 11 (For steady state solution involving parallel fluid flow)

1-5	FTEM1	FP	Inlet temperature for tube 1, °F.
6-10	FTEM2	FP	Inlet temperature for tube 2, °F.

Etc. through Column 70.

Repeat this card as many times as necessary to supply an inlet temperature for every tube in each system.

Columns	Nomenclature	Form	Description	Analysis Page Reference
Card 12	(For steady state solution involving banks and headers fluid flow)			
1-5	FTEM1,1	FP	Inlet temperature for first tube in first system, °F.	
6-10	FTEM2,1	FP	Inlet temperature for first tube in second system, °F.	

Etc. through Column 70.

Repeat this card as many times as needed to supply an inlet temperature table number for every tube in every system.

Card 13	(For transient solution involving parallel fluid flow)		
1-5	NFTEM1	I	Curve number of table for inlet temperature of tube 1.
6-10	NFTEM2	I	Curve number of table for inlet temperature of tube 2.

Etc. through Column 70.

Repeat this card as many times as needed to supply an inlet temperature table number for every tube in every system.

Card 14	(For transient solution involving banks and headers fluid flow)		
1-5	NFTEM1,1	I	Curve number of table for inlet temperature of first tube in system 1.
6-10	NFTEM2,1	I	Curve number of table for inlet temperature of first tube in system 2.

Etc. through Column 70.

Repeat this card as many times as needed to supply an inlet temperature table number for the inlet tube in each system.

Columns	Nomenclature	Form	Description	Analysis Page Reference

Card 15 (For steady state solution involving parallel fluid flow; for transient solution involving parallel fluid flow if NFD = 2 or 3)

1-5	FLOW1	FP	Flow rate of tube 1, lb/hr.
6-10	FLOW2	FP	Flow rate of tube, lb/hr.

Etc. through Column 70.

Repeat this card as many times as needed to supply a flow rate for every tube in every system.

Card 16 (For steady state solution involving banks and headers fluid flow; for transient solution involving banks and headers fluid flow if NFD = 3, see paragraph 4.7)

1-5	FLOW1,1	FP	Total flow rate in system 1, lb/hr.
6-10	FLOW2,1	FP	Total flow rate in system 2, lb/hr.

Etc. through Column 70.

Repeat this card as many times as needed to supply a total flow rate in each system.

Card 17 (For transient solution involving parallel fluid flow or banks and headers fluid flow if NFD = 0)

1-5	NFRC1,1	I	Curve number of table for total flow rate in system 1.
6-10	NFRC2,1	I	Curve number of table for total flow rate in system 2.

Etc. through Column 70.

Repeat this card as many times as needed to supply a total flow rate curve number for each system.

Card 18 (For transient solution involving parallel fluid flow if NFD = 1)

1-5	NFRC1	I	Curve number of table for flow rate of tube 1.
6-10	NFRC2	I	Curve number of table for flow rate of tube 2.

Columns	Nomenclature	Form	Description	Analysis Page Reference

Etc. through Column 70.

Repeat this card as many times as needed to supply a flow rate curve number for every tube in every system.

Card 19 (If NFD = 3)

1-5	NFPC1,1	I	Curve number for total flow in system 1 as a function of pressure drop.
6-10	NFPC2,1	I	Curve number for total flow in system 2 as a function of pressure drop.

Etc. through Column 70.

Repeat this card as many times as needed to supply a curve number for each system.

Parameter Cards 20 and 21 and sometimes 22 are necessary for each valve in non-restart data. Cards 20 and 22 can be included following Parameter Card 2 in restart data. Valves should be numbered 1 through NVLV. Cards 20 and 21 (and 22) for one valve should be together but valve numbers need not be in numerical order. The value of NCHTN (Card 21, Col. 5) influences the format of the cards.

Card 20 (For valves)

Columns	If NCHTN = (Card 21, Column 5)	Nomenclature	Form	Description	
1-3	1,2,3,4,5	NVLVN	I	Valve number.	33
4-5	1,2,3,4,5	NOPMD	I	Operating Mode. = 0, valve is operating. ≠ 0, valve is not operating. A valve can essentially be added on restart.	
6-10	1,2,3,5	NSLMP	I	Sensor lump number. If the bypass tube is imaginary and encompasses whole system, NSLMP = 0.	
	4			Blank	

Columns	If NCHTN = (Card 21, Column 5)	Nomenclature	Form	Description	Analysis Page Reference
11-20	1,2,3,5	FRCMIN	FP F10.5	Minimum fraction of flow required through non-bypass tube(s).	
	4	POSMIN	F10.5	Minimum allowable valve Position from left	37
21-30	1,2,3,5	FRCMAN	FP F10.5	Maximum fraction of flow allowed through non-bypass tube(s).	
	4	POSMAX	FP F10.5	Maximum allowable proportioning valve position measured from left. Milli-inches.	37
31-40	1	SETPT	FP F10.5	Set point of temperature, °F.	34
	2			Blank	
	3,5	T1	FP	Sensor lump temperature, °F. If sensor lump temperature < T1, + 3 valve closes, - 3 valve opens (see Column 5, Card 21).	
	4	FULOPN	FP F10.5	Maximum possible proportioning valve position measured from left. Milli-inches.	37
41-50	1	DBAND	FP F10.5	Bypass valve Dead band, °F	34
	2,4	Blank			
	3,5	T2	FP F10.5	Sensor lump temperature, °F. If sensor lump temperature > T2, + 3 valve opens - 3 valve closes (see Column 5, Card 21)	
51-60	1	RFACT	FP F10.5	Rate factor. Bypass valve. Units are fraction bypass per second per degree, °F.	34

Columns	If NCHTN = (Card 21, Column 5)	Nomenclature	Form	Description	Analysis Page Reference
	2,3,4,5			Blank	
61-70	1	RLIM	FP F10.5	Bypass valve. Rate limit. Usual value .033. Units are fraction bypass per second.	34
	2,3,4,5	Blank			
Card 21	(For valves)				
1-3	1,2,3,4,5	NUMSYS	I	Number of system containing valve.	
4-5	1,2,3,4,5	NCHTN	I	Characterization code. 1, rate limit bypass 2, polynomial bypass +3, on/off, -3 off/on 4, proportioning 5, switching	 33 33 37 37 37
6-10	1,2,3	NTBBYP	I	Number of first tube on bypass side.	35
	4,5	NTBRT	I	Number of first tube on right side. Right side of switching valve closes when $T < T_1$ (col. 31-40, Card 20).	35,36
11-15	1,2,3,4,5	NTBFM	I	Number of "from" tube.	35,36
16-20	1,2,3,4,5	NTBTO	I	Number of "to" tube.	35,36
21-30	1	FRCIN	FP F10.5	Initial fraction of flow assigned to non-bypass tube(s).	
	2,3	Blank			
	4	POSIN	FP F10.5	Initial proportioning valve position measured from left.	37
	5	FRCIN	FP F10.5	Initial fraction of flow assigned to tube(s) on left. Must be 0 or 1.	

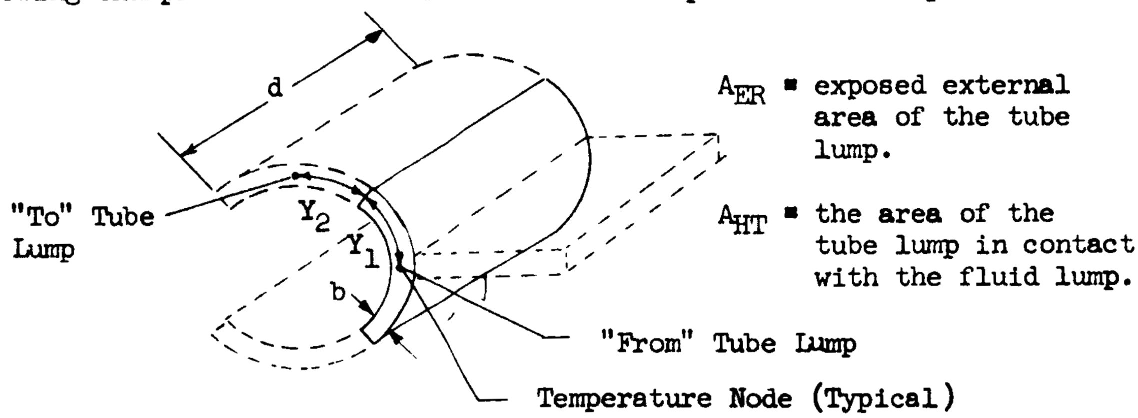
Columns	Nomenclature	Form	Description	Analysis Page Reference
Card 22	(Necessary only if NCHTN = 2 or 4)			
If NCHTN = 2,				
1-10	A_0	FP F10.5	Coefficients in fraction bypass $\chi = A_0 + A_1 T + A_2T^2 + A_3T^3 + A_4T^4$ where T = temperature sensor lump (^oF).	33
11-20	A_1			
21-30	A_2			
31-40	A_3			
41-50	A_4			
If NCHTN = 4,				
1-10	VLVGAN	FP F10.5	Proportioning valve gain. Usual value 1.155. Units are Milli-inches per ^oF.	37
11-20	PPARA	FP F10.5	Panel parameter. Usual value ,2.	38
21-30	GFACT	FP F10.5	Geometry factor. Usual valve .03. GFACT = $(2.92)(10^{-6})(D^2)$ where D is valve orifice diameter in milli-inches. Units are $(\frac{lb}{hr})^2 (\frac{1}{milli\text{-}inch})^2 \frac{1}{1000's\ psi}$	38 37
31-40	VLVTOL	FP F10.5	Proportioning valve null position tolerance. Usual value .001. Milli-inches.	

Thermal Conduction Data

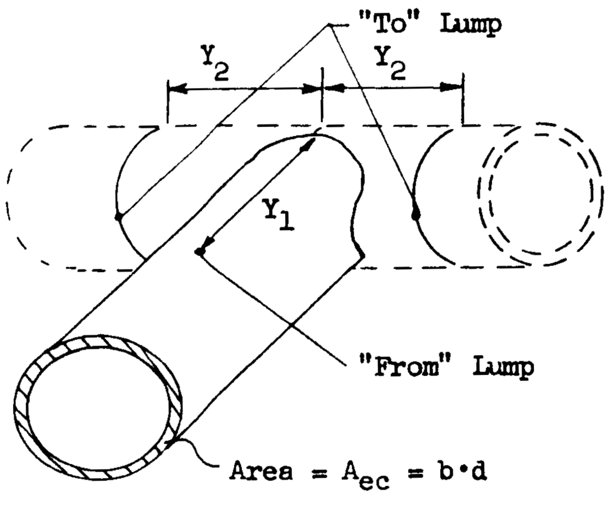
All conduction data for fluid, tube and structure lumps is input in terms of "from" and "to" data such as conduction "from" lump 1 "to" lump 2. Only unique conduction relationships should be specified so that if lump 1 conducts "to" lump 2 then conduction "from" lump 2 "to" lump 1 must not be entered. Lumps can conduct to any number of numerically higher or lower neighboring lumps.

The examples which follow show typical conduction data to illustrate the method.

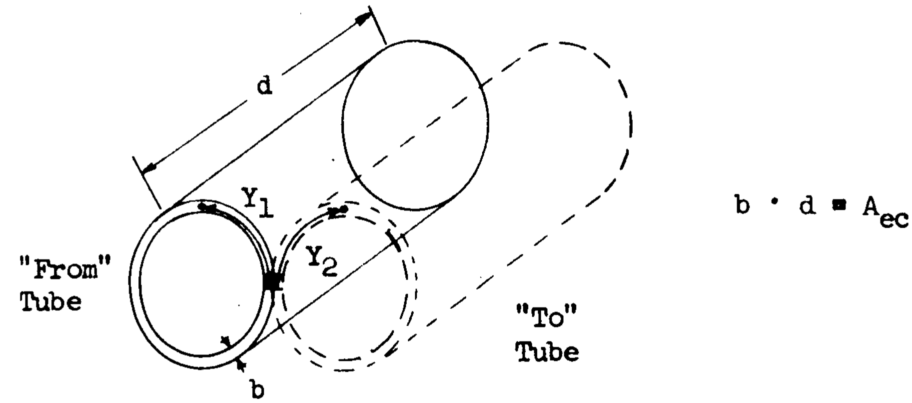
When tube-to-tube heat conduction is other than longitudinal conduction in a tube (for peripheral breakdowns, junctions, and parallel juxtapositioned tubes), conduction information should be input as shown in the following examples for conduction from tube lump 1 to tube lump 2.



Schematic showing conduction breakdown of tube to account for peripheral gradients.

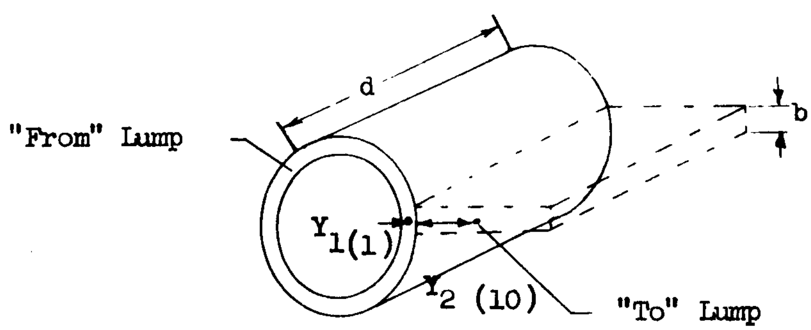


Schematic showing conduction input for conduction between tubes at a junction.

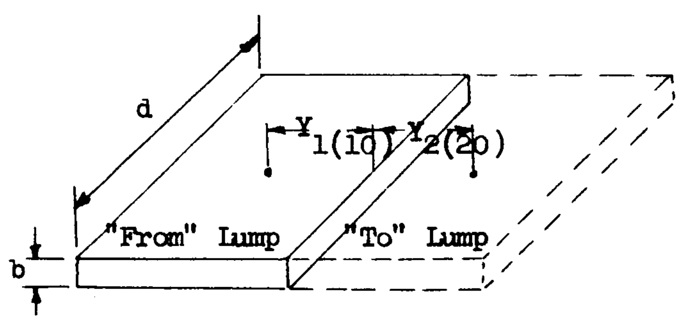


Schematic showing conduction for juxtapositioned tubes.

The tube to structure and structure to structure lump data is input similarly.



Conduction from tube lump 1 to structure lump 10



Conduction from structure lump 10 to structure lump 20

5.2.2 Fluid Data Cards

Columns	Nomenclature	Form	Description	Analysis Page Reference
Card 1				
1-5	NFLT	I	Number of types of fluid lumps.	
Card 2	(Type Data Cards)			
1-5	NDENC	I	Density curve number	
6-10	NCONC	I	Conductivity curve number.	
11-15	NSHC	I	Specific heat curve number.	
16-20	NVISC	I	Viscosity curve number.	
21-25	NFFC	I	Friction factor curve number for Re > 2000.	
26-30	NKPDC	I	$\chi = 2\Delta P/\rho V^2$ curve for pressure drop (may be blank).	25
31-35	NFCT	I	Number of fluid lumps conducted "to". Used only if frozen or stagnant flow is being considered.	42
36-40	NTCT	I	Number of tube lumps conducted "to". Used only if frozen or stagnant flow is being considered.	42
41-50	FLL	F7.5	Fluid lump length, inches.	
51-60	CSA	F10.5	Cross-sectional area, sq. in.	
61-67	WP	F7.5	Wetted Perimeter, inches.	
68-72	FRE	F5.4	Factor for computing friction factor as a function of Reynold's number. Routine sets to 1. if left blank.	

Columns	Nomenclature	Form	Description	Analysis Page Reference
Card 3	(Required if Column 72 of Parameter Card 2 is $\neq$ 0)			
1-5	NREGCD	I	Heat exchanger code = 0, this type lump is not in the heat exchanger = 1, this type lump is in the hot side = 2, this type lump is in the cold side	39
6-10	NHHH	I	= 0, use regular equation for heat transfer coefficient = 1, use a curve of heat transfer coefficient versus flow rate = 2, use a curve of Stanton$\cdot$Prandtl$^{2/3}$ versus Reynold's number.	40
11-15	NHCRV	I	if NHHH = 1 curve number of $h = f(\dot{w})$ if NHHH = 2 curve number of $StPr^{2/3} = f(Re)$	
Card 4	(Required if NFCT + NTCT > 0)			
1-10	FAC	F10.5	Factor for dividing conduction distances and dimensions. Set equal to 1. if not given. Used when conduction dimensions do not fit into five column field.	
11-15	Y1	F5.5	Conduction distance x FAC of this type of "from" lump to first "to" lump.	
16-20	Y2	F5.5	Conduction distance x FAC of first "to" lump listed for this type "from" lump.	
21-25	B	F5.5	Dimensions x FAC for computing effective conduction area for this type "from" lump and first "to" lump.	
26-30	D	F5.5		
31-35 36-40 41-45 46-50			As above for second "to" lump.	
51-55 56-60 61-65 66-70			As above for third "to" lump.	

Columns	Nomenclature	Form	Description	Analysis Page Reference

Repeat Card 4 as needed. FAC should be omitted on all cards which are a repeat of Card 4.

Repeat Card 2 (followed by Cards 3 and 4 if needed) for every fluid lump type. Any variation of lump size, curve numbers, or inclusion in the heat exchanger can be indicated only on the type cards.

Card 5 (Fluid lump cards. One for each fluid lump. The lumps must be numbered 1 through NTFL and must be in numerical order)

Columns	Nomenclature	Form	Description
1-5	LN	I	Lump number.
6-10	NLU	I	Lump upstream. If banks and headers problem, NLU = 0 for first lump in every tube.
11-15	NTB	I	Tube number.
16-20	NTYPE	I	Type number.
21-30	TI	F10.5	Initial temperature, °F.
31-35	NTL1	I	First lump conducted "to".
36-40	NTL2	I	Second lump conducted "to".
41-45	NTL3	I	etc.
46-50 51-55 56-60 61-66 66-70	NTL4 NTL5 NTL6 NTL7 NTL8	I I I I I	The order in which the lumps conducted "to" are listed will depend upon the order in which the conduction data was given on the type cards. The fluid lumps conducted "to" (if any) must be listed before the tube lumps conducted "to" (if any).

Card 6 (Continuation of list of lumps conducted "to". If the number of lumps conducted to by a lump is greater than 8, follow Card 5 with Card 6)

Columns	Nomenclature	Form	Description
1-5	NTL9	I	Ninth lump conducted "to".

Etc. through Column 70.

If the number of lumps conducted "to" is greater than 22, repeat Card 6 as needed.

Columns	Nomenclature	Form	Description	Analysis Page Reference
Card 7 (Necessary only for lumps in the heat exchanger)				
1-5	NADJL	I	Adjacent lump code. Number of hot side lump adjacent to this lump in the heat exchanger. 0 if this lump is a hot side lump.	42

Repeat Card 4 (followed by Cards 5 and 6 if required) for every lump. The lumps must be submitted in increasing order.

5.2.3 **Tube Data Cards**

Columns	Nomenclature	Form	Description	Analysis Page Reference
Card 1				
1-5	NMLT	I	Number of types of tube lumps.	64
Card 2 (Type Data Cards)				
1-5	DENM	F5.2	Density of tube material for type 1, lb/ft^3.	
6-10	NCONC	I	Curve number for conductivity.	
11-15	NSHC	I	Curve number for specific heat.	
16-20	NABC	I	Curve number for absorptivity.	
21-25	NEMC	I	Curve number for emissivity.	
26-30	NTCT	I	Number of tube lumps conducted "to".	
31-35	NFCT	I	Number of structure lumps conducted "to".	
36-38	NDRABC	I	= 0, if not directional absorbing surface ≠ 0, curve number of directional absorptance correction factor (Υ)	43
39-40	LCC	I	= 0, lumps of this type have longitudinal conduction. = 1, do not compute longitudinal conduction for lumps of this type.	
41-50	X1	F10.5	Dimensions, inches. X1·X2·X3 = Volume	
51-60	X2	F10.5	X1/2 = longitudinal conduction distance.	
61-70	X3	F10.5	X2·X3 = area for longitudinal conduction.	
Card 3				
1-10	AHT	F10.5	Area for heat transfer to enclosed fluid lump, sq. in.	
11-20	AE	F10.5	Area of surface for external radiation, sq. in.	

Columns	Nomenclature	Form	Description
21-30	FAC	F10.5	Factor for dividing conduction distances and dimensions.
31-35	Y1	F5.5	Conduction data for first "to" lump given for this type "from" lump.
36-40	Y2	F5.5	
41-45	B	F5.5	
46-50	D	F5.5	
51-55	Y1	F5.5	Conduction data for second "to" lump.
56-60	Y2	F5.5	
61-65	B	F5.5	
66-70	D	F5.5	

If NTCT + NFCT > 2, follow with Card 4.

Card 4 (For nodal, if needed for conduction)

1-10	Blank		
11-15	Y1	F5.5	Conduction data for third "to" lump.
16-20	Y2	F5.5	
21-25	B	F5.5	
26-30	D	F5.5	
31-35	Y1		Conduction data for fourth "to" lump.
36-40	Y2		
41-45	B		
46-50	D		
51-55	Y1		Conduction data for fifth "to" lump.
56-60	Y2		
61-65	B		
66-70	D		

Repeat Card 4 if NTCT + NFCT > 5. If NTCT > 0, the data for tube lump "to" tube lump must be given before the data for tube lump "to" structure lump.

Repeat Cards 2 and 3 (followed by Card 4 if needed) for every tube lump type.

Card 5 (Tube Lump Cards) (One for each tube lump. The lumps must be numbered 1 through NTML and must be entered in numerical order)

1-5	LN	I	Lump number.
6-10	NDL	I	Lump number of tube lump downstream. = 0 for last lump in each tube if headers and banks.

Column	Nomenclature	Form	Description	Analysis Page Reference
11-15	NFL	I	Lump number of enclosed fluid lump.	
16-20	NTYPE	I	Type number of lump.	
21-30	TI	F10.5	Initial temperature, °F.	
31-35	Q1 or NQIC	F5.2 or I	Incident heat value for steady state (BTU/hr-ft^2). For transient, incident heat curve number	
36-40	TW or NTWC	F5.2 or I	Prescribed temperature, °F, for steady state. Prescribed temperature curve number for transient (may be left blank).	
41-45	NTL1	I	First lump conducted "to".	
46-50	NTL2	I	Second lump conducted "to".	
51-55	NTL3	I	Etc.	
56-60	NTL4	I	The order in which the lumps conducted "to" are listed will depend upon the order in which the conduction data was given on the type cards. The tube lumps conducted "to" (if any) must be listed before the structure lumps conducted "to" (if any).	
61-65	NTL5	I		
66-70	NTL6	I		
71-72	NCOS1	I	If NDRABC (Type Card 1) = 0, leave blank If NDRABC ≠ 0, curve number for cosine of angle between surface and incident heat flux, Q_{io}.	44

Card 6 (Continuation of list of lumps conducted "to". If the number of lumps conducted "to" is greater than 6, follow Card 5 with Card 6)

Column	Nomenclature	Form	Description
1-5	NTL	I	Next lump conducted "to".
6-10	NTL		Next lump conducted "to".
Etc. to			
66-70	NTL		

Repeat Card 6 as needed to list all lumps.

Repeat Card 5 followed by Card 6 (if required) for every lump. The lumps must be given in increasing numerical order.

5.2.4 Structure Data Cards

Columns	Nomenclature	Form	Description	Analysis Page Reference
Card 1				
1-5	NT	I	Number of types of structure lumps.	
Card 2 (Structure Lump Type Cards)				
1-5	DEN	F5.2	Density of fin material, lb/ft^3.	
6-10	NCONC	I	Conductivity curve number.	
11-15	NSHC	I	Specific heat curve number.	
16-20	NABC	I	Absorptivity curve number.	
21-25	NEMC	I	Emissivity curve number.	
26-30	NFCT	I	Number of fin lumps conducted "to" by lumps of this type.	
31-40	X1	F10.5	Dimensions of lump, inches.	
41-50	X2	F10.5	$X1 \cdot X2 \cdot X3$ = Volume.	
51-60	X3	F10.5	$X1 \cdot X2$ = External radiation area.	
61-62			Blank	
63-65	NDRABC	I	Directional absorptance code. = 0, not directional absorbing surface. ≠ 0, curve number for directional absorptance factor (Υ)	43
If NFCT > 0, enter Card 3.				
Card 3				
1-10	FAC	F10.5	Factor for dividing conduction distances and dimensions. Routine sets to 1 if not given, use when numbers are too small to fit five column field.	
11-15	Y1	F5.5	Data for conduction to first lump conducted "to" by this type lump.	
16-20	Y2	F5.5		
21-25	B	F5.5		
26-30	D	F5.5		
31-35	Y1		Data for second lump conducted "to" by this type lump.	
36-40	Y2			
41-45	B			
46-50	D			

Columns	Nomenclature	Form	Description	Analysis Page Reference
51-55	Y1		Data for third lump conducted "to" by this type lump.	
56-60	Y2			
61-65	B			
66-70	D			

If NFCT   3, repeat Card 3 as needed. FAC should be omitted on all cards which are a repeat of Card 3.

Repeat Card 2 (followed by Card 3 if needed) for every structure lump type.

Card 4 (Structure Lump Cards) (One for each structure lump. The lumps must be numbered 1 through NSL and must be entered in numerical order)

Columns	Nomenclature	Form	Description	Analysis Page Reference
1-5	LN	I	Lump number.	
6-10	LTYPE	I	Type number of lump.	
11-20	TL	F10.5	Initial temperature of lump, °F.	
21-25	Q or NQIC	F5.2 or I	Incident heat value for steady state (BTU/hr-ft^2) For transient, incident heat curve number	
26-30	TW or NTWC	F5.2 or I	Prescribed temperature, °F, steady state of temperature curve number, transient (may be left blank).	
31-35	NTL1	I	First lump conducted "to".	
36-40	NTL2	I	Second lump conducted "to".	
41-45	NTL3	I	Etc.	
46-50	NTL4	I	The order in which the lumps conducted "to" are listed will depend upon the order in which the conduction data was given on the type cards.	
51-55	NTL5	I		
56-60	NTL6	I		
61-65	NTL7	I		
66-70	NTL8	I		
71-72	NCOS1	I	If NDRABC (Type Card 1) = 0, leave blank If NDRABC $\neq$ 0, curve number for cosine of angle between surface and incident heat flux	44

Card 5 (Continuation of list of lumps conducted "to". If the number of lumps conducted "to" is greater than 8, follow Card 4 with Card 5)

Columns	Nomenclature	Form	Description	Analysis Page Reference
1-5	NTL9	I	Ninth lump conducted "to".	

Columns	Nomenclature	Form	Description	Analysis Page Reference
6-10				
11-15				
Etc. to				
66-70	NTL22		Twenty-second lump conducted "to".	

Repeat Card 5 if number of lumps conducted "to" is greater than 22.

Repeat Card 4 followed by Card 5 (if required) for every lump. The lumps must be entered in increasing numerical order.

5.2.5 Curve Data Cards

Columns	Nomenclature	Form	Description
Card 1	(Curve Header Card)		
4-5	KCRV	I	Kind of curve code. Two curves may be the same number if kind of curve is different.
		0	$\mathcal{K}$ curve for pressure drop, dimensionless = f(Re).
		1	Density of fluid or liquid, lb_m/ft^3 = f(^oF).
		2	Viscosity of fluid, (lb_m/ft-sec)(x 10^3) =(^oF).
		3	Friction factor for fluid, f x 10^3 = f(Re x 10^{-3}). (Used when Re > 2000).
		4	Conductivity, BTU/hr-ft-^oF = f(^oF).
		5	Specific heat, BTU/lb_m ^oF = f(^oF).
		6	Absorptivity, dimensionless = f(^oF).
		7	Emissivity, dimensionless = f (^oF).
		9	Incident heat, BTU/hr-ft^2 = f(hours) (used for transient and/or Q_{io} for directional coatings)
		10	Constant temperature, ^oF = f(hours) (used for transient).
		11	Flow rate curve (total flow rate). If transient and NFD = 0, total flow rate = f(time), lb_m/hr = f(hours). If transient and NFD = 1, flow rate for each tube = f(time) lb_m/hr = f(hours). If NFD = 3, for either steady state or transient total flow rate = f(pressure drop). lb_m/hr = f(1000 x lb_f/sq. in.).
		12	Fluid inlet temperature, ^oF = f(hours). (used for transient).
		24	Curve of heat transfer coefficient as a function of $\dot{w}$. BTU/hr-ft^2-^oF = f(lb_m/hr).
		25	Curve of Stanton (Prandtl)$^{2/3}$ as a function of Reynold's number for definition of heat transfer coefficient.

Columns	Nomenclature	Form	Description
		27	Directional absorptance curve. Dependent variable (r) multiplies absorptance. r = f(cosine ∡).
		28	Curve relating cosine of angle between normal of a surface and the incident flux as a function of time. Cosine ∡ = f(hours).
		13	This card signals the END OF CURVE DATA.
6-10	NC	I	Curve number.
11-15	NP	I	Number of points on curve.
26-72			May be used for curve title.

Cards 2 through 2NP/7 (Curve Data Cards)

Columns	Nomenclature	Form	Description
1-10	X1	FP F10.5	Independent variable.
11-20	X2		
21-30	X3		
Etc.			
	Y1	FP F10.5	Dependent variable.
	Y2		
	Y3		
Etc.			

Start Y1 in the first field after X_{NP}.

Do not write beyond Column 70.

If the number of points given is 1, the value in Columns 11-20 will be used for dependent variable.

5.3 Interruption and Re-Start Procedure

The following conditions during execution will cause a problem to be discontinued by writing the data and variable blocks of core storage on a binary tape:

1. Using the IDUMP = 1 option.

2. Exceeding the maximum number of iterations desired for a steady-state solution.

3. Exceeding the computer request time which is input on the second parameter card.

4. Setting down Sense Switch 5 to interrupt a run and cause an exit to the next job.

5.3.1 Tape Requirements

The binary tape used for writing is loaded on logical unit 11 (A6 at LTV and on NASA 7094). If a dump is expected, a request to ring and mount a blank tape on A6 should be made on the computer request card. All sets of data which are loaded together will dump on the same tape.

The binary dump tape is loaded on logical unit 12 (A7 at LTV,& B6 on NASA 7094) for a re-start. If a data set is dumped again, it will be written on a blank tape on A6. Thus, for certain runs, two tape units are required.

5.3.2 Data Cards for Re-Starting

The first set of data which dumps on the binary tape will be identified as Data Set No. 1 and all following sets which dump will be identified as the set number given on the parameter card and on the listing. These set numbers need not be in consecutive order but must be greater than 1 (one).

Input the first three parameter cards, in order, for every set of data which was dumped on the same tape. A "1" in column 38 of the second card indicates that the problem should be re-started and a "2" in column 38 indicates that the problem should not be re-started. This is needed to bypass a set of data on the dump tape and position the tape to read the next set. If NVLVRS (Columns 21-23 on Parameter Card 2) is non-zero, Cards 20 (and possibly 22) will be inserted following Card 3 for as many values as are to be changed.

The alphanumeric characters for the page heading and any of the parameters on Card 2 or 3 may be changed for the re-start.

If a steady-state solution was completed and dumped by using the IDUMP option, SSTEST must be decreased for a re-start.

If a steady-state solution was dumped because of excessive iteration, the value for MAXI must be increased for re-starting.

If a transient problem was completed and dumped with the IDUMP option, the value of TAU must be increased for re-starting.

If a problem was dumped because of excessive computer time or if a run was interrupted using Sense Switch 5, the problem may be re-started without changing any of the parameters.

There will be a printing of regular output at the time of re-start which should be identical to the printing at the time of interruption.

If several data sets are stacked the routine writes end of file on the dump tape at the end of each data set.

5.4 ASSEMBLY OF BINARY OBJECT DECK AND DATA

5.4.1 Fortran II Operation

The order of assembly for the binary object deck and data deck is given below. The order of subroutines within a chain is optional, and any listed may be omitted in the event that the Fortran Monitor library tape includes that subroutine. The subroutines RESET, CLOCK, and WCLCK may be replaced by dummy subroutines, or by subroutines applicable to the particular system -- a single subroutine in the case of NASA-MSC operation. Information concerning Monitor Control Cards may be obtained by reference to the Fortran II manual.

A. Monitor Control Cards

a. I.D. (or Job) Card
b. Execute Fortran (For NASA-MSC)
c. XEQ

B. Chain 1

a. CHAIN (1, 4)
b. Binary Subroutines CHAIN 1 (Main), SUBP, RESET, CLOCK, WCLCK

C. Chain 2

a. CHAIN (2, 4)
b. Binary Subroutines CHAIN 2 (Main), SUBA, SUBB, SUBP, RESET, CLOCK, WCLCK

D. Chain 3

a. CHAIN (3, 4)
b. Binary Subroutines CHAIN 3 (Main), SUBP, RESET, CLOCK WCLCK

E. Chain 4

a. CHAIN (4, 4)
b. Binary Subroutines CHAIN 4 (Main), SUBP, RESET, CLOCK, WCLCK

F. Chain 5

a. CHAIN (5, 4)
b. Binary Subroutines CHAIN 5 (Main), SUBDP, SUBEND, SUBWT, START, CHECK, SURVEY, POL, XSIMEQF, SUBP, RESET, CLOCK, WCLCK

G. Data

a. Data (Control Card)
b. The data in the order in which it is specified in the instructions given previously, including curve type 13.
c. Other data sets may be added, each a complete entity.

5.4.2 Fortran IV Operation

For operation on UNIVAC systems (Fortran IV) using the overlay provisions, the program is stored on tape, and the data deck with appropriate control cards is submitted. The chain links in Fortran II are called subroutines, i.e., CHAIN 1 (main) becomes subroutine CHAIN 1. No clock routines are required. The routine MAIN with subroutines CHAIN and SUBP are assigned a permanent location. The order of overlay is as follows. Subroutine CHAIN 1 is overlaid by CHAIN 2, SUBA, and SUBB, which in turn is overlaid by CHAIN 3, which in turn is overlaid by CHAIN 4, which is finally replaced by CHAIN 5 and associated subroutines. Operation on current IBM machines with Fortran IV forces the data space to be prohibitively small, thus is not considered.

The order of setup is as follows:

1. Job
2. ASG A = Program Tape Number
3. ASG I = DUMP (Scratch Tape for Re-starting)
4. ASG J = Tape Number of Re-start Tape (if applicable)
5. TRW A
6. IN A
7. Map Prog
8. Seg Main ... } Overlay Cards
9. Seg ... }
10. XQT Prog
11. Data Cards in Order Specified in Instructions
12. EOF
13. FIN

5.5 CORE STORAGE SPACE REQUIREMENTS

Almost all of the input to this routine is stored in a block of core called DATA. Basically, the size of this block is determined by the size of 7090 core (32768 locations) and the size of the Chain 5 link. The size of the DATA block is fixed by subroutine START. To change the size (up to a maximum of 37000 total locations), ITOT in subroutine START must be reset and the subroutine assembled. For operation under the FORTRAN monitor system, the size of DATA is 17,000 locations. For operation on the UNIVAC 1107/1108 the size is 37,000 locations. These storage values are allocated as shown in the following paragraph.

5.5.1 Breakdown of Core Space

The following values are based on the Fortran II Monitor system.

Item	Number Core Locations Used
1. System (≈12000 on Fortran IV)	100
2. Chain 5 Main Routine	4650
3. SUBDP	5000
4. SUBEND	541
5. SUBWT	148
6. START	74
7. CHECK	188
8. SURVEY	154
9. POL	186
10. TRPOL	448
11. REVPOL	203
12. SUBP	50
13. RESET	179
14. CLOCK	30
15. WCLCK	71
16. Library Subroutines (including XS1MEQF)	2805
17. I/O Buffers	205
18. Some Data Space not in Data	233
	15165
19. DATA	17600
	32765

5.5.2 Breakdown of DATA Block Size

A. Basic formula for determining amount of core space in DATA block that a radiator setup will require:

3 NSYS + 10 NTUBE + 14 NFLT + 6 NTFL + 14 NMLT + 8 NTML

+ 3 (NTTOT + NTTOS) + NLCTBT + CURSP + 8 NT + 6 NSL

+ 3 NSTOS + NLCTBS

B. In Addition:

1. If this is a banks and headers problem (NPFC ≠ 0), add the following to basic formula:

   NSYS + 2 NFLOWP + MAXTB + $(\text{MAXTB} - 2)^2$ + FPSP

2. If there are any valves add the following to basic formula:

   25 NVLVS

3. If freezing is to be considered (NFC ≠ 0), add the following to the basic formula:

   1 NTUBE + 3 (NFTOF + NFTOT) + NLCTBF

4. If there are any heat exchangers (NREG $\neq$ 0), add the following to the basic formula:

   3 NFLT + 1 NTFL

C. Identification of symbols used in above formulas.

   1. CURSP - Curve space for all curves except specific heat curves.

      CURSP = NCR1 + 2NP1 + 2 (NCR2 + NP2), where

      NCR1 - Number of curves other than specific heat curves.
      NP1 - Number of points on all curves other than specific heat curves.
      NRC2 - Number of specific heat curves.
      NP2 - Number of points on specific heat curves.

      Specific heat curves need twice the space of other curves because they generate enthalpy curves.

   2. FPSP - Flow path space. Number of 5 column fields on Parameter Card 9 containing tube numbers (do not count blank fields).

   3. MAXTB - Number of tubes in system having greatest number of tubes.

   4. NFLOWP - Total number of flow paths in all systems.

   5. NFLT - Number of types of fluid lumps.

   6. (NFTOF + NFTOT) - Number of sets of conduction data given on the fluid type cards.

      NFTOF - Total of number of fluid lumps conducted "to" as listed in Columns 31-35 on Fluid Data Card 2.

      NFTOT - Total of number of tube lumps conducted "to" as listed in Columns 36-40 on Fluid Data Card 2.

   7. NLCTBF - Number of lumps conducted "to" by fluid lumps. This is a count of all lumps listed as being conducted "to" on Structure Data Cards 4 and 5.

   8. NLCTBS - Number of lumps conducted "to" by structure lumps. A count of all lumps listed as being conducted "to" on Structure Data Cards 4 and 5.

9. NLCTBT - Number of lumps conducted "to" by tube lumps. A count of all lumps listed as being conducted "to" on Tube Data Cards 5 and 6.

10. NMLT - Number of types of tube lumps.

11. NSL - Number of structure lumps.

12. NSTOS - Number of sets of conduction data given on the structure type cards. It is also the total number of structure lumps conducted "to" as listed in Columns 26-30 on Structure Data Card 2.

13. NSYS - Number of systems.

14. NT - Number of types of structure lumps.

15. NTFL - Number of fluid lumps.

16. NTML - Number of tube lumps.

17. (NTTOT + NTTOS) - Number of sets of conduction data given on the tube type cards.

    NTTOT - Total of number of tube lumps conducted "to" as listed in Columns 26-30 on Tube Data Card 2.

    NTTOS - Total of number of structure lumps conducted "to" as listed in Columns 31-35 on Tube Data Card 2.

18. NTUBE - Total number of tubes in all systems.

19. NVLVS - Number of valves.

5.6 ERROR MESSAGES

A resume of errors detected in reading the data will be printed throughout the data listing. If errors are found, the statement "Run discontinued because of error in data" will be printed at the end of the data listing. Some errors prevent the continuance of data reading and an immediate stop occurs.

All error messages in Chain 5 are self-explanatory with the exception of the one in SUBDP. To save core space but still facilitate error tracking, instead of explaining the error in detail, the value of an error code KON7 was varied. For better understanding of the error message "Error in SUBDP KON7 = "X", a table showing correlation between all possible values of KON7 and probable errors follows.

KON7	Explanation
0	In using the interpolation subroutine POL on the inlet temperature curves, a variable was found to be out of the range of the table.
1	In using the interpolation subroutine POL on the flow rate curves = f(time), a variable was found to be out of the range of the table.
2	The last tube in some system does not have the largest number of any tube in that system, the first tube in some system does not have the smallest number of any tube in that system, or a number has been skipped in numbering the tubes. Check Parameter Card 9.
3,4	In using the interpolation subroutine POL on the flow rate curves = f(time), a variable was found to be out of the range of the table.
5	In using the interpolation subroutine POL on the pressure loss curves, friction factor curves, specific heat curves, viscosity curves, or density curves, a variable was found to be out of the range of the table.
6	Check Parameter Card 9.
7	The first tube in some system does not have the smallest number of any tube in that system. Check Parameter Card 9.
8	Check Parameter Card 9. Possibly two flow paths begin with the same tube but end with two different tubes.
9	Check Parameter Card 9.
10	The last tube in some system does not have the largest number of any tube in that system. Check Parameter Card 9.
11,12	In using the interpolation subroutine POL on the enthalpy curves, a variable was found to be out of the range of a table.
13,14	Check Parameter Card 9.
15	The first tube in a system is frozen.

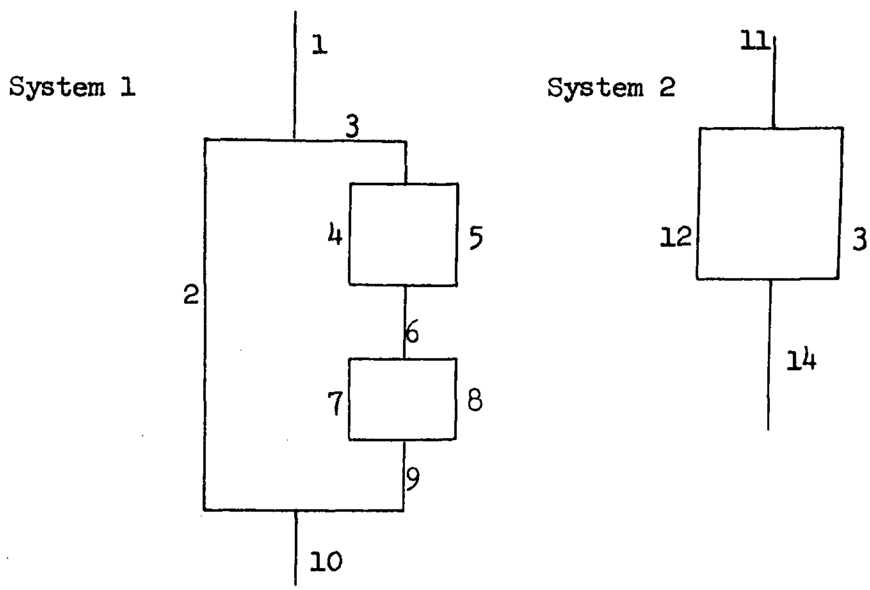
KON7	Explanation
16	The last tube in a system is frozen.
17,18	Check Parameter Card 9.
19	In using interpolation subroutine POL on inlet temperature curves, a variable was found to be out of the range of a table.
25	An illegal value has been included in a parallel flow problem.
26	Check parameter cards 14 and 7 to see that the flow paths are correct and that the valve is in the correct system.
28	In using the interpolation subroutine POL on the NFPC curves, a variable was found to be out of the range of the table.
29,41	Left and right tubes for a valve are not downstream of "from" tube.
30	Routine error. No data change required.
34	A flow path is listed which has a first tube that no other flow path contains.
35,36	Error made while checking for number of flow paths with same first and last tube.
37,38	A tube that is listed on Parameter Card 8 as a feeder is not listed in flow paths.
39	Error made while setting-up SIMEQ.
40,42	A flow path exists in which the number of the last tube is less than or equal to the number of the first tube.
43	The first tube in one flow path is the first tube in no other flow path.
44	A flow path exists which has less than three tubes.

All the above errors will cause the run to be terminated.

6.0 SAMPLE PROBLEM

6.1 THERMAL MODEL DESCRIPTION

The sample problem selected was one of a series of checkout problems. The values selected for the inout are not necessarily intended to represent physical dimensions of any real system. The schematic diagram of the flow network is shown in the sketch below.



Two tube lumps in the small system and the two structure lumps are directionally sensitive lumps.

6.2 INPUT DATA LISTING

The cards as input were listed according to the data input format specified in Section 5. The listing of the cards is shown in Table 1. For convenience the listing is ruled into five-column fields.

6.3 CHECKOUT PRINTING

The data deck was run with the checkout printing option. The data read-in format and checkout printing are shown in Table 2. The checkout printing may be used to examine internally calculated values such as heat transfer coefficients, frictional and bend loss pressure drops, and maximum time increments. An examination of the time increments for each lump may reveal that certain lumps which are not thermally important to the solution have small time increments. In such a case the time increment may be selected (see Section 4.4) such that fewer iterations are required. Care should be exercised that the lumps with overridden time increments do not affect the transient analysis.

An explanation of the terms appearing in the checkout printing is included below. The units are the same as input except where indicated.

Pressure Drop Subroutine Checkout Printing

I	fluid lump number
TYPE	fluid type of I
TUBE	tube containing I
FREZ	0 if not frozen, 1 if frozen
DEN	lump density
UI	viscosity of lump
FLL	lump length, ft
CSA	cross-sectional area, ft^2
WP	wetter perimeter, ft
RE	Reynold's number
F	friction factor (includes $(\mu_b/\mu_w)^{-.14}$ and friction factor coefficient)
FR	flow rate
LUMP DELP	pressure drop in I from viscous effect, psi x 1000
K	pressure drop in I from $\mathcal{K}$ loss, psi x 1000
SH	specific heat
TUBE ACCUM DELP	accumulated pressure drop in tube, psi x 1000
DPRAD	system pressure drop, psi x 1000

The pressure drop subroutine print appears for each time the calculation is performed until pressure drops are balanced.

Fluid Lump Checkout Printing

I	lump number
TI	present temperature at I, °R
WL	surrounding tube lump number
TWALL	prescribed temperature of lump. Meaningless on non-boundary lumps
NLU	upstream lump number
TU	upstream lump's present temperature, °R
G	HI x area for heat transfer
H	(on NAVTC = 0) G/2 x TU
HI	heat transfer coefficient x $(\mu_b/\mu_w)^{.14}$
ACON	sum of coefficient of T_f on the right side of equation 11, page 12.
ATEM	right side of equation 11, page 12, if $T_f = 0$.
DTAU	time increment of stability requirement
TYPE	type of fluid lump
RE	Reynold's number
PR	Prandtl number
COND	lump conductivity
DEN	lump density
SP HEAT	lump specific heat
VIS BULK	viscosity evaluated at bulk (fluid temperature)

VIS WALL	viscosity evaluated at enclosing tube's temperature
WEIGHT	fluid lump weight
HEAT TRANSFER COEFFS	entry length prediction and the developed flow prediction

Following this print for each lump, the values of I, ACON, ATEM and DTAU are summarized separately.

<u>Tube Lump Checkout Printing</u>

I	lump number
NDL	lump number downstream
TI	present temperature
TD	present temperature of tube downstream
CONI	conductivity of I
COND	conductivity of lump downstream
U	conductance to last lump conducted "to"
EM	emissivity of lump
AB	absorptivity of fin
Q	incident heat value
ACON(NDL)	ACON for downstream lump
ATEM(NDL)	ATEM for downstream lump
ACON(I)	QRA (see below) plus sum of coefficients of T_t in equation 8, page 9.
ATEM(I)	sum of all UAT products (T associated with proper U) in equation 8, page 9.
DTAU	stability required time increment
USUM	sum of all conductance "from" tube lump I and "to" tube lump I from tube J where $J < I$.
UTSUM	sum of conductance temperature "from" lump I and "to" lump I from J if $J < I$.
QA	(Q)(AREA)(Absorptivity)
QRA	(EM)(AREA)(σ)(T^3)

Following this print for each tube lump, the values for I, ACON, ATEM, and DTAU are summarized separately.

<u>Structure Lump Checkout Printing</u>

I	structure lump number
Q	incident heat
CONI	conductivity of I
WEIGHT	weight of lump
SO HEAT	specific heat
USUM	sum of all conductances from tube lumps, "to" other fin (structure) lumps and from J if $J < I$.
UTSUM	sum of product of the conductances with respective temperatures "to" all lumps and from $J < I$.
QA	incident heat addition rate
QR	(emissivity)(area)(σ) T^3

ACON	sum of conductance-area products plus QR
ATEM	sum of UAT products plus QA
DTAU	time increment required for stability

Following time information for all lumps, the values of I, ACON, ATEM, and DTAU are summarized in a separate listing. In the event that the two values of ACON, ATEM, and DTAU are not consistent, the latter tabulation is correct. The former value includes, in general, less than all conduction information because it does not have the contribution of conductance from those lumps conducted from, which the latter includes.

6.4 SAMPLE OUTPUT

The normal output at iteration 4 (Time = TAU) is shown in Table 3. All output is self-explanatory with temperature and flow rates given in numerical order. The statement "transient problem completed" means that Time has reached the indicated transient time TAU. At the end of the output a limited group of parameters is printed for each fluid lump. This group appears each time the problem exits the machine, whether for restart or at completion.

```
SAMPLE PROBLEM FOR CHECKOUT OF OFF AXIS AND DIRECTIONAL COATINGS
LVVM25    .001               1 2.0  1   .003
  .001                                                                1
   14   14   14    2    2   10                1 9   1
 .575  1.0
    5    2
    2    1   10    2   11   14
    1    2   10         1    3    5    6         1    3    4    6
    6    8    9   10         6    7    9   10        11   12   14
   11   13   14
    0    1
    1    2
    1    2
    1
    1    2    3    4    5                  12.       .1       4.8
    1         1    1   70.
    2         2    1   70.
    3         3    1   70.
    4         4    1   70.
    5         5    1   70.
    6         6    1   70.
    7         7    1   70.
    8         8    1   70.
    9         9    1   70.
   10        10    1   70.
   11        11    1   70.
   12        12    1   70.
   13        13    1   70.
   14        14    1   70.
    2
100.     6    7    8    9                  12.       .12       .12
   14.4
100.     6    7    8    9           1      12.       .12       .12
             144.
    1         1    1   70.       1
    2         2    1   70.       1
    3         3    1   70.       1
    4         4    1   70.       1
    5         5    1   70.       1
    6         6    1   70.       1
    7         7    1   70.       1
    8         8    1   70.       1
    9         9    1   70.       1
   10        10    1   70.       1
   11        11    1   70.       1
   12        12    2   70.       1
   13        13    2   70.       1                                    2
   14        14    1   70.       1                                    3
    1
100.     6    7    8    9   12.       12.       .012           1
    1    1   70.        1
    2    1   70.        1                                             2
    9    9    1               INCIDENT FLUX                           3
             100.
    9    1    1               ZERO QI
              0.
```

TABLE 1 DATA INPUT LISTING

```
   11        1         1                               FLOW 1
                      10.
   11        2         1                               FLOW 2
                       5
   12        1         1                               INLET T
                       0.
   12        2         1                               INLET T
                       0.
   27        1         3                               MOD ANGLE CURVE
  0.0                 0.7         1.0                   .7        .9                1.0
   28        2         1                               COS ANGLE
                      .5
   28        3         1                               COS ANGLE
                      .866
    1        1         1                              DENSITY FLUID
                      70.
    4        2         1                              COND FLUID
                      .32
    5        3         1                              FLUID SP HT
                      .76
    2        4         1                              FLUID VISC
                       5.
    3        5         1                              FRICTION FACTOR
                       3.2
    4        6         1                              FIN COND
                     100.
    5        7         1                              FIN SP HT
                       0.2
    6        8         1                              FIN ABSO
                       1.0
    7        9         1                              FIN EMIT
                       1.0
   13
```

TABLE 1 DATA INPUT LISTING

```
                                                          PAGE   1
SAMPLE PROBLEM FOR CHECKOUT OF OFF AXIS AND DIRECTIONAL COATINGS
LVVM25                  DATA SET    1

   CONVERGENCE FACTOR              .9000

   PRINT TEMPERATURE DISTRIBUTION EVERY 1.000 HR.

   PRESSURE DROP TOLERANCE IS    .00100 TIMES PRESSURE DROP IN FLOW PATH.

   TRANSIENT, TOTAL TIME IS    .0030 HR.

   NUMBER OF SYSTEMS                  2

   NUMBER OF TUBES                   14

   NUMBER OF FLUID LUMPS             14

   NUMBER OF TUBE LUMPS              14

   NUMBER OF FIN LUMPS                2

   HEAT TRANSFER COEFFICIENT FACTORS
     ENTRY LENGTH   .5750    FULLY DEVELOPED  1.0000

   NORMAL INCIDENT HEAT FLUX CURVE NUMBER IS    9
   OUTLET TEMPERATURE WILL BE USED FOR FLUID FLOW

   SYSTEM     1 CONTAINS THE FOLLOWING FLOWPATHS

        FLOWPATH     1 CONSISTS OF TUBES NUMBERED
               1,  2, 10,

        FLOWPATH     2 CONSISTS OF TUBES NUMBERED
               1,  3,  5,  6,

        FLOWPATH     3 CONSISTS OF TUBES NUMBERED
               1,  3,  4,  6,

        FLOWPATH     4 CONSISTS OF TUBES NUMBERED
               6,  8,  9, 10,

        FLOWPATH     5 CONSISTS OF TUBES NUMBERED
               6,  7,  9, 10,

   SYSTEM     2 CONTAINS THE FOLLOWING FLOWPATHS

        FLOWPATH     1 CONSISTS OF TUBES NUMBERED
              11, 12, 14,

        FLOWPATH     2 CONSISTS OF TUBES NUMBERED
              11, 13, 14,


   INLET TEMPERATURE CURVE NUMBER FOR INLET TUBE IN SYSTEM    1          1

   INLET TEMPERATURE CURVE NUMBER FOR INLET TUBE IN SYSTEM    2          2
```

TABLE 2 CHECKOUT PRINTING

```
                                                                 PAGE    2
SAMPLE PROBLEM FOR CHECKOUT OF OFF AXIS AND DIRECTIONAL COATINGS
LVVM25                    DATA SET     1

   CURVE NUMBER FOR TOTAL FLOW=F(TIME) IN SYSTEM     1             1

   CURVE NUMBER FOR TOTAL FLOW=F(TIME) IN SYSTEM     2             2

   NODAL SOLUTION

   MINIMUM TIME INCREMENT =      .001000000
```

TABLE 2 CHECKOUT PRINTING

SAMPLE PROBLEM FOR CHECKOUT OF OFF AXIS AND DIRECTIONAL COATINGS
LVVM25 DATA SET 1

FLUID LUMP DATA

NUMBER OF TYPES OF LUMPS 1

TYPE NUMBER 1

DENSITY CURVE NUMBER	1
CONDUCTIVITY CURVE NUMBER	2
SPECIFIC HEAT CURVE NUMBER	3
VISCOSITY CURVE NUMBER	4
FRICTION FACTOR CURVE NUMBER	5
K CURVE FOR PRESSURE DROP	-0
NO. OF FLUID LUMPS CONDUCTED TO	-0
NO. OF TUBE LUMPS CONDUCTED TO	-0
FLUID LUMP LENGTH	12.00000000 INCHES
CROSS SECTIONAL AREA	.10000000 SQ.IN.
WETTED PERIMETER	4.80000000 INCHES
FRICTION FACTOR COEF	1.00000000

FLUID LUMP DATA

LUMP	UP	TUBE	TYPE	TEMPERATURE	LUMPS CONDUCTED TO
1	-0	1	1	70.000000	
2	-0	2	1	70.000000	
3	-0	3	1	70.000000	
4	-0	4	1	70.000000	
5	-0	5	1	70.000000	
6	-0	6	1	70.000000	
7	-0	7	1	70.000000	
8	-0	8	1	70.000000	
9	-0	9	1	70.000000	
10	-0	10	1	70.000000	
11	-0	11	1	70.000000	
12	-0	12	1	70.000000	
13	-0	13	1	70.000000	
14	-0	14	1	70.000000	

SUM OF FLUID LUMP LENGTHS IN EACH TUBE (INCHES)

12.0000	12.0000	12.0000	12.0000	12.0000
12.0000	12.0000	12.0000	12.0000	12.0000
12.0000	12.0000	12.0000	12.0000	

DATA SPACE USED 341

TABLE 2 CHECKOUT PRINTING

```
SAMPLE PROBLEM FOR CHECKOUT OF OFF AXIS AND DIRECTIONAL COATINGS
LVVM25                DATA SET    1

TUBE LUMP DATA

NUMBER OF TYPES OF LUMPS     2

TYPE NUMBER     1
  DENSITY           100.0000 LBS./CU.FT.
  CONDUCTIVITY CURVE NUMBER          6
  SPECIFIC HEAT CURVE NUMBER         7
  ABSORPTIVITY CURVE NUMBER          8
  EMISSIVITY CURVE NUMBER            9
  VOLUME (X1,X2,X3)                        .172800 CU.INS.
  AREA FOR LONG. CONDUCTION (X2,X3)        .014400 SQ.INS.
  COND. DIST. FOR LONG. COND. (X1/2.)     6.000000 INCHES
  WILL LONG. CONDUCTION BE COMPUTED         YES
  NO. OF TUBE LUMPS CONDUCTED TO           -0
  NOT DIRECTIONAL COATINGS TYPE
  NO. OF STRUCTURE LUMPS CONDUCTED TO      -0
  AREA FOR HEAT TRANSFER                 14.400000 SQ.INS.
  AREA FOR EXTERNAL RADIATION             -.000000 SQ.INS.

TYPE NUMBER     2
  DENSITY           100.0000 LBS./CU.FT.
  CONDUCTIVITY CURVE NUMBER          6
  SPECIFIC HEAT CURVE NUMBER         7
  ABSORPTIVITY CURVE NUMBER          8
  EMISSIVITY CURVE NUMBER            9
  VOLUME (X1,X2,X3)                        .172800 CU.INS.
  AREA FOR LONG. CONDUCTION (X2,X3)        .014400 SQ.INS.
  COND. DIST. FOR LONG. COND. (X1/2.)     6.000000 INCHES
  WILL LONG. CONDUCTION BE COMPUTED         YES
  NO. OF TUBE LUMPS CONDUCTED TO           -0
  DIRECTIONL ABSCRPTNCE FACTR CRV NO.       1
  NO. OF STRUCTURE LUMPS CONDUCTED TO      -0
  AREA FOR HEAT TRANSFER                  -.000000 SQ.INS.
  AREA FOR EXTERNAL RADIATION           143.999990 SQ.INS.

TUBE LUMPS

LUMP  NDL  NFL TYPE TEMPERATURE Q/COSB   T,WALL  LUMPS CONDUCTED TO

   1   -0    1   1   70.000000      1      -0
   2   -0    2   1   70.000000      1      -0
   3   -0    3   1   70.000000      1      -0
   4   -0    4   1   70.000000      1      -0
   5   -0    5   1   70.000000      1      -0
   6   -0    6   1   70.000000      1      -0
   7   -0    7   1   70.000000      1      -0
   8   -0    8   1   70.000000      1      -0
   9   -0    9   1   70.000000      1      -0

  10   -0   10   1   70.000000      1      -0
  11   -0   11   1   70.000000      1      -0
  12   -0   12   2   70.000000      2      -0
```

TABLE 2 CHECKOUT PRINTING

```
SAMPLE PROBLEM FOR CHECKOUT OF OFF AXIS AND DIRECTIONAL COATINGS
LVVM25                   DATA SET    1

   13   -0   13    2   70,000000        3       -0
   14   -0   14    1   70,000000        1       -0

  SUM OF TUBE LUMP LENGTHS IN EACH TUBE (INCHES)

      12,0000     12,0000     12,0000     12,0000     12,0000
      12,0000     12,0000     12,0000     12,0000     12,0000
      12,0000     12,0000     12,0000     12,0000

  TOTAL AREA FOR EXTERNAL RADIATION FOR TUBE LUMPS = 288,00000 SQ. IN.

DATA SPACE USED      483
```

TABLE 2 CHECKOUT PRINTING

SAMPLE PROBLEM FOR CHECKOUT OF OFF AXIS AND DIRECTIONAL COATINGS
LVVM25 DATA SET 1

FIN LUMP DATA

NUMBER OF TYPES OF LUMPS 1

```
TYPE                              1
DENSITY                     100.00000 LBS./CU.FT.
WEIGHT                         .10000 LBS.
EXTERNAL RADIATION AREA      1.00000 SQ.FT.
CONDUCTIVITY CURVE NUMBER          6
SPECIFIC HEAT CURVE NUMBER         7
ABSORPTIVITY CURVE NUMBER          8
EMISSIVITY CURVE NUMBER            9
NO. OF LUMPS CONDUCTED TO         -0
DIRECTIONAL ABSORPTANCE FACTOR CURVE NO.    1
```

LUMP	TYPE	TEMPERATURE	Q/COSB	WALL TEMP.	LUMPS CONDUCTED TO
1	1	70.000000	2	-0	
2	1	70.000000	3	-0	

TOTAL SURFACE AREA FOR FIN LUMPS = 288.00000 SQ. IN.

DATA SPACE USED 504

TABLE 2 CHECKOUT PRINTING

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```
SAMPLE PROBLEM FOR CHECKOUT OF OFF AXIS AND DIRECTIONAL COATINGS
LVVM25                   DATA SET    1

  CURVE DATA

       9     9     1    -0    -0       INCIDENT FLUX
         -.0000000       100.0000000

       9     1     1    -0    -0       ZERO QI
         -.0000000          .0000000

      11     1     1    -0    -0       FLOW 1
         -.0000000        10.0000000

      11     2     1    -0    -0       FLOW 2
         -.0000000         5.0000000

      12     1     1    -0    -0       INLET T
         -.0000000          .0000000

      12     2     1    -0    -0       INLET T
         -.0000000          .0000000

      27     1     3    -0    -0       MOD ANGLE CURVE
          .0000000          .7000000       1.0000000        .7000000
          .9000000         1.0000000

      28     2     1    -0    -0       COS ANGLE
         -.0000000          .5000000

      28     3     1    -0    -0       COS ANGLE
         -.0000000          .8660000

       1     1     1    -0    -0     DENSITY FLUID
         -.0000000        70.0000000

       4     2     1    -0    -0     COND FLUID
         -.0000000          .3200000

       5     3     1    -0    -0     FLUID SP HT
         -.0000000          .7600000

       5     3     2    -0    -0ENTHALPY CURVE - GENERATED FROM ABOVE.
          .0000000      1000.0000000        .0000000      759.9999900

       2     4     1    -0    -0     FLUID VISC
         -.0000000         5.0000000

       3     5     1    -0    -0     FRICTION FACTOR
         -.0000000         3.2000000

       4     6     1    -0    -0     FIN COND
```

TABLE 2 CHECKOUT PRINTING

SAMPLE PROBLEM FOR CHECKOUT OF OFF AXIS AND DIRECTIONAL COATINGS
LVVM25 DATA SET 1

```
         -.0000000      100.0000000

      5      7      1    -0    -0     FIN SP HT
         -.0000000         .2000000

      6      8      1    -0    -0     FIN ABSO
         -.0000000        1.0000000

      7      9      1    -0    -0     FIN EMIT
         -.0000000        1.0000000

     13     -0     -0    -0    -0
```

DATA SPACE USED 567

IF NECESSARY TO STOP, THE FOLLOWING PROCEDURE WILL WRITE A DUMP TAPE WHICH CAN BE USED TO RE-START
(1) IF A BLANK TAPE WAS NOT MOUNTED ON A6 DURING SET-UP, RING AND MOUNT ONE,
(2) SET DOWN SENSE SWITCH 5,
(3) WAIT FOR MESSAGE TO RESET SENSE SWITCH.

CHECK OUT PRINTING FOR PRESSURE DROP SUBROUTINE

I	TYPE	TUBE	FREZ	DEN F	UI FR	FLL LUMP DELP	CSA K	WP SH	RE TUBE ACCUM DELP
1	1	1	0	70.00000000 2.88000000	5.00000000 10.00000000	.99999999 40.92035400	.00069444 .00000000	.39999999 .76000000	5.55555550 40.92035400
2	1	2	0	70.00000000 5.75999990	5.00000000 5.00000000	.99999999 20.46017600	.00069444 .00000000	.39999999 .76000000	2.77777780 20.46017600
3	1	3	0	70.00000000 5.75999990	5.00000000 5.00000000	.99999999 20.46017600	.00069444 .00000000	.39999999 .76000000	2.77777780 20.46017600
4	1	4	0	70.00000000 11.51999980	5.00000000 2.50000000	.99999999 10.23008850	.00069444 .00000000	.39999999 .76000000	1.38888888 10.23008850
5	1	5	0	70.00000000 11.51999980	5.00000000 2.50000000	.99999999 10.23008850	.00069444 .00000000	.39999999 .76000000	1.38888888 10.23008850
6	1	6	0	70.00000000	5.00000000	.99999999	.00069444	.39999999	2.77777780

TABLE 2 CHECKOUT PRINTING

				5,75999990	5,00000000	20,46017600	,00000000	,76000000	20,46017600
7	1	7	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	1,38888888
				11,51999980	2,50000000	10,23008850	,00000000	,76000000	10,23008850
8	1	8	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	1,38888888
				11,51999980	2,50000000	10,23008850	,00000000	,76000000	10,23008850
9	1	9	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	2,77777780
				5,75999990	5,00000000	20,46017600	,00000000	,76000000	20,46017600
10	1	10	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	5,55555550
				2,88000000	10,00000000	40,92035400	,00000000	,76000000	40,92035400
1	1	1	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	5,55555550
				2,88000000	10,00000000	40,92035400	,00000000	,76000000	40,92035400
2	1	2	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	4,44444440
				3,59999990	8,00000000	32,73628400	,00000000	,76000000	32,73628400
3	1	3	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	1,11111115
				14,39999920	2,00000000	8,18407120	,00000000	,76000000	8,18407120
4	1	4	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	,55555557
				28,79999900	1,00000001	4,09203540	,00000000	,76000000	4,09203540
5	1	5	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	,55555557
				28,79999800	1,00000003	4,09203560	,00000000	,76000000	4,09203560
6	1	6	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	1,11111110
				14,39999980	2,00000000	8,18407110	,00000000	,76000000	8,18407110
7	1	7	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	,55555555
				28,80000000	1,00000000	4,09203550	,00000000	,76000000	4,09203550
8	1	8	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	,55555555
				28,80000000	1,00000000	4,09203550	,00000000	,76000000	4,09203550
9	1	9	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	1,11111110
				14,39999980	2,00000000	8,18407110	,00000000	,76000000	8,18407110
10	1	10	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	5,55555550
				2,88000000	10,00000000	40,92035400	,00000000	,76000000	40,92035400
UPRAD IN SYSTEM				1 =	114,57699				
11	1	11	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	2,77777780
				5,75999990	5,00000000	20,46017600	,00000000	,76000000	20,46017600
12	1	12	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	1,38888888
				11,51999980	2,50000000	10,23008850	,00000000	,76000000	10,23008850
13	1	13	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	1,38888888
				11,51999980	2,50000000	10,23008850	,00000000	,76000000	10,23008850
14	1	14	0	70,00000000	5,00000000	,99999999	,00069444	,39999999	2,77777780
				5,75999990	5,00000000	20,46017600	,00000000	,76000000	20,46017600

UPRAD IN SYSTEM 2 = 51,15044

TABLE 2 CHECKOUT PRINTING

```
SAMPLE PROBLEM FOR CHECKOUT OF OFF AXIS AND DIRECTIONAL COATINGS
LVVM25                 DATA SET    1

 COMPUTER TIME=     ,000

 INITIAL CONDITIONS

 FLOW RATES (LBS,/HR,) IN SYSTEM    1
        10,00000000   8,00000000   2,00000000   1,00000001   1,00000003
         2,00000000   1,00000000   1,00000000   2,00000000  10,00000000

 FLOW RATES (LBS,/HR,) IN SYSTEM    2
         5,00000000   2,50000000   2,50000000   5,00000000

 PRESSURE DROPS (X1000,) (LBS,/SQ, IN,) IN SYSTEM    1
        40,92035400  32,73628400   8,18407120   4,09203540   4,09203560
         8,18407110   4,09203550   4,09203550   8,18407110  40,92035400

 PRESSURE DROPS (X1000,) (LBS,/SQ, IN,) IN SYSTEM    2
        20,46017600  10,23008850  10,23008850  20,46017600

 POWER REQUIREMENT (X 1000,)     2883,131100 FT,LB,/HR,

 TOTAL HEAT REJECTED           -531,999980 BTU/HR, IN SYSTEM    1

 TOTAL HEAT REJECTED               ,000000 BTU/HR, IN SYSTEM    2

 WEIGHT                          ,340000 LBS,


FLUID LUMP CHECK CUT PRINTING

   I         TI        WL      TWALL       NLU       TU          G          H          HI       ACON      ATEM       DTAU
 TYPE        RE        PR      COND,       DEN,  SP, HEAT  VIS,BULK   VIS,WALL     WEIGHT  HEAT TRAN, COEFFS,

   1 529,68999         14 529,68999         -0 459,69000  16,86528     ,00000 168,65280  24,46528**********   ,0013591
   1   5,55556  42,75000     ,32000  70,00000    ,76000    5,00000    5,00000    ,04861 168,65280 168,65280

   2 529,68999         14 529,68999         -0 529,68999  16,86528     ,00000 168,65280  22,94528**********   ,0014491
   1   4,44444  42,75000     ,32000  70,00000    ,76000    5,00000    5,00000    ,04861 168,65280 168,65280

   3 529,68999         14 529,68999         -0 529,68999  16,86528     ,00000 168,65280  18,38528973 8,49860  ,0018085
   1   1,11111  42,75000     ,32000  70,00000    ,76000    5,00000    5,00000    ,04861 168,65280 168,65280

   4 529,68999         14 529,68999         -0 529,68999  16,86528     ,00000 168,65280  17,62528933 5,93410  ,0018865
   1    ,55556  42,75000     ,32000  70,00000    ,76000    5,00000    5,00000    ,04861 168,65280 168,65280
```

TABLE 2 CHECKOUT PRINTING

5	529,68999	14	529,68999	-0	529,68999	16,86528	,00000	168,65280	17,62528 9335,93410	,0018865
1	,55556	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280 168,65280	
6	529,68999	14	529,68999	-0	529,68999	16,86528	,00000	168,65280	18,38528 9738,49860	,0018085
1	1,11111	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280 168,65280	
7	529,68999	14	529,68999	-0	529,68999	16,86528	,00000	168,65280	17,62528 9335,93410	,0018865
1	,55556	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280 168,65280	
8	529,68999	14	529,68999	-0	529,68999	16,86528	,00000	168,65280	17,62528 9335,93410	,0018865
1	,55556	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280 168,65280	
9	529,68999	14	529,68999	-0	529,68999	16,86528	,00000	168,65280	18,38528 9738,49860	,0018085
1	1,11111	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280 168,65280	
10	529,68999	14	529,68999	-0	529,68999	16,86528	,00000	168,65280	24,46528**********	,0013591
1	5,55556	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280 168,65280	
11	529,68999	14	529,68999	-0	529,68999	16,86528	,00000	168,65280	20,66528**********	,0016090
1	2,77778	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280 168,65280	
12	529,68999	14	529,68999	-0	529,68999	-,00000	,00000	168,65280	1,90000 1006,41097	,0175000
1	1,38889	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280 168,65280	
13	529,68999	14	529,68999	-0	529,68999	-,00000	,00000	168,65280	1,90000 1006,41097	,0175000
1	1,38889	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280 168,65280	
14	529,68999	14	529,68999	-0	529,68999	16,86528	,00000	168,65280	20,66528**********	,0016090
1	2,77778	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280 168,65280	

I	ACON	ATEM	DTAU
1	24,4652790	12427,0137000	,0013591
2	22,9452790	12153,8848000	,0014491
3	18,3852790	9738,4986000	,0018085
4	17,6252790	9335,9341000	,0018865
5	17,6252790	9335,9341000	,0018865
6	18,3852790	9738,4986000	,0018085
7	17,6252790	9335,9341000	,0018865
8	17,6252790	9335,9341000	,0018865
9	18,3852790	9738,4986000	,0018085
10	24,4652790	12959,0136000	,0013591
11	20,6652790	10946,1915000	,0016090
12	1,9000000	1006,4109700	,0175000
13	1,9000000	1006,4109700	,0175000
14	20,6652790	10946,1915000	,0016090

TABLE 2 CHECKOUT PRINTING

TUBE LUMP CHECK OLT PRINTING

I	NDL	TI AB USUM	TD G UTSUM	CONI ACON(NDL) GA	COND ATEM(NDL) GRA	U ACON(I)	E ATEM(I)	DTAU
1	-0	529,68999000 ,00000000 16,86527900	,00000000 ,00000000 8933,36970000	100,00000000 10946,19150000 -,00000000	,00000000 8933,36970000 -,00000000	,00000000 16,86527900	1,00000000 8933,36970000	,00010673
2	-0	529,68999000 ,00000000 16,86527900	,00000000 ,00000000 8933,36970000	100,00000000 10946,19150000 -,00000000	,00000000 8933,36970000 -,00000000	,00000000 16,86527900	1,00000000 8933,36970000	,00010673
3	-0	529,68999000 ,00000000 16,86527900	,00000000 ,00000000 8933,36970000	100,00000000 10946,19150000 -,00000000	,00000000 8933,36970000 -,00000000	,00000000 16,86527900	1,00000000 8933,36970000	,00010673
4	-0	529,68999000 ,00000000 16,86527900	,00000000 ,00000000 8933,36970000	100,00000000 10946,19150000 -,00000000	,00000000 8933,36970000 -,00000000	,00000000 16,86527900	1,00000000 8933,36970000	,00010673
5	-0	529,68999000 ,00000000 16,86527900	,00000000 ,00000000 8933,36970000	100,00000000 10946,19150000 -,00000000	,00000000 8933,36970000 -,00000000	,00000000 16,86527900	1,00000000 8933,36970000	,00010673
6	-0	529,68999000 ,00000000 16,86527900	,00000000 ,00000000 8933,36970000	100,00000000 10946,19150000 -,00000000	,00000000 8933,36970000 -,00000000	,00000000 16,86527900	1,00000000 8933,36970000	,00010673
7	-0	529,68999000 ,00000000 16,86527900	,00000000 ,00000000 8933,36970000	100,00000000 10946,19150000 -,00000000	,00000000 8933,36970000 -,00000000	,00000000 16,86527900	1,00000000 8933,36970000	,00010673
8	-0	529,68999000 ,00000000 16,86527900	,00000000 ,00000000 8933,36970000	100,00000000 10946,19150000 -,00000000	,00000000 8933,36970000 -,00000000	,00000000 16,86527900	1,00000000 8933,36970000	,00010673
9	-0	529,68999000 ,00000000 16,86527900	,00000000 ,00000000 8933,36970000	100,00000000 10946,19150000 -,00000000	,00000000 8933,36970000 -,00000000	,00000000 16,86527900	1,00000000 8933,36970000	,00010673
10	-0	529,68999000 ,00000000 16,86527900	,00000000 ,00000000 8933,36970000	100,00000000 10946,19150000 -,00000000	,00000000 8933,36970000 -,00000000	,00000000 16,86527900	1,00000000 8933,36970000	,00010673

TABLE 2 CHECKOUT PRINTING

11	-0	529,68999000	,00000000	100,00000000	,00000000	,00000000	1,00000000	
		,00000000	,00000000	10946,1915000	8933,3697000	16,86527900	8933,3697000	,00010673
		16,86527900	8933,36970000	-,00000000	-,00000000			
12	-0	529,68999000	,00000000	100,00000000	,00000000	,00000000	1,00000000	
		,00000000	,50000000	10946,1915000	8933,3697000	,25710551	42,1428560	,00700102
		,00000000	,00000000	42,1428560	,25710551			
13	-0	529,68999000	,00000000	100,00000000	,00000000	,00000000	1,00000000	
		,00000000	,86600000	10946,1915000	8933,3697000	,25710551	82,7318640	,00700102
		,00000000	,00000000	82,7318640	,25710551			
14	-0	529,68999000	,00000000	100,00000000	,00000000	,00000000	1,00000000	
		,00000000	,00000000	10946,1915000	8933,3697000	16,86527900	8933,3697000	,00010673
		16,86527900	8933,36970000	-,00000000	-,00000000			

I	ACON	ATEM	DTAU
1	16,8652790	8933,3697000	,0001067
2	16,8652790	8933,3697000	,0001067
3	16,8652790	8933,3697000	,0001067
4	16,8652790	8933,3697000	,0001067
5	16,8652790	8933,3697000	,0001067
6	16,8652790	8933,3697000	,0001067
7	16,8652790	8933,3697000	,0001067
8	16,8652790	8933,3697000	,0001067
9	16,8652790	8933,3697000	,0001067
10	16,8652790	8933,3697000	,0001067
11	16,8652790	8933,3697000	,0001067
12	,2571055	42,1428560	,0070010
13	,2571055	82,7318640	,0070010
14	16,8652790	8933,3697000	,0001067

TABLE 2 CHECKOUT PRINTING

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STRUCTURE LUMP CHECK CUT PRINTING

I	Q / QA	CON1 / QR	WEIGHT / ACON	SP, HEAT / ATEM	USUM / CTAU	UTSUM
1	,5000000 42,1428560	100,0000000 ,2571055	,1000000 ,2571055	,2000000 42,1428560	,0000000 ,0700102	,0000000
2	,8660000 82,7318640	100,0000000 ,2571055	,1000000 ,2571055	,2000000 82,7318640	,0000000 ,0700102	,0000000

I	ACON	ATEM	DTAU
1	,2571055	42,1428560	,0700102
2	,2571055	82,7318640	,0700102

TABLE 2 CHECKOUT PRINTING

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SAMPLE PROBLEM FOR CHECKOUT OF OFF AXIS AND DIRECTIONAL COATINGS
LVVM25                  DATA SET    1

  TIME=   .00400 HOURS   TIME INC.= .0010000   @@@@@@ LUMP    0
  COMPUTER TIME=     .060 MINUTES   ROUTINE ITERATIONS=     4

  FLOW RATES (LBS./HR.) IN SYSTEM    1
          10.00000000    8.00000000    2.00000000    1.00000001    1.00000003
           2.00000000    1.00000000    1.00000000    2.00000000   10.00000000

  FLOW RATES (LBS./HR.) IN SYSTEM    2
           5.00000000    2.50000000    2.50000000    5.00000000

  PRESSURE DROPS (X1000.) (LBS./SQ. IN.) IN SYSTEM    1
          40.92035400   32.73628400    8.18407120    4.09203540    4.09203560
           8.18407110    4.09203550    4.09203550    8.18407110   40.92035400

  PRESSURE DROPS (X1000.) (LBS./SQ. IN.) IN SYSTEM    2
          20.46017600   10.23008850   10.23008850   20.46017600

  POWER REQUIREMENT (X 1000.)     2883.131100 FT.LB./HR.

  TOTAL HEAT REJECTED            -525.910450 BTU/HR. IN SYSTEM    1

  TOTAL HEAT REJECTED               .000000 BTU/HR. IN SYSTEM    2

  WEIGHT                           1.020555 LBS.

  FLUID LUMP TEMPERATURES (DEGREES F.)

       38.03324     63.07042     68.10534     69.97121     69.97121
       69.99950     70.00000     70.00000     70.00000     69.19875
       70.00000     70.00000     70.00000     70.00000

  TUBE LUMP TEMPERATURES (DEGREES F.)

       43.99564     66.12525     68.96551     69.98904     69.98904
       70.00000     70.00000     70.00000     70.00000     69.64900
       70.00000    -30.89659     16.30687     70.00000

  STRUCTURES LUMP TEMPERATURES (DEGREES F.)

       52.55290     60.09282

  TRANSIENT PROBLEM COMPLETED.
TYPE      RE        PR      COND.      DEN.   SP. HEAT  VIS.BULK   VIS.WALL    WEIGHT  HEAT TRAN. COEFFS.
  1    5.55556  42.75000   .32000  70.00000    .76000   5.00000   5.00000    .04861 168.65280 168.65280
  1    4.44444  42.75000   .32000  70.00000    .76000   5.00000   5.00000    .04861 168.65280 168.65280
  1    1.11111  42.75000   .32000  70.00000    .76000   5.00000   5.00000    .04861 168.65280 168.65280
  1     .55556  42.75000   .32000  70.00000    .76000   5.00000   5.00000    .04861 168.65280 168.65280
```

TABLE 3 SAMPLE OUTPUT

1	,55556	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280	168,65280
1	1,11111	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280	168,65280
1	,55556	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280	168,65280
1	,55556	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280	168,65280
1	1,11111	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280	168,65280
1	5,55556	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280	168,65280
1	2,77778	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280	168,65280
1	1,38889	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280	168,65280
1	1,38889	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280	168,65280
1	2,77778	42,75000	,32000	70,00000	,76000	5,00000	5,00000	,04861	168,65280	168,65280

TABLE 3 SAMPLE OUTPUT

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