N73-23946
CR-128913

CASE FILE
COPY

VOUGHT MISSILES
AND SPACE COMPANY
TEXAS DIVISION

P. O. Box 6267

Dallas, Texas 75222

NASA/MSC CONTRACT
NAS 9-10810

RADIATOR DESIGN SYSTEM
COMPUTER PROGRAMS

00.1479

13 October 1971

Submitted By:

VOUGHT MISSILES AND SPACE COMPANY
LTV AEROSPACE CORPORATION
P. O. Box 6267 - Dallas, Texas 75222

To

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
Houston, Texas

Prepared By:

C. L. Wiggins
C. L. Wiggins

J. A. Oren
J. A. Oren

J. B. Dietz

Approved By:

R. J. French
R. J. French, Supervisor
Environmental Control/
Life Support Group

TABLE OF CONTENTS

	Page
1.0 SUMMARY	1
2.0 INTRODUCTION	3
3.0 STEADY STATE DESIGN ROUTINE	4
3.1 General Routine Description	4
3.2 Analytical Methods	5
3.2.1 Groundrules and Assumptions	5
3.2.2 Description of Calculation Methods	13
3.2.3 Determination of Fluid and Metal Properties	18
3.2.4 Weight Penalty Equations	20
3.3 Routine Operation	25
3.4 User's Manual	28
3.4.1 Univac 1108 Subroutine Requirements	28
3.4.2 MSC Run Submission Requirements	29
3.4.3 Run Time and Output Estimation	29
3.4.4 SSDR Data Card Preparation	31
3.4.5 Run Failure Analysis	43
4.0 TRANSIENT PERFORMANCE ROUTINE	44
4.1 Purpose	44
4.2 Routine Description and Analytical Methods	44
4.2.1 Groundrules and Assumptions	44
4.2.2 Temperature and Flow Analysis	47
4.2.3 Component Description	56
4.3 Routine Options	61
4.3.1 Automatic Nodal Subdivision Subroutines (SUBANS, SUBRAD, and SUB2D)	61
4.3.2 Plot Options	83
4.3.3 Checkout Print	86
4.3.4 Restart	86
4.3.5 Edit	86
4.3.6 Specified Temperature Nodes	88
4.4 User's Manual	89
4.4.1 Transient Performance Routine (TPR)	89
4.4.2 Automatic Nodal Subdivision Cards	103
4.4.3 Plot Program	113

TABLE OF CONTENTS (Cont'd.)

		Page
5.0	COMPUTER INCIDENT HEAT ROUTINE	115
6.0	REFERENCES	131
APPENDICES		
A	Determination of Radial Fin Effectiveness In a Non-Zero Sink Temperature Environment	A-1
B	Determination of Fin Effectiveness for a Heat Absorbing Fin	B-1

LIST OF FIGURES

Figure Number	Description	Page
3-1	RADIATOR PANEL FLOW CONNECTIONS	8
3-2	TWO DIMENSIONAL PANEL CHARACTERIZATION FOR SSDR	12
3-3	RADIATOR PANEL GEOMETRY DEFINITION	23
3-4	SSDR PROGRAM FLOW CHART	26
3-5	INPUT DATA CARD REQUIREMENTS	32
4-1	TRANSIENT PERFORMANCE ROUTINE SYSTEM	45
4-2	FLOW SYSTEM OPTIONS	46
4-3	BYPASS VALVE OPERATION	57
4-4	RECTANGULAR PANEL RADIATOR MODEL	63
4-5	RECTANGULAR PANEL EXAMPLE PROBLEM - OVERALL DIMENSIONS. .	64
4-6	RECTANGULAR PANEL EXAMPLE PROBLEM - NODAL BREAKDOWN AND DIMENSIONS.	65
4-7	RECTANGULAR PANEL EXAMPLE PROBLEM - INCIDENT HEAT ZONE BREAKDOWN AND DIMENSIONS	66
4-8	CIRCULAR PANEL EXAMPLE PROBLEM - COORDINATE SYSTEM AND OVERALL DIMENSIONS	71
4-9	CIRCULAR PANEL EXAMPLE PROBLEM - NODAL BREAKDOWN AND DIMENSIONS	72
4-10	CIRCULAR PANEL EXAMPLE PROBLEM - INCIDENT HEAT ZONES . .	73
4-11	INCIDENT HEAT ZONE DETERMINATION FOR TWO INTERSECTING BOUNDARY LINES.	77
4-12	TWO-DIMENSIONAL PANEL NODAL BREAKDOWN	79
4-13	TWO-DIMENSIONAL PANEL LUMP TYPE CLASSIFICATION	81
4-14	TWO-DIMENSIONAL LUMP NUMBERING	82
5-1	ILLUSTRATION OF METHOD USED TO SELECT POINTS	116
A-1	DIFFERENTIAL ELEMENT OF A RADIAL FIN	A-3
A-2	RADIAL FIN EFFECTIVENESS VS PROFILE NUMBER FOR SINK TEMPERATURE RATIO = 0.0	A-9
A-3	RADIAL FIN EFFECTIVENESS VS PROFILE NUMBER FOR SINK TEMPERATURE RATIO = 0.5	A-11

LIST OF FIGURES (Cont'd.)

Figure Number	Description	Page
A-4	RADIAL FIN EFFECTIVENESS VS PROFILE NUMBER FOR SINK TEMPERATURE RATIO = 0.6	A-13
A-5	RADIAL FIN EFFECTIVENESS VS PROFILE NUMBER FOR SINK TEMPERATURE RATIO = 0.7	A-15
A-6	RADIAL FIN EFFECTIVENESS VS PROFILE NUMBER FOR SINK TEMPERATURE RATIO = 0.8	A-17
A-7	RADIAL FIN EFFECTIVENESS VS PROFILE NUMBER FOR SINK TEMPERATURE RATIO = 0.9	A-19
B-1	VALUES OF FIN EFFECTIVENESS FOR SINK TO BASE TEMPERATURE RATIOS GREATER THAN 1.0	B-5

LIST OF TABLES

Table Number	Description	Page
3-1	GENERAL GROUNDRULES	6
3-2	PANEL/SYSTEM HEAT LOAD CONTROL	9
3-3	HEAT LOAD CONTROL AND PANEL FLOW PATTERNS	10
3-4	INDEX NUMBERS FOR THE SSDR FLUIDS AND METALS	39
4-1	EXAMPLE (SERPENTINE) PROBLEM - TYPICAL UPSTREAM AND DOWNSTREAM LUMP NUMBERS	69
4-2	EXAMPLE (PARALLEL) PROBLEM - TYPICAL UPSTREAM AND DOWNSTREAM LUMP NUMBERS	69
4-3	CIRCULAR PANEL EXAMPLE PROBLEM - TYPICAL UPSTREAM AND DOWNSTREAM LUMP NUMBERS	75
4-4	CIRCULAR PANEL EXAMPLE PROBLEM - INCIDENT HEAT ZONE SPECIFICATION	84
4-5	TWO-DIMENSIONAL EXAMPLE PROBLEM-TYPICAL UPSTREAM AND DOWNSTREAM LUMP NUMBERS	85

1.0 SUMMARY

This report describes the effort of the LTV Aerospace Corporation Vought Missiles and Space Company, Texas Division under Task 1.1.2 of NASA Contract NAS9-10810. The purpose of this effort was to extend the capability of an existing system of computer routines, the Radiator Design System (RDS), described in Reference 1, to produce an Advanced Radiator Design System (ARDS).

The ARDS consists of three separate routines which are (1) the steady state design routine, version 2 (SSDR-2), (2) the Transient Performance Routine Version 2(TPR-2), and (3) the Computer Incident Heat Data Routine (CIHR).

The SSDR determines a weight optimized radiator (or set of radiator panels) and low load control technique which satisfy user input requirements for maximum and minimum heat rejection, number and type of radiator panels, area limitations, structural support weight penalties, fluid properties, radiator material properties, micrometeoroid protection requirements, pressure drop (and associated pumping power penalty), minimum allowable fluid temperature, and use of supplemental expendable heat sink devices (such as water boilers or sublimators). It optimizes the radiator(s)-control technique combination by variation of tube diameter, tube spacing, fin thickness and flow path arrangement within limits specified by the user. It then outputs a definition of all panel and control technique configurations (including regenerator weight if applicable) within ten percent of a minimum weight design. The latest version (SSDR-2) can be used to design solar absorbers as well as radiators. In addition, the characterizations of two-dimensional fins, fluid heat transfer coefficients, friction factor and weight calculations are significantly improved over the previous version.

By use of the TPR, the user may select a SSDR design and quickly determine its transient performance in a radiator subsystem consisting of the radiator and heat load control valving, subsystem piping and/or a regenerative heat exchanger. The results of the TPR can be used to judge the adequacy of effective environments and effective heat loads used for the initial steady state design. The SSDR and TPR can be run sequentially to iterate on a weight optimum subsystem design which satisfies transient requirements. The TPR includes automatic output plotting, interruption and restart capability, provisions for use of input data from magnetic tapes which can be edited to incorporate design changes, or changes for parametric performance studies. The TPR is facilitated by SUBANS and SUBRAD which generate nodal lumped parameter TPR input data from a user specification of overall radiator panel dimensions, fluid flow path geometry, number of flow paths, and specification of zones for discrete time variant incident heat values. SUBANS divides one dimensional panels and SUBRAD divides radial panels.

With these two subroutines, the user may also automatically generate nodal models with varying degrees of fineness to establish accuracy requirements consistent with preliminary design objectives and minimization of computer time used.

The CIHR permits the user to specify the vehicle orbit and orientation and obtain the incident heat curves on punched cards in TPR format with the minimum number of points. No change was made to the CIHR under this contract.

2.0 INTRODUCTION

The projected trends of future long duration space vehicles indicate the need for minimum weight space radiator subsystems which can operate over heat load ranges that are much wider than the capabilities of current subsystem design. The upward trend in maximum heat rejection requirements of low temperature radiators required for environmental control systems necessitates increases in radiator panel area to the extent that deployed radiator panels in addition to multiple panels which are integral with the space vehicle structure may be required. However, during period of dormant or low activity operation, reduced space vehicle heat loads may cause complete radiator fluid stagnation or freezing due to the heat rejection capacity of large radiator areas. The limit of radiator low heat load operation (minimum of the heat load range) is established by the coolant fluid freezing point and by the heat load control method employed on the radiator panels (e.g., flow stoppage in a portion of the radiator tubes) and in the radiator subsystem (e.g., fluid bypass or regeneration). The use of mechanical shuttering devices to block the radiator view of the space environment is not considered practical for large area systems because of excessive weight and system complexity. The weight of large area integral and deployed panels must be minimized during design since the radiators become a significant portion of the overall spacecraft weight.

Experience with previous radiator systems has shown that transient performance is a key factor which must be considered during conceptual and preliminary spacecraft design phases to avoid defining excessive radiator area or over complicating low heat load radiator control techniques. The set of radiator design programs summarized herein were developed to provide the analyst with a capability to generate optimum weight radiator panels or sets of panels from practical design considerations, including transient performance. In addition, modifications to existing detailed transient radiator analysis programs to improve capability and user convenience were implemented.

3.0 STEADY STATE DESIGN ROUTINE

The Steady State Design Routine Version 2 (SSDR-2) written to determine the optimum weight design of radiator or absorber panels is described in this section of the report. The SSDR is capable of steady state design of weight optimized radiator or solar absorber panels consistent with given space vehicle operational characteristics and constraints. The panels designed with SSDR-2 can be easily analyzed with the Transient Performance Routine (TPR) described in Section 4.0 to establish transient performance in a radiator subsystem (consisting of the radiator and heat load control valving and/or a regenerative heat exchanger). The analyst can use TPR results to iteratively rerun SSDR with modified design constraints in order to establish a weight optimized design which yields desired radiator subsystem transient response characteristics.

3.1 GENERAL ROUTINE DESCRIPTION

The SSDR-2 radiator or absorber design requirements are input into the routine by the user and include: the maximum heat load, minimum heat load, the inlet temperature at maximum heat load, the required system exit temperature (mix temperature), panel area availability, panel thermal properties, and the effective thermal environment at maximum and minimum heat load. The design requirements at maximum heat load are used to size the system for the various panel geometries considered.

The SSDR-2 optimizes the system weight at maximum heat load by variation of the tube diameter, tube spacing (number of tubes), panel flow path connection (series and/or serpentine tube connections), and panel fin thickness. Each of these parameters are varied independently within limits imposed by the program or input by the user[1]. The system configuration must then meet or exceed the minimum heat load design requirements in order for it to be considered an optimum design.

In addition to the satisfying of the above design requirements, the radiator or absorber system optimized by the SSDR-2 must also meet or consider the following operational constraints: the system panel pressure drop must not exceed the maximum allowed, the transport fluid temperature at minimum heat load must not be less than a specified input value[2], and the panel area used for heat rejection cannot exceed the maximum available.

If the panel pressure drop exceeds the maximum allowed, the particular panel configuration analyzed is not considered for the optimum design. The maximum allowable pressure drop constraint is input data and may be deleted by the user. In this case the SSDR-2 utilizes a pumping power penalty (user input) to account for the influence of pressure drop in determining an optimum weight panel or set of panels.

---

1 System designs using previously developed radiator or absorber panel configurations can be analyzed by user specification of one or all of these variable parameters. The specified parameter overrides the instructions within the routine for its variation.

2 For solar absorbers, the fluid temperature at the minimum heat load must not be more than a specified value.

The minimum allowable fluid temperature (user input) will force the SSDR-2 to reject all heat load control methods that result in radiator exit temperatures at minimum heat load operation which are less than the minimum allowed.

If the radiators cannot reject the maximum heat load with given radiator panel area, the routine assumes that an expendable heat rejection system is in the system to dissipate the excess heat. The excess heat dissipation with a boiler/sublimator is optional and may be deleted by the user.

3.2 ANALYTICAL METHODS

3.2.1 Groundrules and Assumptions

Fifteen general SSDR-2 groundrules are tabulated in Table 3-1. The most significant of these is use of a pair of effective thermal environments for steady state design at maximum and minimum heat load conditions. For many spacecraft missions the system heat load and thermal environment may be in transient modes for a majority of the mission duration. Thus the SSDR user must estimate a maximum effective absorbed heat (for example in the sunlit portion of a planet orbit) which will not result in oversized panel area. This is required because the panel will not reach equilibrium operating conditions at the peak environmental heat absorption point in the orbit. Similarly in the shadowed portion of the orbit the radiator will not be at steady state conditions as it views the actual minimum environmental heat flux for a short period, leading to a need for an effective minimum absorbed heat input to SSDR-2. If a short duration minimum environmental heat absorption is used, an overly complex low heat load control method may be specified by the SSDR-2.

The transient nature of the radiator heat loads (rejection requirements) should also be considered when using the SSDR-2. Specification of equilibrium heat loads which will not be realized during the mission can similarly lead to unnecessary complication of radiator design requirements.

If a panel is to be designed to satisfy such transient mission requirements, the user can estimate effective absorbed heats and heat loads initially, run SSDR-2, and use the routine design in TPR to evaluate the reasonableness of his estimate. The two programs can thus be run sequentially to iterate on an optimum radiator subsystem design.

Multiple panel systems may be designed by the SSDR-2. These systems may consist of panels which are identical to each other or panels which may be of different geometries (width, tube diameter, fin thickness). The panels may be flowed connected in series or in parallel depending on user specification. The effective thermal environment may be different for each panel. A detailed description of the constraints of multiple panel systems follows.

Panels may be connected for parallel flow with the following conditions:

TABLE 3-1

GENERAL GROUNDRULES

a. The SSDR-2 utilizes a pair of effective absorbed heat fluxes to establish the radiator design under maximum and minimum environmental heat influx conditions.

b. The radiator or absorber system consists of fin-tube panels and heat load control methods.

c. The panels may be connected in series or in parallel as described in Section 3.2.2.

d. The panels are fin-tube surfaces with simple rectangular fins and round tubes.

e. The panel edges are adiabatic.

f. Heat transfer resistance of the surface coatings is assumed negligible.

g. Steady state operation of the system is assumed.

h. The tube temperature is assumed constant around the tube periphery.

i. The tube edge of radiating fin segments are assumed to have uniform longitudinal temperature.

j. The temperature across the fin thickness is assumed uniform.

k. The fin midppint between flowing tubes is adiabatic.

l. The absorbed heat (or equivalent sink temperature) is uniform for a radiator panel.

m. Longitudinal conduction in the fin, tube, and fluid is neglected.

n. The radiant interchange between the panel fins and tubes is assumed to be zero.

o. The tubes and fins of all panels are of a uniform material. The material properties are evaluated at the panel base temperature.

a. Parallel flow systems are limited to two panels flowed in parallel.

b. Parallel panels are of identical design.

c. The absorbed heat may be different for each panel.

d. The coolant flow is equally divided between the panels unless the sink temperature is greater than the inlet temperature for one panel. If the sink temperature is greater than the inlet temperature for one panel the flow bypasses that panel.

Figure 3-1(a) shows a typical radiator or absorber system with the panels connected for parallel flow.

Panels may be connected in series with the following conditions:

a. Panels connected in series are limited to 10 panels.

b. Panels may be of two different types. Panels of the same type are identical to each other for all the variables being considered (e.g. fin thickness, tube spacing, etc.).

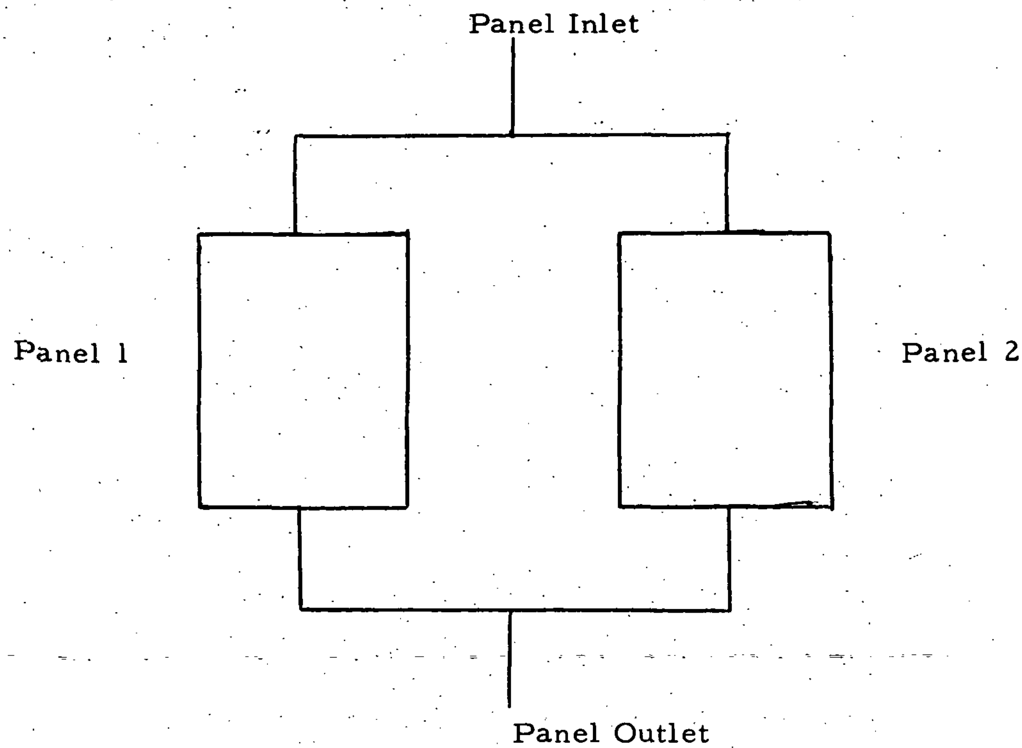
c. All panels of the same type must be sequentially arranged.

d. The absorbed heat may be different for each panel.

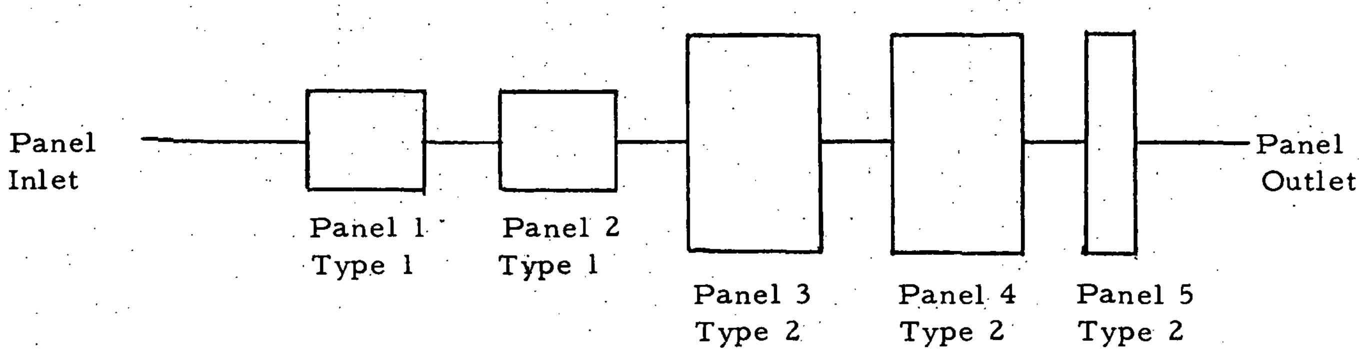
Figure 3-1(b) shows a typical system with the panels connected for series flow.

Fourteen heat load control methods considered by the SSDR-2 to assure adequate system performance at minimum heat load are described in Table 3-2. The control methods consist of bypass, regenerative, valve stagnation, and various combinations of all three of these. The control methods are in many instances combined with panel tube patterns to yield wide range heat load radiators. By inputting a zero for the minimum heat load the SSDR-2 will calculate, as an option, the minimum possible heat load for the optimum system design for each of the control methods. This routine option is useful for design problems in which the system minimum heat load is not defined. The control methods are, in many instances, integrated with panel flow patterns and as shown in Table 3-2 are generally in order of increasing heat load range and control method complexity. The definitions of the seven Table 3-2 headings are presented in Table 3-3.

The two-dimensional panel characterization used in SSDR is shown in Figure 3-2. The method of characterization assumes a triangular panel for panel designs where the required area is less than one-half the available area. Two triangular panels are assumed for required area greater



(a) PANELS CONNECTED FOR PARALLEL FLOW SYSTEM



(b) PANELS CONNECTED FOR SERIES FLOW SYSTEM

FIGURE 3-1 PANEL FLOW CONNECTIONS

TABLE 3-2

PANEL/SYSTEM HEAT LOAD CONTROL
(See Table 3-3 For Definition of Headings)

	Panel Flow System		Heat Load Control					
Configuration	Series	Parallel	Bypass	Regen.	Valve Stag.	1-D Tube Pattern	2-D Tube Pattern	Notes
1	x		x			x		
2	x			x		x		
3	x		x	x		x		1
4		x	x			x		
5		x		x		x		
6		x	x	x		x		1
7		x			x	x		
8		x			x		x	2
9		x	x		x	x		
10		x	x		x		x	2
11		x		x	x	x		
12		x		x	x		x	2
13		x	x	x	x	x		3
14		x	x	x	x		x	3, 2

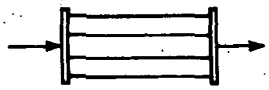
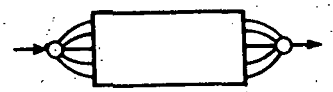
1. The Bypass-Regenerative control method will be considered only if Bypass control and Regenerative control methods are not feasible.

2. Two dimensional tube pattern radiator panels will be considered only if one dimensional tube pattern panels are not feasible for this control method.

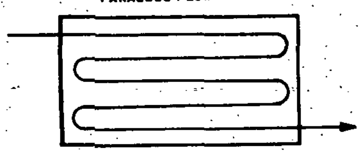
3. The Bypass-Regenerative-Stagnation control method will be considered only if Bypass-Stagnation control and Regenerative-Stagnation control methods are not feasible.

TABLE 3-3
HEAT LOAD CONTROL AND PANEL FLOW PATTERNS

PARALLEL/SERIES FLOW PATTERNS

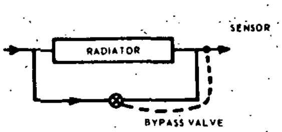
PARALLEL FLOW



SERIES SERPENTINE FLOW

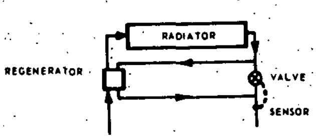
Parallel Flow Paths may be joined by large low velocity headers or central flow distribution manifolds depending upon the type of fluid used and the method of heat load control.

BYPASS AND REGENERATIVE HEAT LOAD CONTROL



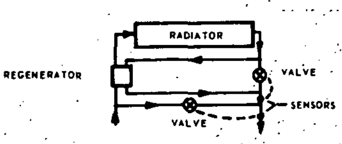
BYPASS CONTROL

At low load, fluid is bypassed around the panel to reduce average radiator temperature, thereby reducing the heat rejection. The design limit is reached when the fluid outlet temperature nears its freezing point.



REGENERATIVE CONTROL

At low load, the temperature of the fluid at the radiator inlet is reduced to achieve a lower average radiator temperature as the fluid outlet temperature nears its freezing point at the design limit. This provides wider heat load control than bypass control but adds another system component which can become quite heavy. System pressure drop with full flow through the radiator at low load also limits this design.



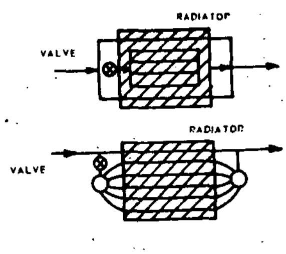
COMBINED BYPASS AND REGENERATIVE CONTROL

A combination of regeneration and fluid bypass with two valves may be utilized to decrease the size of the regenerator and improve pressure loss at low load, but logic to transfer control from the bypass valve to the regenerator flow control valve must be provided in the system.

TABLE 3-3 (Continued)

HEAT LOAD CONTROL AND PANEL FLOW PATTERNS

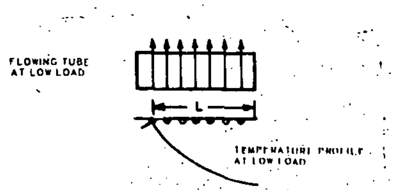
STAGNATION HEAT LOAD CONTROL



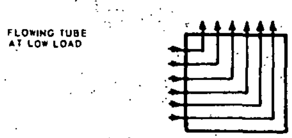
VALVE STAGNATION

An automatic or manually operated valve can be used to shut-off flow in a bank of tubes to decrease radiating fin effectiveness. The design may allow for fluid freezing in the non-flowing tubes if necessary to achieve a sufficiently wide variation of radiator heat rejection. The warm tube(s) on the panel can be used to provide heat to the frozen tubes for resumption of full flow. This valve stagnation method can be used in addition to system bypass and regenerative heat load control.

EFFECT OF TUBE PATTERN ON HEAT LOAD CONTROL



ONE DIMENSIONAL RADIATING FIN

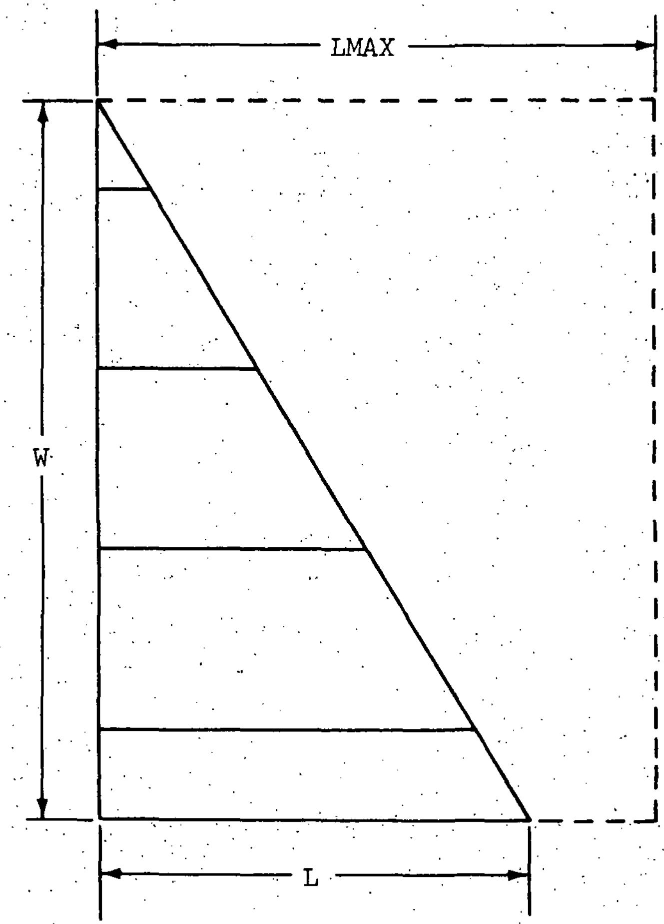


TWO DIMENSIONAL RADIATING FIN

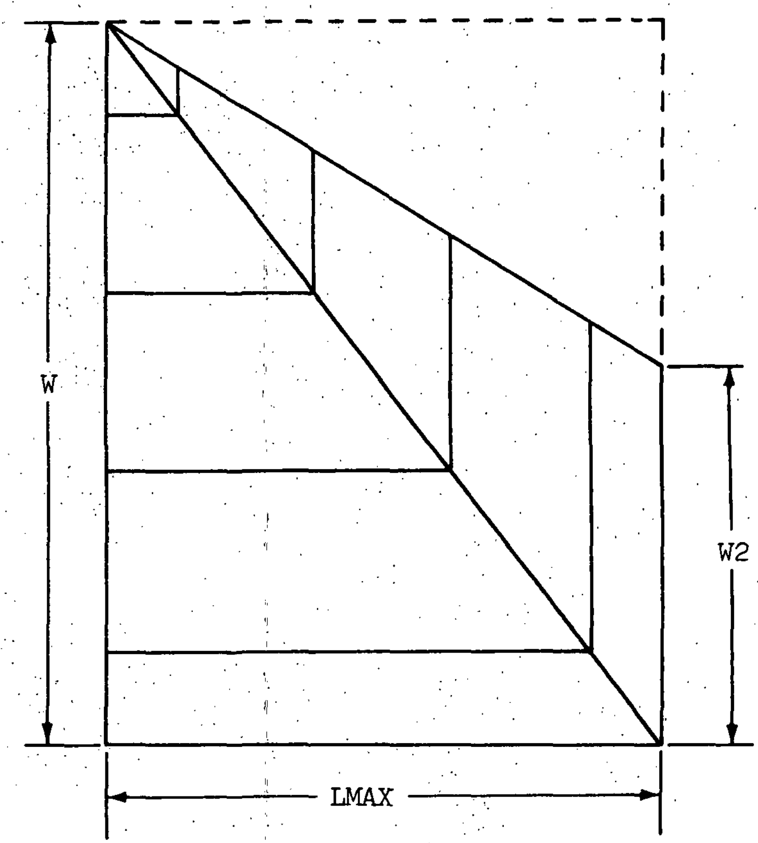
Parallel tubes which flow in one direction on a rectangular panel yield a low load stagnated flow temperature profile which can be approximated by one dimensional fin theory to calculate low load performance using L as the fin half width. A limiting low load fin effectiveness is reached as a result of limitations on panel thickness and the speed with which full flow for high load heat rejection must be re-established.

Parallel tubes in which flow turns at 90° on a panel will yield a deeper low load stagnated flow temperature profile which can be approximated by radial fin theory. For similar overall panel geometries the radial fin will provide twice the heat load control range. These tube patterns can be used with any of the methods described above.

FIGURE 3-2 TWO DIMENSIONAL PANEL CHARACTERIZATION FOR SSDR-2



CONFIGURATION FOR AREA REQUIRED
< 1/2 MAXIMUM AREA AVAILABLE



CONFIGURATION FOR AREA REQUIRED
> 1/2 MAXIMUM AREA AVAILABLE

than one-half the available area as shown in Figure 3-2. With this procedure, the tube spacing remains constant for the entire radiator panel.

3.2.2 Description of Calculation Methods

A brief description of the analytical techniques and calculation methods are presented in this section.

The internal convective heat transfer coefficient is calculated assuming fully developed flow conditions for the two flow regimes: transition and turbulent. For the laminar flow regimes an average value of heat transfer coefficient is used which includes that for the entry length region of flow for each panel. Assuming constant temperature per unit length, the convection coefficient is given by:

$$h = \frac{k}{D} [Nu]$$

where:

h = the internal flow convection coefficient
k = fluid thermal conductivity
Nu = Nusselts Number
D = the hydraulic diameter of the flow tube

The commonly used equations for determining the turbulent and transition flow Nusselt Numbers are used in the computer routines. For the laminar flow regime a curve fit has been made for the mean Nusselt Number which includes the effect of entry length (Ref. 2). The fluid properties used are the effective fluid properties as defined in Section 3.2.3.

For Reynolds Numbers less than 1900 the curve fit for the mean Nusselt Numbers used:

$$Nu = 3.65 + \frac{.0668\ (D/X)\ RePr}{1 + .04[(D/X)RePr]^{2/3}}$$

For Reynolds Numbers greater than 6400, the Dittus-Boelter equation for turbulent flow is used:

$$Nu = 0.023\ R_e^{.8}\ Pr^{1/3}$$

For Reynolds Numbers between 1900 and 6400, a modified H. Hausen expression for flow in the transition region is used:

$$Nu = 0.166[R_e^{2/3} - 125]\ Pr^{1/3}$$

where:

$$Nu = \text{Nusselts Number} = \frac{hD}{k}$$

X = the distance from flow entrance

Re = Reynolds Number

$= \frac{4\dot{m}}{\mu P}$

$\dot{m}$ = mass flow rate

μ = viscosity of the fluid

P = wetted perimeter

Pr = Prandtl Number

$= \frac{\mu C_P}{k}$

C_P = specific heat of the fluid

In many instances, panels with stagnation control techniques require the prime flow tube (that radiator tube with the highest flow during low load stagnation) to have a larger diameter than the other tubes for optimum design. This occurs because pressure drop constraints at low load often requires a larger diameter than the optimum for the remainder of the panel. In SSDR the user has the option to specify either that all tubes be identical or that all tubes except the prime tube are identical.

The radiator panel pressure loss is calculated by the Fanning equation for a single phase incompressible fluid. The fluid properties used in the pressure drop equation are the effective fluid properties as defined in Section 3.2.3. The pressure drop for each panel is calculated by:

$$\Delta P = f\ L/D\ \rho_e\ V^2/2g$$

The SSDR calculates the friction factor for laminar flow by the relation:

$$f = \frac{64}{Re},\ Re < Re_L$$

For turbulent flow the friction factor is calculated by:

$$f = \frac{0.316}{(Re)^{1/4}}\quad Re > Re_t$$

For the transition region a polynominal curve fit is used to remove any discontinuities from the friction factor curve:

$$f = A\ Re^3 + B\ Re^2 + C\ Re + D$$

The constants, A, B, C, and D can be determined from the four conditions:

(1) $f = f_L$ at $Re = Re_L$ (beginning of the transition region)

(2) $f = f_t$ at $Re = Re_t$ (end of the transition region)

(3) $\frac{df}{dRe} = -64\ (Re_L)^{-2}$ at $Re = Re_L$

(4) $\frac{df}{dRe} = \frac{-.079}{(Re)_t^{1.25}}$ at $Re = Re_t$

where:

f = friction factor

L = panel flow length

D = tube diameter

$\overline{\rho}_e$ = effective fluid density

V = fluid velocity

Re = Reynolds Number

Re_L = laminar end of transition region

Re_t = turbulent end of transition region

The radiator fin effectiveness is defined as the ratio of the heat rejected by the actual fin to the heat which would be rejected if the fin were at the fin base temperature. Fin effectiveness is dependent on the fin geometry (length, thickness), the fin material properties, the base temperature, and thermal environment. Values of fin effectiveness have been obtained (and presented in the literature) by numerically integrating the non-linear fin heat flux differential equations. Curve fits of fin effectiveness for flat rectangular fins were obtained in Reference (3) and are employed for the SSDR effectiveness calculations.

The characterization of a heat absorbing fin is included in the SSDR. The differential equation describing the heat flow in a one-dimensional radiating fin was integrated for a reasonable range of boundary conditions to obtain effectiveness for values of sink temperature greater than the fin base temperature. A curve fit of the information was performed and the results programmed into SSDR. An equation was derived that results in effectiveness values with a $\pm 1\%$ degree of accuracy for sink to base temperature ratios under a prescribed boundary. For a detail discussion of heat absorbing fin characterization see Appendix B.

The rectangular fin effectiveness equations are a function of the sink-to-base temperature ratio and the rectangular fin parameter:

$$T_r = (T_s/T_b)^4$$

$$\lambda v = \frac{Y^2 \epsilon \sigma T_b^3}{KZ \cdot N_{surf}}$$

where:

T_r = sink to base temperature ratio

λv = rectangular fin parameter

Y = fin length

ϵ = thermal emissivity

σ = Stefan - Boltzmann constant

T_b = fin base temperature, °R

K = thermal conductivity, BTU/hr ft°R

Z = fin thickness, ft

N_{surf} = number of fin radiating surfaces (1 or 2)

T_s = effective sink temperature, °R

Circular fin effectiveness theory is used for radiator panels operating at minimum heat load and employing two dimensional tube pattern - stagnation heat load control methods (see Table 3-3). Values of circular fin effectiveness were obtained by numerically integrating the non-linear heat flux differential equations. Curve fits were made and included in SSDR effectiveness calculations. Circular fin effectiveness determination is presented in detail in Appendix A.

The fin effectiveness equations for circular fins are a function of the fin parameter and the radius ratio:

$$\lambda c = \frac{(r_o - r_i)^2 \epsilon \sigma T_b^3}{KZ \, N_{surf}}$$

$$R_r = \frac{r_o}{r_i}$$

where:

λc = circular fin parameter

R_r = radius ratio

r_o = radius of fin outer edge

r_i = radius of fin inner edge

Micrometeoroid protection requirements for the radiator panel tubes are considered in radiator weight calculations by the use of a tube thickness equation. The tube thickness is a function of the probability of penetration, the exposed tube area, and the mission duration. The thickness equation will thus calculate the tube wall thickness necessary for radiator system compatibility with the mission definition. The user may specify a minimum tube thickness (which overrides the calculated thickness) to be considered in the event that the micrometeoroid protection requirement is not as severe as the required panel manufacturing constraints. The equation for the calculation of the required tube thickness is given below:

$$t_t = \text{WPT1} \times (\text{Time} \times A_t)^{\text{WPT2}} \tag{3.1}$$

where:

t_t = tube thickness - ft

Time = mission duration - days

A_t = total tube projected area - ft^2

WPT1, WPT2 = equation constants

The radiator area required to reject the design maximum heat load is calculated by iterating on the area and heat balance between the fluid, tube, and panel until the required heat rejection and temperature performance is obtained. The base temperature is calculated by equating the heat radiated by the panel to heat lost from the fluid through an iterative process. For the conditions where the required heat rejection cannot be met due to area limitations, the excess heat not rejected by the system is assumed to be rejected by a water boiler/sublimator. The heat balance equations used in the iterative process is given below:

$$\text{Panel} - Q_R = \eta A[\epsilon \sigma T_B^4 - Q_A]$$

$$\text{Fluid} - Q_R = \omega C_p(T_{in} - T_{out})$$

$$\text{Tube} - Q_R = hA(T_f - T_B)$$

where:

Q_R = heat rejected

η = fin effectiveness

ϵ = thermal emissivity

σ = Stefan - Boltzman constant

T_B = base temperature

Q_A = heat absorbed by panel

$\dot{\omega}$ = system flow rate

C_p = fluid specific heat

T_{in} = panel inlet temperature

T_{out} = panel outlet temperature

hA = heat transfer coefficient

$T_f = \dfrac{T_{in} + T_{out}}{2}$

For control methods where a regenerator is used the heat rejected by the regenerator is calculated as shown below.

$$Q_{REGN} = \dot{\omega} C_p (T_{mix} - T_{out})$$

3.2.3 Determination of Fluid and Metal Properties

Fluid Properties

Thermal Conductivity

The fluid thermal conductivity is calculated by:

$$K_f(T) = KF0 + KF1 \times T + KF2 \times T^2 + KF3 \times T^3 \quad \text{(Equation 3.2)}$$

where:

$K_f(T)$ = thermal conductivity $\dfrac{BTU}{hr \times ft \times {}^\circ R}$

T = temperature - °R

KF0, KF1, KF2, KF3 - equation constants

The effective fluid thermal conductivity for a radiator panel is

$$\overline{K}_e = \frac{1}{T_o - T_i} \int_{T_i}^{T_o} K_f(T)\, dT$$

Density

The fluid density is calculated by:

$$\rho f(T) = DF0 + DF1 \times T + DF2 \times T^2 + DF3 \times T^3 \qquad (3.3)$$

where:

$\rho f(T)$ = fluid density - lb_m/ft^3

T = temperature - ^oR

DF0, DF1, DF2, DF3 - equation constants

The effective fluid density for a radiator panel is

$$\overline{\rho}_e = \frac{1}{T_o - T_i} \int_{T_i}^{T_o} \rho_f(T)\, dT$$

Specific Heat

The fluid specific heat is calculated by:

$$C_p(T) = CP0 + CP1 \times T + CP2 \times T^2 + CP3 \times T^3 + CP4 \times T^4 \qquad (3.4)$$

where:

$C_p(T)$ = specific heat - BTU/lb_m

T = temperature - ^oR

CP0, CP1, CP2, CP3, CP4 - equation constants

The effective specific heat for a radiator panel is:

$$\overline{C}_{pe} = \frac{1}{T_o - T_i} \int_{T_i}^{T_o} C_p(T)\, dT$$

Dynamic Viscosity

The fluid viscosity is calculated by:

$$\log_e [\mu_{(T)}] = (MU0+MU1/T + \frac{MU2}{T^2} + \frac{MU3}{T^3} + \frac{MU4}{T^4} + \frac{MU5}{T^5}) \qquad (3.5)$$

where:

$\mu(T)$ = fluid viscosity - lb_m/ft-hr

T = temperature - °R

MU0, MU1, MU2 - equation constants

The effective fluid viscosity for a radiator panel is:

$$\overline{\mu}_e = \frac{1}{T_o - T_i} \int_{T_i}^{T_o} \mu(T)\, dT$$

Metal Properties

The metal conductivity is calculated by:

$$K_m(T) = KM0 + KM1 \times T + KM2 \times T^2 + KM3 \times T^3 \qquad (3.6)$$

where:

$K_m(T)$ = thermal conductivity - BTU/hr-ft-°R

T = temperature - °R

KM0, KM1, KM2, KM3 - equation constants

The metal density is calculated by:

$$\rho_m(T) = DM0 + DM1 \times T + DM2 \times T^2 + DM3 \times T^3 \qquad (3.7)$$

where:

$\rho_m(T)$ - metal density - lb_m/ft^3

T = temperature - °R

DM0, DM1, DM2, DM3 - equation constants

3.2.4 Weight Penalty Equations

The weight associated with a radiator or absorber system consists of the tubes, manifolds, interconnecting tubing, fluid, radiating fins, control valves, regenerator, panel support structure, weight due to pumping power, and excess heat penalty due to water boiling requirements at high heat load. The equations used in SSDR-2 to calculate radiator system weight are presented in this section.

Radiator Tube Weight:

$$W_T = N \times \rho_M \times L \times \pi \times t_T (D_T + t_T) (\text{REDUNP} + 1) \qquad (3.8)$$

Manifold Weight:

$$W_M = \text{NMANT} \times \rho_M \times Y \times \pi \times t_M(D_M + t_M) (\text{REDUNP} + 1) \qquad (3.9)$$

Interconnecting Tube Weight:

$$W_L = \rho_M \times \text{XLL} \times \pi \times t_L (D_L + t_L) (\text{REDUNP} +1) \qquad (3.10)$$

Tube Fluid Weight:

$$W_{TF} = N \times \overline{\rho}_e \times L \times \pi \times \frac{D_T^2}{4} (\text{REDUNP} + 1) \qquad (3.11)$$

Manifold Fluid Weight:

$$W_{MF} = \text{NMANT} \times \overline{\rho}_e \times Y \times \pi \times \frac{D_M^2}{4} (\text{REDUNP} + 1) \qquad (3.12)$$

Connecting Tube Fluid Weight:

$$W_{LF} = \overline{\rho}_e \times \text{XLL} \times \pi \times \frac{D_L^2}{4} (\text{REDUNP} + 1) \qquad (3.13)$$

where:

W_T = weight of tubes per panel - lb_m

W_M = weight of manifolds per panel - lb_m

W_L = weight of connecting lines - lb_m

W_{TF} = weight of fluid in tubes - lb_m

W_{MF} = weight of fluid in manifolds - lb_m

W_{LF} = weight of fluid in connecting lines - lb_m

N = number of tubes of panel

NMANT = number of manifolds per panel

ρ_M = density of metal - lb_m/ft^3

$\overline{\rho}_e$ = effective fluid density - lb_m/ft^3

L = length of tubes - ft

Y = width of panel - ft

XLL = connecting line length upstream of panel - ft

t_T = tube thickness - ft

t_M = manifold thickness - ft

t_L = connecting line thickness - ft

D_T = tube inside diameter - ft

D_M = manifold inside diameter - ft

D_L = connecting line inside diameter - ft

REDUNP = number of redundant fluid systems

Radiating Fin Weight: (See Figure 3-3)

$$W_{fin} = \rho_m \times X \times Z \times Y \tag{3.14}$$

W_{fin} = weight of radiating fin - lb_m

ρ_m = density of metal - lb_m/ft^3

X = length of fin - ft

Z = fin thickness - ft

Y = width of fin - ft, $[Y \text{ panel} - N(D + 2\, t_t)]$

Control Valve Weight:

$$W_V = NVT \times WPV \times (REDUNP + 1) \tag{3.15}$$

where:

W_V = weight of valves per panel - lb_m

NVT = number of valves per panel

WPV = weight per valve - lb_m

REDUNP = number of redundant fluid systems

Regenerator Weight:

$$W_R = Q_R \times WPR \tag{3.16}$$

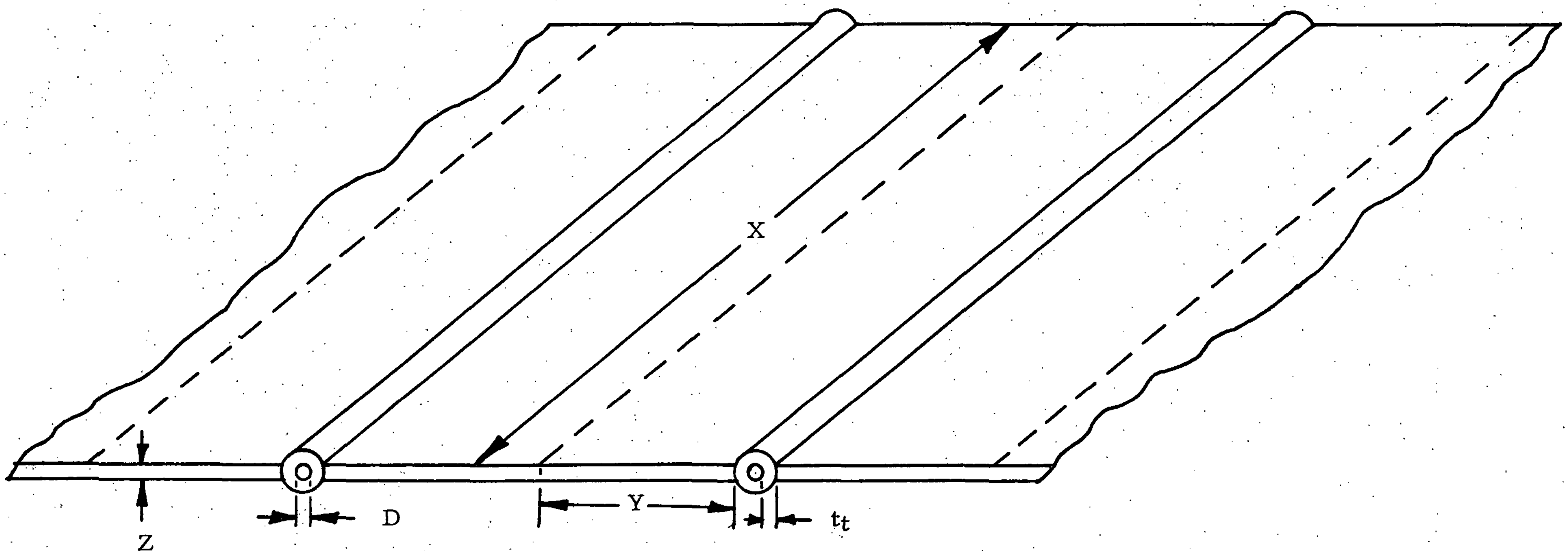


FIGURE 3-3 RADIATOR PANEL GEOMETRY DEFINITION

where:

W_R = regenerator weight - lb_m

Q_R = heat transfer across regenerator - BTU/hr

WPR = regenerator weight penalty constant - lb_m/(BTU/hr)

<u>Radiator Structural Support Weight</u>:

$$W_S = WPS1 + WPS2 \times A + WPS3 \times A^2 \tag{3.17}$$

where:

W_S = structural weight - lb_m

A = panel area - ft^2

WPS1, WPS2, WPS3 - structural weight penalty constants

<u>Pump Power Weight Penalty</u>:

$$W_P = WPPP \times \Delta P \times W_{tot} / \overline{\rho}_e \times 144 \tag{3.18}$$

where:

W_p = pump power weight - lb_m

ΔP = pressure drop - psi

W_{tot} = total coolant weight flow - lb_m/hr

WPPP = pump power weight penalty - lb_m/(ft-lb_f/hr)

$\overline{\rho}_e$ = effective coolant density - lb_m/ft^3

<u>Excess Heat Rejection Weight Penalty</u>:

$$W_{eh} = WPEH \times Time \times (Q_{max} - Q_{rej}) \tag{3.19}$$

where:

W_{eh} = excess heat rejection weight - lb_m

WPEH = weight penalty - lb_m/(BTU/hr) - days

Time = mission duration - days

Q_{max} = required heat rejection - BTU/hr

Q_{rej} = actual heat rejection - BTU/hr

3.3 ROUTINE OPERATION

The calculation procedures and the overall operational flow of the Steady State Design Routine are presented in this portion of the report.

The SSDR can be conveniently partitioned into ten major sections which are functionally independent. These major sections are defined as: (1) input, (2) initialization calculations, (3) panel geometry estimate, (4) system area estimate, (5) low heat load feasibility determination, (6) maximum heat load performance and area determination, (7) weight calculations, (8) system low load performance calculations, (9) optimum design and off design parameter storage, and (10) output. The SSDR program operational flow chart, showing the relationship between the major sections, is presented in Figure 3-4. The calculation procedures and operations of each major program section shown in Figure 3-4 are summarized below.

(100)* <u>Input</u> - Reads the data input from cards, checks for input errors, and writes diagnostic messages for any errors. The data card input required is described in Section 3.4.4, and a resume of input errors (fatal and non-fatal) is presented in Section 3.4.5.

(200) <u>Initialization Calculations</u> - Limits for the parameters varied during radiator system optimization are set, sink temperatures and average environments are calculated, and the input units are converted to the FPH system. The fluid properties curve coefficients are called from the properties library or from the input data. The flow rate at maximum heat load and the system inlet temperature at minimum heat load are calculated. The limits of radiator panel fluid temperature and flow rate at minimum heat load are also set for each of the various control methods.

(300) <u>Panel Geometry Estimate</u> - The tube diameter, number of tubes, and the number of panel flow paths are estimated for each panel type for use in the system are estimate. The average of the parameter limits is used to determine the diameter and the number of tubes. If either or both of these variables has been specified in the input, the specified input value is used. The number of flow paths is set equal to the number of tubes (parallel flow). The pressure drop is calculated using the chosen geometry and the total radiator area available. If the panel pressure drop design requirement is exceeded, the number of tubes and/or the tube diameter is increased until the pressure drop requirement is satisfied.

(400) <u>System Area Estimate</u> - The radiator system area is estimated for use in determining the feasibility of the various low heat load control methods. The above panel geometry, the average thermal environment, an average radiator panel fin effectiveness, the fluid to tube heat transfer, and the limits of panel fin thickness are used to iteratively calculate the radiator panel area.

---

* Numbers refer to the statement numbers in the Program and on Figure 3-4.

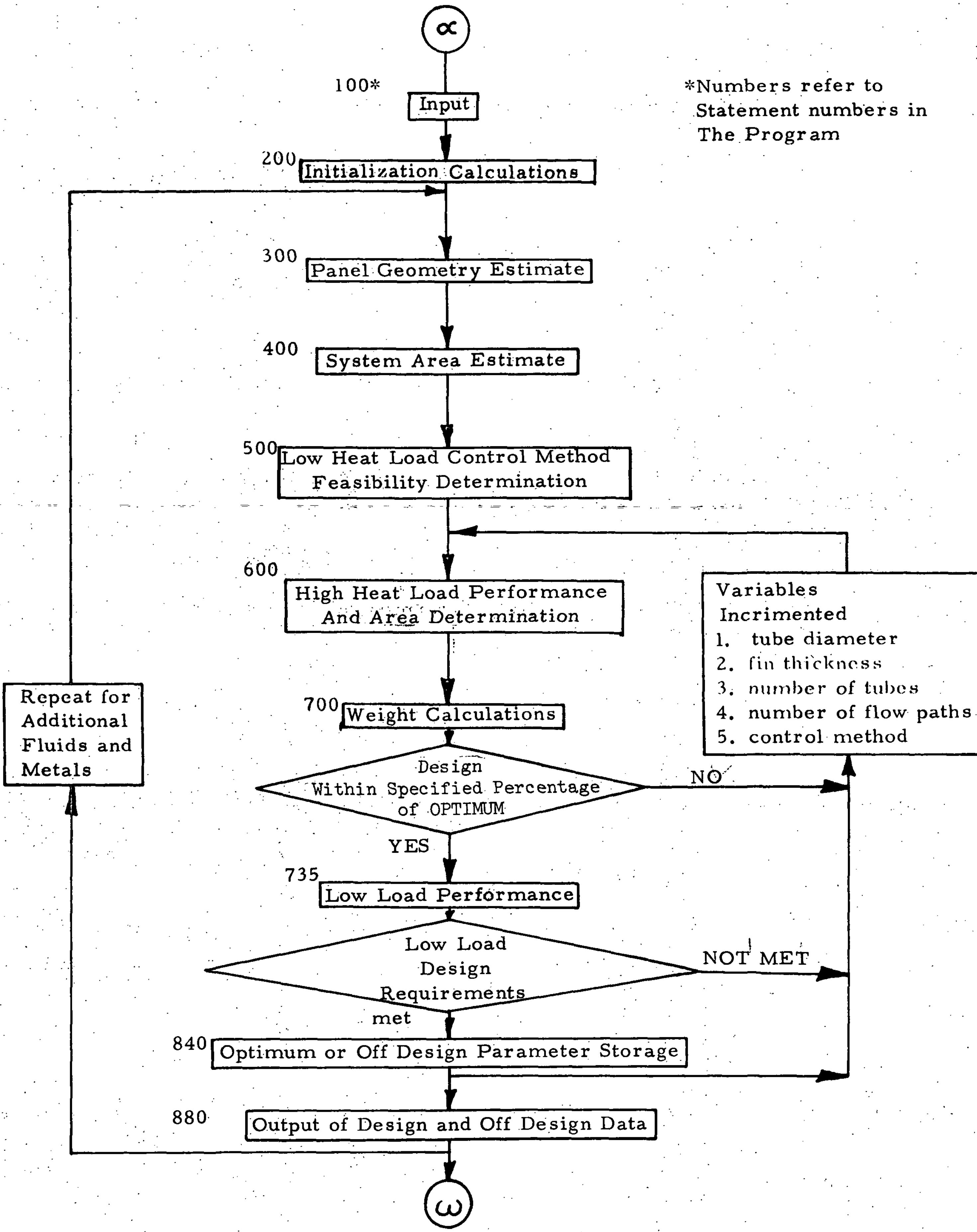


FIGURE 3-4 SSDR PROGRAM FLOW CHART

(500) <u>Low Heat Load Control Method Feasibility Determination</u> - The feasibility of each of the eleven low heat load control methods is determined using the estimated system area - geometry, the control method temperature and flow limits, and the minimum thermal environment. The radiator system performance must meet the minimum heat load requirement and pressure drop requirement if the control method is to be considered feasible and is to be used during the weight optimization procedures that follow. Unless specified by input, the combination control methods (i.e. bypass - regenerative) will not be considered if the less complex control methods are feasible (see Table 3-2).

The subsequent sections of the program begin the radiator system optimization process. As shown in the flow chart of Figure 3-4, the weight optimization is accomplished by: calculating the required radiator area and performance at maximum heat load for a given set of geometry parameters and heat load control method (600); determining the system weight (700); and, if the system is optimum or within the specified percentage of the previous optimum, calculating the minimum heat load performance (735). If the system then meets all the performance requirements, the design is stored within the program for later printout (840). The optimization process above is performed parametrically by systematically varying the panel geometry parameters of tube diameter, fin thickness, number of tubes (tube spacing), and the number of flow paths. Details of these five program sections are described below.

(600) <u>High Heat Load Performance and Area Determination</u> - The radiator area required to reject the design maximum heat load is calculated (in this section) by iterating on the area and heat balance between the fluid, tube, and panel until the required heat rejection and temperature performance is obtained. If the pressure drop limitation is not met in the performance calculations, the parameter variables are incremented and the procedures are repeated again. For the conditions where the required heat rejection cannot be met due to area limitations, the excess heat not rejected by the system is assumed to be rejected by a water boiler/sublimator.

(700) <u>Weight Calculations</u> - The system weight due to the radiator panel fins, tubes, fluid, manifold, interconnecting tubing, control valves, supporting structure, pump power weight penalty, and excess heat weight penalty is calculated using the equations of Section 3.2.4.

The ratio of heat rejection to weight is calculated. If this ratio is greater than the optimum or within a specified percentage of the optimum (off design condition), the program proceeds with the low heat load performance calculations. If the ratio is not within the specified percentage of the optimum, the parameter variables are incremented and the routine returns to the high heat load section for additional calculations.

(735) <u>Low Load Performance</u> - The minimum heat load radiator performance is determined by iterating on radiator panel fluid temperatures or panel flow rate (depending on the heat load control method) until the heat

balance between the fluid, tube, and radiating panel is obtained. The calculated performance must meet the design heat rejection requirement, within the minimum fluid temperature limitation, and must also meet the panel pressure drop requirements if the radiator system is to be considered an optimum or an "off" design system. If these requirements are not met, the parameter variables are incremented and the routine returns to the high heat load calculations.

For the routine option which calculates the minimum heat load possible by the system, the program iterates on fluid temperature or flow rate, and heat load until the heat balances are obtained. The pressure drop requirement at the minimum heat load is not considered for the minimum heat load determination option.

(840) Optimum or Off Design Parameter Storage - After the optimum or off design radiator system has been configured and has met the low heat load performance requirements, the area requirements, geometry parameters (fin thickness, tube diameter, etc.), and maximum and minimum heat load performance predictions are stored in data arrays (for each control method and panel type) for later output. If a new optimum system is calculated during the systematic parameter variation, the old optimum and each of the off design systems are checked to make sure that they are within the specified percentage of the new system heat to weight ratio. If they are not, the old designs are purged from the off design storage arrays. Up to fifty off designs can be stored in the routine.

(880) Output of Design and Off Design Data - The output of the optimum radiator system and the off design systems for each control method is accomplished in this part of the routine.

3.4 USER'S MANUAL

The Steady State Design Routine (SSDR) was written in FORTRAN V for use on the NASA-MSC Univac 1108 computer. A description of the Univac 1108 computer requirements, an explanation of the input data required, and a SSDR run failure analysis are presented in the sections that follow.

3.4.1 Univac 1108 Subroutine Requirements

The following is a list of the Univac 1108, FORTRAN V, system subroutines which are required for use with the SSDR:

1.	NERR$	13.	DEPTH
2.	NEXP6$	14.	NFMT$
3.	NXPAF$	15.	NIER$
4.	NXPAX$	16.	NTNPT$
*5.	EXP	*17.	FLOATX
*6.	ALOG	18.	NEXP$X
7.	NOUT$	19.	CONVTX
8.	NTAB$	20.	NININ$
9.	NFTV$	*21.	SQRT
10.	NIOIN$	*22.	TANH
11.	NOTIN$	23.	NSTOP$
12.	FPACK$		

* These five subroutines are necessary regardless of the system on which the program is run.

3.4.2 MSC Run Submission Requirements

For operation on the MSC Univac 1108 system (FORTRAN V), the SSDR program is stored on magnetic tape and the data deck with the appropriate monitor controls are submitted on punched cards. The order of punched card data deck and control card set up is as follows:

```
$ JOB

7
8 - ASG - A = XXXXX (Program Tape Number)

7
8 - XQT - CUR

--TRW-A

--IN-A

--TRI-A

7
8 - XQT - DECK 1

    DATA CARDS (See Section 3.4.4)

7
8 - EOF
```

"A" is the tape on which the SSDR program is stored and is always an input tape. (The number of the "A" tape should be punched immediately following the equal sign without skipping any spaces.)

The data deck and control card set up must be accompanied by a MSC Form 588 run request card. The input tape number and the problem run time required are designated on this run request card.

3.4.3 Run Time and Output Estimation

The run time for the SSDR may be estimated for the Univac 1108 by using the following equation:

$$\text{RTIME} = 0.6 \times \text{NFLUID} \times \text{NMETAL} \times \left[\frac{\text{DMAX-DMIN}}{\text{DD}}\right] \times \left[\frac{\text{ZMAX-ZMIN}}{\text{DZ}}\right] \times \frac{1}{\text{STMIN}}$$

where:

RTIME - computer run time, minutes

NFLUID = number of fluids considered

NMETAL = number of metals considered

DMAX = maximum tube diameter considered, in

DMIN = minimum tube diameter considered, in

DD = diameter increment, in

ZMAX = maximum panel thickness considered, in

ZMIN = minimum panel thickness considered, in

DZ = panel thickness increment, in

STMIN = minimum tube spacing, in

For the cases using the maximum and minimum values for tube diameter, panel thickness, and tube space stored within the SSDR, the run time may be estimated from:

RTIME = 10.0 x NFLUID x NMETAL

The expressions for run time estimation are approximations since the amount of time spent during convergence for high heat load panel optimization and on low heat load performance calculation may vary considerably from design to design.

The printed output from the SSDR may be estimated by

NPAGES = 7 x NCON x NFLUID x NMETAL x NPT + 3

where:

NPAGES = number of pages of printed output

NCON = number of low heat load control methods to be considered

NFLUID = number of fluids to be considered

NMETAL = number of metals to be considered

NPT = number of panel types to be considered

The number of pages of printed output may be somewhat less than estimated from the above equation depending on how many designs are within the specified percentage of the weight of the optimum design.

3.4.4 SSDR Data Card Preparation

An explanation of the input data required by the SSDR is presented in this section of the report. The flow chart of Figure 3-5, showing the data card order and requirements, is intended to supplement the input description of the following paragraphs.

Floating point data input is designated by the format specification "F". The decimal point for this data may be written in any column of the field and its position will override the indicated position in the format specification. Interger data input, as designated by the Format "I", must be right adjusted within the specified field.

Columns	Format	Fortran Nomenclature	Description
Card 1 (Title Card)			
1-75	15A5	TITLE	Any 75 alphameric characters to be used for page heading.
Card 2			
1-10	F10.0	QMAX	Design maximum heat load, BTU/hr. QMAX $>$ 0 for radiator systems. QMAX $<$ 0 for solar absorber systems.
11-20	F10.0	QMIN	Design minimum heat load, BTU/hr. If blank, program will calculate the minimum heat load possible. QMIN $>$ 0 for radiator systems. QMIN $<$ 0 for solar absorber systems.
21-30	F10.0	TINF	Radiator system inlet temperature at design maximum heat load, °F.
31-40	F10.0	TMIXF	Radiator system mixed outlet temperature, °F.
41-50	F10.0	DPMAX	Maximum allowable radiator system pressure drop, PSI. If blank, the system pressure drop constraint is not considered.
51-60	F10.0	TIME	Mission duration, days. Used in tube thickness Equation (3.1) and excess heat Equation (3.12).
61-70	F10.0	RET	Reynolds number at which flow becomes turbulent (pressure drop equations). If blank, program sets RET = 4000.

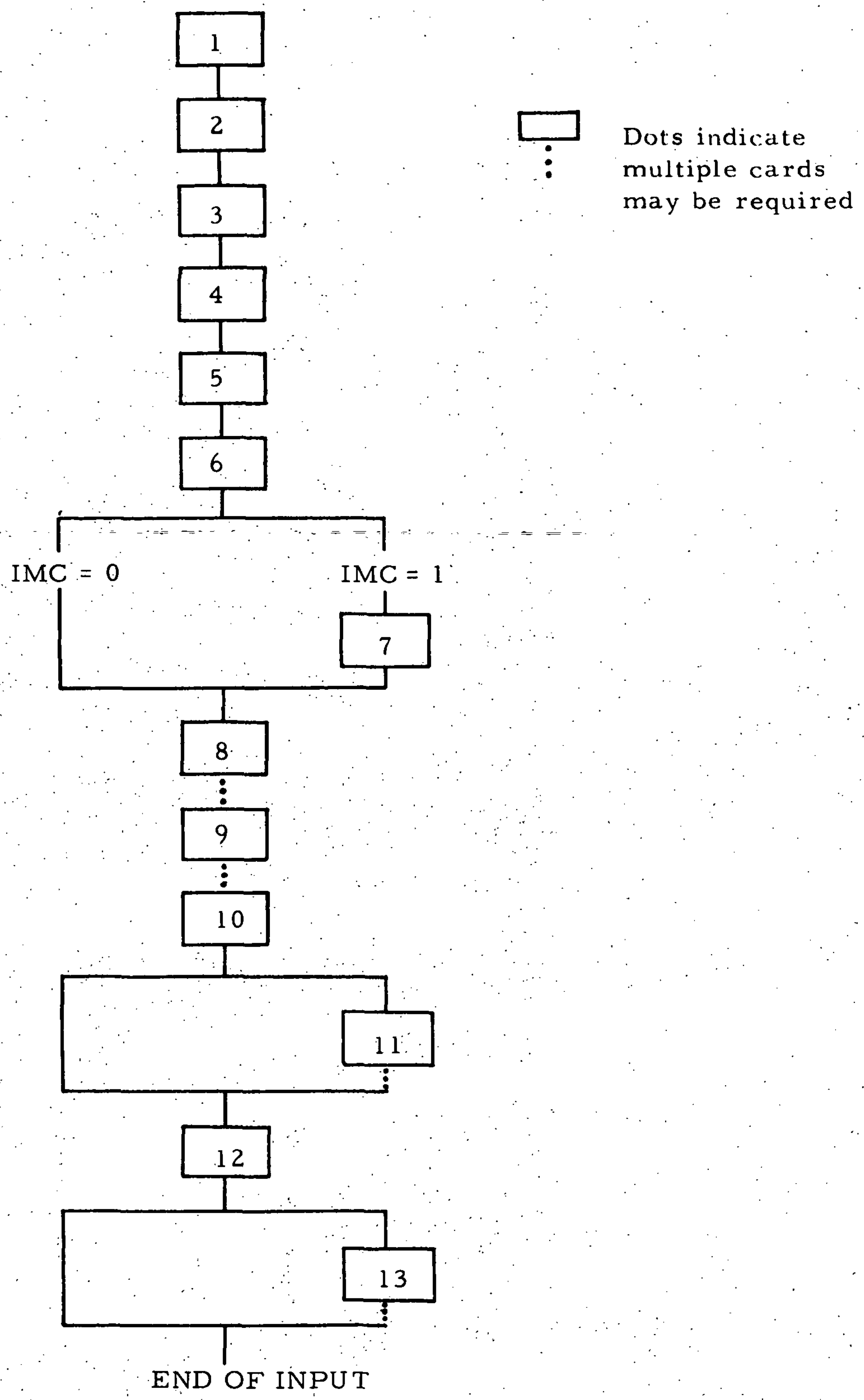


FIGURE 3-5. INPUT DATA CARD REQUIREMENTS

Columns	Format	Fortran Nomenclature	Description
71-80	F10.0	REL	Reynolds number at which flow goes from the laminar to the transition region (pressure drop equations). If blank, program set REL = 2000.

Card 3 (Constants, Weight Penalty Equations)

Columns	Format	Fortran Nomenclature	Description
1-10	F10.0	WPPP	Constant, pumping power weight penalty Equation (3.11), $lb_m/(ft\text{-}lb_f/hr)$ If WPPP $\angle$ 0, the program sets WPPP = 0.005.
11-20	F10.0	WPR	Constant, regenerator weight penalty Equation (3.9), lb_m/BTU/hr). If WPR $\angle$ 0, the program sets WPR = 0.002.
21-30	F10.0	WPT1	Constants, tube thickness Equation (3.1).
31-40	F10.0	WPT2	If WPT1 $\angle$ 0, the program sets WPT1 = 9.16×10^{-5}, and WPT2 = 0.351.
41-50	F10.0	TTMIN	Minimum tube thickness to be considered, inches. Overrides value from the tube thickness equation if less than TTMIN. If TTMIN $\angle$ 0, the program assumes TTMIN = 0.035.
51-60	F10.0	WPEH	Constant, excess heat rejection weight penalty Equation (3.12), lb_m/(BTU/hr)/Day. If WPEH $\angle$ 0, the program assumes WPEH = 0.008. If WPEH = 0, the program assumes WPEH = ∞ .
61-70	F10.0	WPV	Constant, valve weight penalty Equation (3.8), lb_m/ valve. If WPV $\angle$ 0, the program sets WPV = 1.0.
71-80	F10.0	REDUNP	Number of redundant fluid systems.

Columns	Format	Fortran Nomenclature	Description
Card 4 (Constants, Weight Penalty Equations)			
1-10	F10.0	TOLOD	Weight percent from optimum considered program printout off designs. If TOLOD $\angle$ 0, the program sets TOLOD = 10.
11-20	F10.0	WPS1 (1)	Constants, structural weight penalty Equation (3.8), panels of type 1.
21-30	F10.0	WPS2 (1)	If WPS1 (1) $\angle$ 0, the program sets WPS1 (1) = 2.0,
31-40	F10.0	WPS3 (1)	WPS2 (1) = 0.2, WPS3 (1) = 0.
41-50	F10.0	WPS1 (2)	Constants, structural weight penalty Equation (3.10), panels of
51-60	F10.0	WPS2 (2)	type 2. If WPS1 (2) $\angle$ 0, the program sets
61-70	F10.0	WPS3 (2)	WPS1 (2) = 2.0, WPS2(2) = 0.2, WPS3 (2) = 0.
Card 5			
1-10	F10.0	DMINI	Minimum tube diameter to be considered, inches. If DMINI $\leq$ 0, the program will set DMINI = 0.125.
11-20	F10.0	DMAXI	Maximum tube diameter to be considered, inches. If DMAXI $\leq$ 0., the program sets DMAXI = 1.0.
21-30	F10.0	DD	Tube diameter increment, inches. If DD $\leq$ 0, the program sets DD = 0.125.
31-40	F10.0	STMIN	Minimum tube spacing to be considered, inches. If STMIN $\leq$ 0, the program sets STMIN = 4.0 .
41-50	F10.0	STMAX	Maximum tube spacing to be considered, inches If STMAX $\leq$ 0, the program sets STMAX =36.0 .

Columns	Format	Fortran Nomenclature	Description
51-60	F10.0	ZMINI	Minimum fin thickness to be considered, inches If ZMINI ≤ 0, the program sets ZMINI = 0.010.
61-70	F10.0	ZMAXI	Maximum fin thickness to be considered, inches. If ZMAXI ≤ 0, the program sets ZMAXI = 0.10.
71-80	F10.0	DZ	Fin thickness increment, inches. If DZ ≤ 0, the program sets DZ = 0.01.
Card 6			
1-5	I5	NP	Radiator panel system index. NP = 1, radiator panels are in series. NP = 2, radiator panels are in parallel.
6-10	I5	NST (1)	Number of panels of type 1. If NP = 2, the program sets NST (1) = 2.
11-15	I5	NST (2)	Number of panels of type 2. If NP = 2, the program sets NST (2) = 0.
16-20	I5	IPUMP	Pump power penalty index. IPUMP = 0, penalty calculated at maximum heat load IPUMP = 1, penalty calculated a low heat load IPUMP = 2, penalty calculated at average heat load
21-25	I5	IPRID	Prime tube diameter index. IPRID > 0, prime tube diameter is calculated IPRID ≤ 0, all tubes are of same diameter
26-30	I5	NFLUID	Number of radiator coolant fluids to be considered. Maximum limit is NFLUID = 10.
31-35	I5	NMETAL	Number of radiator metals to be considered. Maximum limit is NMETAL = 10.
36-40	I5	IMC	= 0, all heat load control methods are to be considered. = 1, heat load control methods are specified on Card 7.

Columns	Format	Fortran Nomenclature	Description
Card 7 (Heat Load Control Method Specification)(Omit this card for IMC = 0)			
		ICON (i)	Control Index = 0, do not consider = 1, consider
1-5	I5	ICON (1)	Bypass control index
6-10	I5	ICON (2)	Regenerative control index
11-15	I5	ICON (3)	Bypass-Regenerative control index
16-20	I5	ICON (4)	Stagnation control index, one dimensional tube pattern
21-25	I5	ICON (5)	Stagnation control index, two dimensional tube pattern
26-30	I5	ICON (6)	Bypass-Stagnation control index, one dimensional tube pattern
31-35	I5	ICON (7)	Bypass-Stagnation control index, two dimensional tube pattern
36-40	I5	ICON (8)	Regenerative-Stagnation control index, one dimensional tube pattern
41-45	I5	ICON (9)	Regenerative-Stagnation control index, two dimensional tube pattern
46-50	I5	ICON (10)	Bypass-Regenerative-Stagnation control index, one dimensional tube pattern
51-55	I5	ICON (11)	Bypass-Regenerative-Stagnation control index, two dimensional tube pattern
Card 8 (Panel Type Data Card)			
Panel Type 1			
1-10	F10.0	AMAX (1)	Maximum area available each panel, ft^2
11-20	F10.0	YP (1)	Panel width, ft.
21-30	F10.0	E (1)	Panel thermal emissivity
31-40	F10.0	FT (1)	Panel tube emissive factor. (FT (1) = 1.0 for tube projected area as the effective radiating area.) If blank, program will set FT (1) = 1.0.
41-45	F5.0	DS (1)	Specified tube diameter, inches. If blank, program will optimize tube diameter.

Columns	Format	Fortran Nomenclature	Description
46-50	F5.0	ZS (1)	Specified fin thickness, inches. If blank, program will optimize fin thickness.
51-54	I4	NSURF (1)	Number of panel surfaces radiating.
55-58	I4	NTS (1)	Specified number of tubes. If blank, program will optimize the number of tubes.
59-60	I2	NFPS (1)	Specified number of parallel flow paths on the panel. = 0, program will optimize the number of flow paths = -1, program will consider all tubes connected in parallel. = 1, program will only consider serpentine panel flow = 1, -1, 0, NFPS (1) should divide into NTS (1) evenly.
61-65	F5.0	DLL (1)	Diameter of panel fluid connecting lines, inches.
66-70	F5.0	DMAN (1)	Manifold diameter of cylindrical manifold, inches
71-75	F5.0	TMAN (1)	Manifold material thickness, inches.
76-80	F5.0	ZMINS (1)	Fin thickness not attributable to radiator panel. (No weight penalty for radiator system), inches.

Repeat Card 8 for panel type 2. (NST (2), Card 6, must be positive.)

Card 9 (Panel Data Card)

Panel 1

1-4			Blank
5-10	A6	PANEL (1)	Panel name, any six alphameric characters
11-20	F10.0	QAMAX (1)	Heat absorbed by panel from environment at maximum heat load, BTU/hr-ft.^{2}
21-30	F10.0	QAMIN (1)	Heat absorbed by panel from environment at minimum heat load, BTU/hr-ft^2.

Columns	Format	Fortran Nomenclature	Description
31-40	F10.0	FP (1)	Panel emissive factor. If FP (1) is blank, program sets FP (1) = 1.0.
41-50	F10.0	XLL (1)	Fluid connecting line length upstream of the panel, feet. The first panel line length should include the return length (down stream) from the last panel.
51-55	I5	NMAN (1)	Number of manifolds on this panel.
56-60	I5	NV (1)	Number of valves on this panel.

Repeat Card 9 for each panel. Total number of cards needed = NST (1) + NST (2).

Card 10 (Fluid Data Card)

Columns	Format	Fortran Nomenclature	Description
1-10	I10	IFLUID (1)	Index of fluid number 1. (See Table 3-4 for list of index numbers.)
11-20	F10.0	TMINF (1)	Fluid 1, minimum* allowable temperature, °F.
21-30	I10	IFLUID (2)	Index of fluid 2.
31-40	F10.0	TMINF (2)	Fluid 2 minimum* allowable temperature, °F.
41-50	I10	IFLUID (3)	Index of fluid 3.
51-60	F10.0	TMINF (3)	Fluid 3 minimum* allowable temperature, °F.
61-70	I10	IFLUID (4)	Index of fluid 4.
71-80	F10.0	TMINF (4)	Fluid 4 minimum* allowable temperature, °F.

Repeat Card 10 as many times as needed to supply IFLUID and TMINF for each fluid.

* For solar absorbers, this is the maximum allowable fluid temperature, °F.

TABLE 3-4

INDEX NUMBERS FOR THE SSDR
FLUIDS AND METALS

FLUID INDEX	FLUID NAME	PROGRAM NOMENCLATURE	POUR POINT* TEMP. °F
1	RS89-A	RS89-A	-65.
2	MSC-198	MSD198	-140.
3	60/40 Propylene Glycol	PRO-GL	-76.
4	Freon 21	F-21	-211.
5	FC-43	FC-43	-58.
6	FC-75	FC-75	-135.
7	Freon E-3	E-3	-160.
8	Water	WATER	32.
9	80/20 Methanol-Water	ME-H20	-65.

METAL INDEX	METAL NAME	PROGRAM NOMENCLATURE
1	Aluminum, 75S-T6	75S-T6
2	Magnesium, AN-M-29	AN-M29
3	Berrylium	BE
4	Stainless Steel, SS301	SS-301
5	Aluminum, 6061 T6	6061T6

Columns	Format	Fortran Nomenclature	Description

Cards 11 A, B, C, and D (Fluid Properties Data)

Cards 11A, 11B, 11C, and 11D are needed only for those fluids whose properties are not included in the program. Cards 11A, B, C, and D are needed for each IFLUID = 0 on Card 10.

Card 11A

Columns	Format	Fortran Nomenclature	Description
1-6	A6	FLUID (I)	Fluid name, any six alphameric characters.

Card 11B

Columns	Format	Fortran Nomenclature	Description
1-10	F10.0	KFO	Curve coefficients for the fluid thermal conductivity Equation (3.2).
11-20	F10.0	KF1	
21-30	F10.0	KF2	
31-40	F10.0	KF3	
41-50	F10.0	DFO	Curve coefficients for the fluid density Equation (3.3).
51-60	F10.0	DF1	
61-70	F10.0	DF2	
71-80	F10.0	DF3	

Card 11C

Columns	Format	Fortran Nomenclature	Description
1-10	F10.0	CPO	Curve coefficients for the fluid specific heat Equation (3.4).
11-20	F10.0	CP1	
21-30	F10.0	CP2	
31-40	F10.0	CP3	
41-50	F10.0	CP4	
51-60	F10.0	MUO	Curve coefficients for the fluid dynamic viscosity Equation (3.5).
61-70	F10.0	MU1	
71-80	F10.0	MU2	

Columns	Format	Fortran Nomenclature	Description
Card 11D			
1-10	F10.0	MU3	Curve coefficients for dynamic viscosity Equation (3.5). (continued)
11-20	F10.0	MU4	
21-30	F10.0	MU5	
Card 12 (Metal Data Card)			
1-5	I5	IMETAL (1)	Index of metal number 1, (See Table 3-4 for list of metal index numbers.)
5-10	I5	IMETAL (2)	Index of metal number 2.
11-15	I5	IMETAL (3)	Index of metal number 3.
16-20	I5	IMETAL (4)	Index of metal number 4.
21-25	I5	IMETAL (5)	Index of metal number 5.
26-30	I5	IMETAL (6)	Index of metal number 6.
31-35	I5	IMETAL (7)	Index of metal number 7.
36-40	I5	IMETAL (8)	Index of metal number 8.
41-45	I5	IMETAL (9)	Index of metal number 9.
46-50	I5	IMETAL (10)	Index of metal number 10.

Cards 13A and B (Metal Properties Data)

Cards 13A and 13B are needed only for those metals whose properties are not included in the program. Cards 13A and 13B are needed for each IMETAL =) on Card 12.

Columns	Format	Fortran Nomenclature	Description
Card 13A			
1-6	A6	METAL (I)	Metal name, any six alphameric characters.
Card 13B			
1-10	F10.0	KMO	Curve coefficients for the metal thermal conductivity Equation (3.6).
11-20	F10.0	KM1	
21-30	F10.0	KM2	
31-40	F10.0	KM3	
41-50	F10.0	DMO	Curve coefficients for the metal density Equation (3.7).
51-60	F10.0	DM1	
61-70	F10.0	DM2	
71-80	F10.0	DM3	

3.4.5 Run Failure Analysis

A resume of the fatal and nonfatal errors detected during the data card input will be printed by the SSDR. Fatal errors will cause the SSDR to end further data processing while nonfatal errors will cause certain input data to be ignored. The diagnostic message printed by the SSDR for the fatal and/or nonfatal errors will contain the name of the input variable and the card number on which the variable is located.

The fatal errors in the input data that will cause program termination are:

Card 2: QMAX = 0

Card 6: NST(1) > 10
NST(2) > 10
NST(1) + NST(2) > 10
NFLUID > 10
NMETAL > 10

Card 8: AMAX (IT) ≤ 0
YP (IT) ≤ 0
E (IT) ≤ 0

Nonfatal errors possible in the input of data are:

Card 10: IFLUID (I) > 9

Card 12: IMETAL (I) > 5

The data for each nonfatal error will be ignored by the SSDR.

In addition to the input data errors, the routine may fail to design a radiator system due to design constraints imposed by the program user. These constraints consist of pressure drop limitation and radiator area - excess heat weight penalty availability.

If the radiator system cannot be designed at high heat load for the pressure drop limitation imposed (DPMAX, Card 2), the program will print a diagnostic message indicating the minimum pressure drop that can be achieved and then terminate calculations. If the radiator system cannot be designed to meet the pressure drop limitation at low heat load for a particular control method, the program will print a diagnostic message indicating the minimum pressure drop that can be achieved and omit further calculations for the control method.

Under certain conditions the available radiator area for the required high load heat rejection may not be sufficient (AMAX(IT), Card 8) and, therefore, a radiator system cannot be designed without the use of a water sublimator or boiler to reject the excess heat. If this situation occurs, WPEH on Card 3 of the input must be reasonable to assure meaningful system design. The program prints out of the possibility of inadequate radiator area exists.

4.0 TRANSIENT PERFORMANCE ROUTINE

This section contains the purpose, analytical methods employed, and user's instructions for the Transient Performance Routine (TPR).

4.1 PURPOSE

The TPR was developed to provide rapid, easily obtainable evaluation of the thermal response of radiators and solar absorbers designed by the SSDR. The TPR results can be interpreted to provide new inputs to the SSDR to iterate on the initial steady state radiator design. The TPR utilizes a time varying environmental heat flux simulation to determine orbital radiator and solar absorber performance whereas the SSDR utilizes a pair of effective environmental heat fluxes for minimum and maximum design points. The results from TPR can be used to judge the adequacy of the effective environments initially used in SSDR. By using TPR results to adjust these environments for subsequent design iterations with SSDR, an optimum radiator or absorber which satisfies transient response requirements can be evolved.

4.2 ROUTINE DESCRIPTION AND ANALYTICAL METHODS

The TPR utilizes a simplified LVVM25 (Reference 4) data input with a predetermined flow system thermal model suited to analysis of any number of parallel or series flow* radiator panels. The detailed nodal data needed for transient finite difference analyses of either one or two-dimensional radiator panels is generated by coupling the TPR with the Automatic Nodal Subdivision Subroutines (SUBANS and SUBRAD) described in Section 4.3.1. The user may easily generate nodal models of either rectangular or circular radiator panels with varying degrees of fineness to establish the number of nodes required for accurate transient simulation of radiator performance. Any desired combination of rectangular and circular panels can be accommodated by TPR (See Figure 4-1 and 4-2) with the condition that all parallel flow panels be located upstream of any series flow panel.

The predetermined flow system (Figure 4-1) provides for combinations of valves and use of a regenerator to simulate any of the low load control methods described in Table 3-3. The TPR includes automatic output plotting, restart capability, provisions for use of cyclic incident heat curves and use of data tapes and editing. The program computational speed is significantly better than that of the basic general purpose LVVM25 routine. A detailed description of the routine is given below.

4.2.1 Groundrules and Assumptions

The following are the groundrules which were established by LTV as guidelines for the development of the TPR. Several assumptions are inherently contained in the routine because of these groundrules.

(a) Flow paths are written in to correspond to the skeleton flow system (see Figure 4-1) for flow rate and inlet temperature.

* All options apply to solar absorbers as well as radiators.

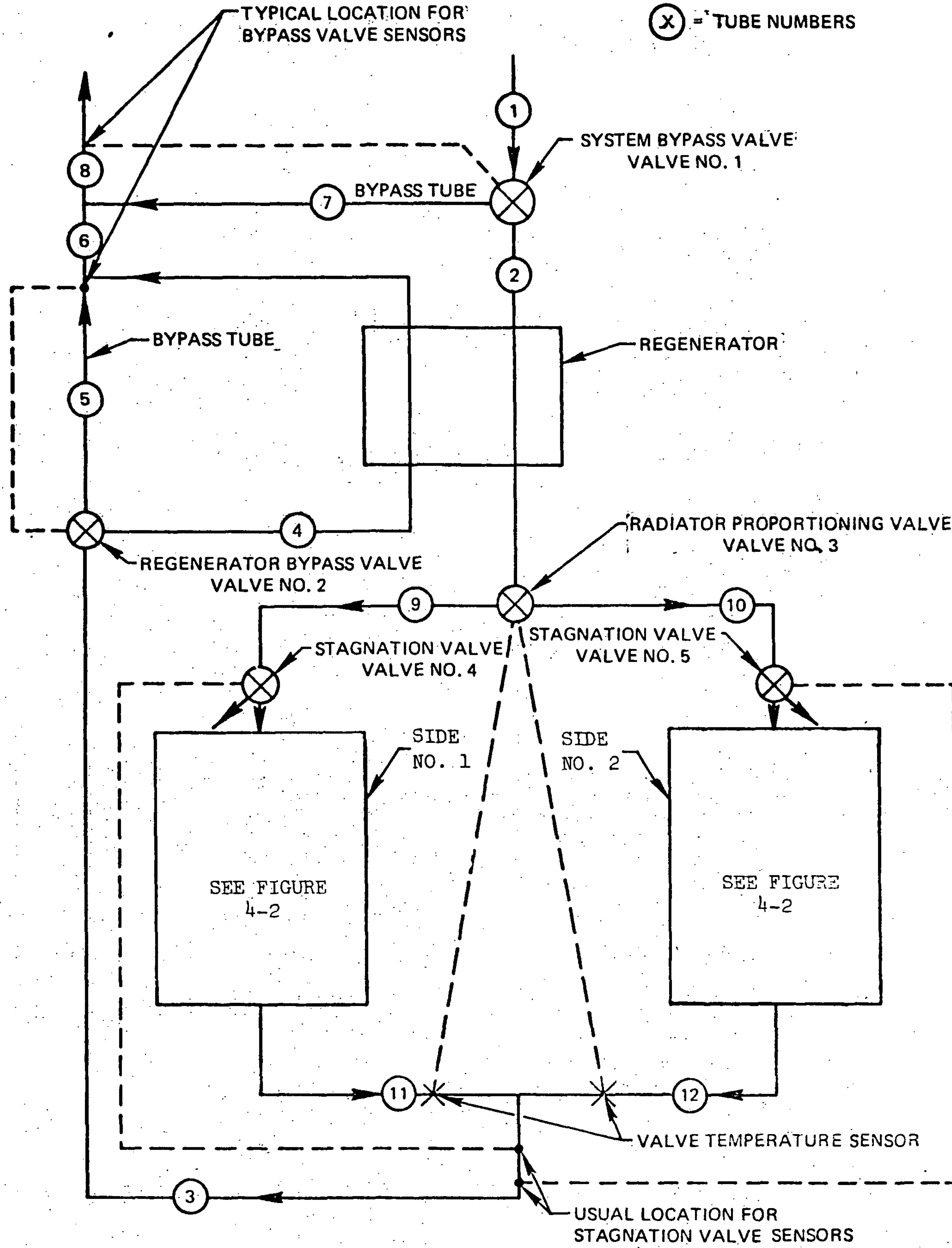


FIGURE 4-1 TRANSIENT PERFORMANCE ROUTINE SYSTEM

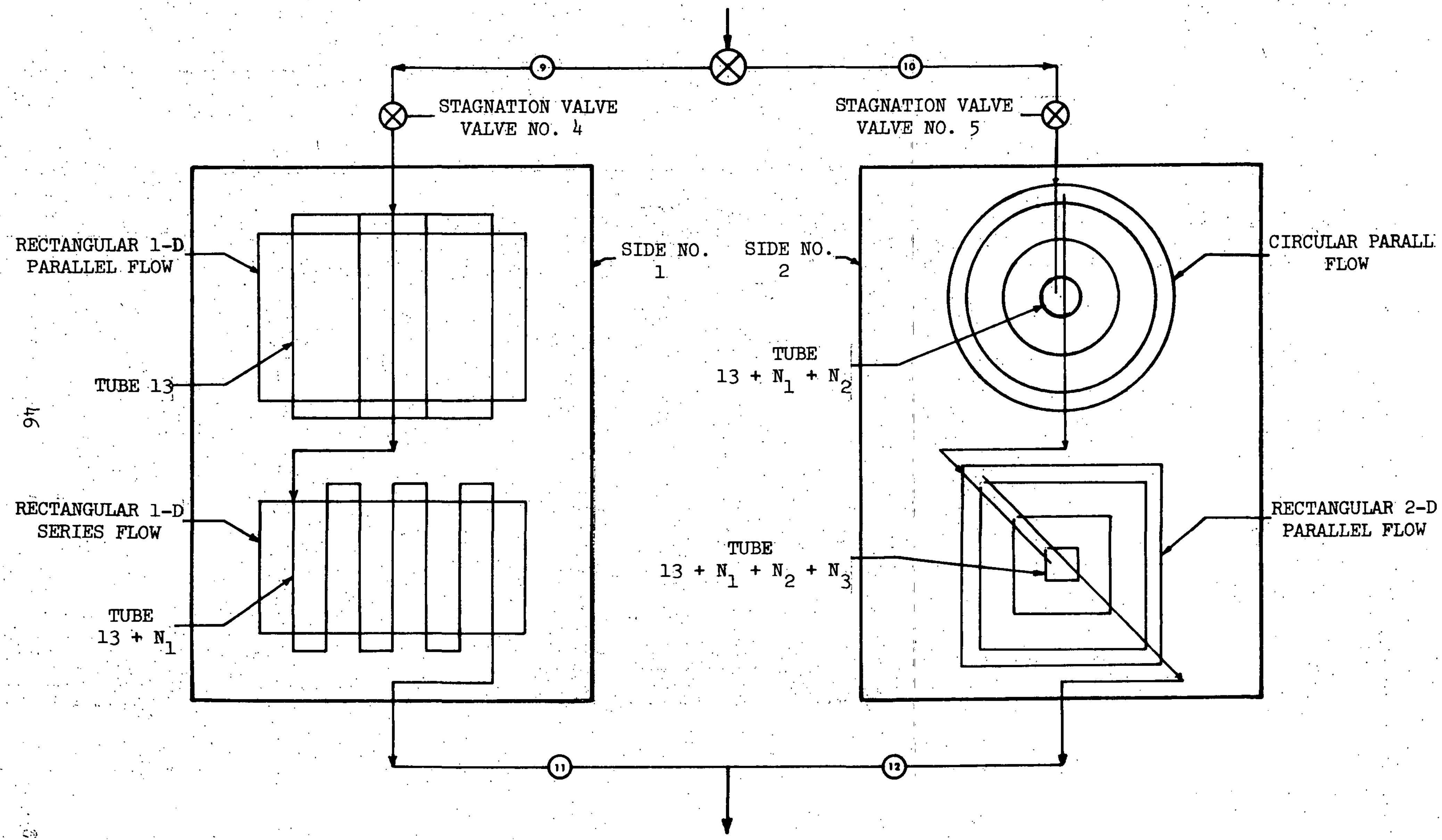


FIGURE 4-2 FLOW SYSTEM OPTIONS

(b) The pressure-flow balance on each radiator panel is performed assuming parallel flow for the panel tubes. (i.e., manifold losses between tubes are neglected). A minimum of 2 tubes must exist on each radiator panel. Also, at least one tube lump and one fluid lump must exist for each tube.

(c) The fluid lump number must be identical to the enclosing tube lump number.

(d) There are 5 valves in the system. The valve locations in the flow paths are written in the routine, but the valve parameters are input. It is up to the user to manipulate the valves (by shutting off, etc.) to obtain the desired flow configurations.

(e) Proportioning valve - Programming was performed to give three options for the proportioning valve: (1) normal flow proportioning, (2) no proportioning, and (3) locked one way for single panel operation.

(f) The regenerator is analyzed by a steady state effectiveness method. The regenerator mass may be approximated by adding 1/4 of the regenerator thermal capacitance into each inlet tube lump and the tube lumps immediately downstream of each added lump.

(g) A baseline thermal model for the flow system plumbing and regenerator is provided so that the user may concentrate on the analysis of the radiator panel design. If details of flow system plumbing and/or regenerator are known, or if the baseline model is not practical for fluids and flow rates under consideration, the user can replace or alter the dimensions or number of nodes in the baseline model.

4.2.2 Temperature and Flow Analysis

Temperature Analysis - Finite difference approximations of the differential equations governing the temperatures for transient conditions are solved using the forward differencing (explicit) method. These equations and the method are described in detail in Reference 4. The assumptions that have been made are:

(1) The fluid and metal thermodynamic properties are constant within any element for a given time increment but may vary between elements.

(2) Cylindrical surfaces are approximated by small rectangular segments.

(3) Radiant interchange is not considered.

A problem with flowing fluid is considered to have three types of finite - difference lumps; i.e., fluid lumps, structure lumps, and tube lumps which interface with the structure and fluid lumps. The governing equations for each type of lump are:

(1) Fluid Lump (The option to use an average of fluid lump inlet and outlet temperature with the hA term which is discussed in Reference 4 is not available in this routine).

$$T_f^{i+1} = T_f^{i} + \frac{\Delta\tau}{w_f C_{pf}} \left[\dot{w} C_{pf} (T_{fu}^{i} - T_f^{i}) + h_f A_f (T_t^{i} - T_f^{i}) \right] \quad \text{(Equation 4-1)}$$

where:

w_f = weight of the fluid in lump f

= $A_c(\rho)(L)$ where ρ is the density, L is the lump length, and A_c is the lump cross sectional area

C_{pf} = specific heat of the fluid in lump f

T_f^i = temperature of the fluid at time τ

T_f^{i+1} = temperature of the fluid at time $\tau + \Delta\tau$

$\Delta\tau$ = time increment for next calculation

$\dot{w}$ = fluid flow rate

T^i_{fu} = temperature of fluid lump directly upstream of lump f in the flow path at time T

h_f = fluid convective heat transfer coefficient

A_f = area for convection heat transfer

T_t^i = temperature of enclosing tube lump at time τ

(2) Tube lump equation

$$T_t^{i+1} = T_t^{i} + \frac{\Delta\tau}{w_t c_t} \left[\sum_j U_{tj}(T_j^{i} - T_t^{i}) + \sum_s U_{ts} (T_s^{i} - T_t^{i}) + \alpha_t A_e Q_t^{i} - \epsilon_t \sigma A_e (T_t^{i})^4 + h_f A_f (T_f^{i} - T_t^{i}) \right] \quad (4\text{-}2)$$

where:

w_t = tube lump weight

c_t = specific heat of the tube

$T_t^{\,i}$ = temperature of the tube lump at time τ

$T_t^{\,i+1}$ = temperature of the tube lump at time $\tau + \Delta\tau$

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

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

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

$T_s^{\,i}$ = temperature of adjacent fin or structure lump s at time τ

$Q_t^{\,i}$ = incident heat on tube lump t at time τ

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

$T_f^{\,i}$ = fluid lump temperature at time τ

(3) Structure lump equation

$$T_s^{\,i+1} = T_s^{\,i} + \frac{\Delta\tau}{w_s c_s}\Big[\sum_t U_{ts}(T_t^{\,i} - T_s^{\,i}) + \sum_j U_{sj}(T_j^{\,i} - T_s^{\,i}) + \alpha_s A_s Q_s^{\,i} - \epsilon_s\, \sigma\, A_s (T_s^{\,i})^4 \Big] \qquad (4\text{-}3)$$

where:

w_s = weight of lump

c_s = specific heat of lump s

$T_s^{\,i}$ = temperature of lump s at time τ

$T_s^{\,i+1}$ = temperature of lump s at time $\tau + \tau$

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

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

K_s is the thermal conductivity of lump s

K_j is the thermal conductivity of lump j

$T_j^{\,i}$ = temperature of adjacent tube lump j at time τ

$Q_s^{\,i}$ = incident heat flux on lump s at time τ

A_s = area of lump s (for radiation)

α_s = absorptivity of lump s for incident heat flux

ϵ_s = emissivity of lump s

U_{ts} = the conductance between structure lump s and adjacent tube lump t

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

The heat transfer coefficient between the fluid and tube is given in Reference 4-1 as:

Laminar Entry Length:

$$h_f = 1.86\ (K_f/D)\left(\frac{Re\ Pr\ D}{L}\right)^{1/3} \left(\frac{\mu b}{\mu w}\right)^{0.14} F_1 \qquad (4\text{-}4)$$

Laminar flow fully developed:

$$h_f = 3.66\ \frac{K_f}{D}\left(\frac{\mu b}{\mu w}\right)^{0.14} F_2 \qquad (4\text{-}5)$$

Turbulent Flow:

$$h_f = .027\ \frac{K_f}{D}\left(\frac{\mu b}{\mu w}\right)^{0.14} (Re)^{0.8}\ (Pr)^{1/3} \qquad (4\text{-}6)$$

where:

h_f = convective heat transfer coefficient

K_f = fluid conductivity

L = length from tube entrance

D = tube hydraulic 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

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

F_2 = developed flow heat transfer coefficient factor

A value of F_1 of 0.575 and F_2 of 1.0 was found to fit the Graetz solution for constant wall temperature as shown in Reference 4-1. These methods of calculating heat transfer coefficients were retained in Transient Performance Routine.

Flow and Pressure Drop Analysis - The pressure drop calculations for the Transient Performance Routine are performed as discussed in Reference 4. That is, the pressure drop for each fluid lump is calculated by:

$$\Delta P = \frac{\dot{w}^2}{2 \rho A_c^2} \left[\frac{f(WP)\ L\ F_3\ (\mu_b/\mu_w)^{-.14}}{A_c} + K \right] \qquad (4\text{-}7)$$

where:

$\dot{w}$ = tube fluid flow rate

ρ = fluid density

A_c = fluid lump cross sectional area

f = friction factor

L = 16/Re for Reynolds numbers less than 2000 and is read from input for Reynolds numbers greater than 2000

WP = wetted perimeter

L = fluid lump length

μ_b = fluid viscosity evaluated at fluid bulk temperature

μ_w = fluid viscosity evaluated at tube wall temperature

F_3 = pressure factor for non-circular ducts; is 1.0 for circular ducts

K = number of fluid dynamic head losses

The pressure drop for each tube is determined by summing the pressure drops of the lumps in the tube.

The system flow rate-pressure drop balance is determined as follows. For each iteration:

(1) The new flow rate entering the system is read from the flow rate versus time curve.

(2) New valve positions are determined (as described in 4.2.3).

(3) New flow rates for tubes 2 through 8 are determined as follows:

$$\dot{w}_2 = X_1\dot{w}_1 \qquad \left\{ \begin{array}{l} X_1 = \text{Flow fractions determined by valve \#1} \\ X_2 = \text{Flow fractions determined by valve \#2} \end{array} \right\}$$

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

$$\dot{w}_4 = X_2\dot{w}_2$$

$$\dot{w}_5 = (1 - X_2)\ \dot{w}_2$$

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

$$\dot{w}_7 = (1 - X_1)\ \dot{w}_1$$

$$\dot{w}_8 = \dot{w}_1$$

(4) The flow rates for $\dot{w}_9$ through $\dot{w}_{13+2n-1}$ (where n is the number of tubes on each radiator) are multiplied by the quantity $\dot{w}_{2_{new}}/\dot{w}_{2_{old}}$.

(5) A check is made to see if either valve 4 or 5 changed position:

(a) If there is a change from stagnation condition to parallel flow condition the flow through each of the parallel flow tubes is $\dot{w}_9/n$ or $\dot{w}_{10}/n$ depending on whether valve 4 or valve 5 changed positions.

(b) If the change was from parallel flow condition to stagnated flow condition $\dot{w}_{13} = \dot{w}_9$ and $\dot{w}_{13+n} = \dot{w}_{10}$.

(6) Pressure drop per lump is calculated by equation 4-7 and the pressure drop for all the lumps in a tube are summed to obtain the pressure drop per tube.

(7) K is calculated for each tube by

$$K = \frac{\Delta P_{tube}}{\dot{w}_{tube}}$$

(8) For each radiator panel in the parallel flow condition (not stagnated) the flow is determined as follows:

(a) Calculate: $\Delta P_{side\ 1} = \dot{w}_9 / \sum_{\substack{i=13, \\ 13+n-1}} 1/K_i$

$$\Delta P_{side\ 2} = \dot{w}_{10} / \sum_{\substack{i=13+n, \\ 13+2n-1}} 1/K_i$$

(b) Calculate the new flow in each parallel path by

$$w_i = \Delta P_{panel}/K_i$$

(9) Add the pressure drop around each of the two parallel flow paths, i.e.,

$$\Delta P_L = \Delta P_9 + \Delta P_{P1} + \Delta P_{11} + \Delta P_{VL}$$

$$\Delta P_R = \Delta P_{10} + \Delta P_{P2} + \Delta P_{12} + \Delta P_{VR}$$

where:

ΔP_L = pressure drop around left path
ΔP_R = pressure drop around right path
ΔP_9 = pressure drop in tube 9
ΔP_{10} = pressure drop in tube 10
ΔP_{11} = pressure drop in tube 11
ΔP_{12} = pressure drop in tube 12
ΔP_{VL} = pressure drop in left side of proportioning valve
ΔP_{RV} = pressure drop in right side of proportioning valve

(10) If there is flow in both sides of the proportioning valve, solve for flow around each of the two parallel paths by (see Proportioning Valve under Section 4.2.3).

$$\dot{w}_9 = \frac{-b + \sqrt{b^2 - 4\ ac}}{2\ a}$$

where:

$$a = E\left[\frac{1}{X_1^2} - \frac{1}{X_2^2}\right]$$

$$b = K_{LT} + K_{RT} + \frac{2\ E\ \dot{w}_2}{X_2^2}$$

$$c = K_{RT}\ \dot{w}_2 - \frac{E(\dot{w}_2)^2}{X_2^2}$$

E = proportionality factor

X_1 = valve position from left

X_2 = valve position from right

$$K_{LT} = \frac{\Delta P_9 + \Delta P_{side\ 1} + \Delta P_{11}}{\dot{w}_9}$$

$$K_{RT} = \frac{\Delta P_{10} + \Delta P_{side\ 2} + \Delta P_{12}}{\dot{w}_{10}}$$

$$\dot{w}_{10} = \dot{w}_2 = \dot{w}_9$$

$$\dot{w}_{11} = \dot{w}_9$$

$$\dot{w}_{12} = \dot{w}_{10}$$

(11) Flow rates $\dot{w}_{13}$ through $\dot{w}_{13+n-1}$ are multiplied by

$$\frac{\dot{w}_{9_{new}}}{\dot{w}_{9_{old}}}$$

Flow rates $\dot{w}_{13+n}$ through $\dot{w}_{13+2n-1}$ are multiplied by

$$\frac{\dot{w}_{10_{new}}}{\dot{w}_{10_{old}}}$$

(If flow rate is through one side only, (10) and (11) are not performed)

(12) Parallel flow paths are checked for pressure drop balance. If all balance within a specified tolerance, DPTOL in data input, calculations are complete.

(13) If pressure drops are not balanced, the flow rate for each tube is averaged with previous flow rate as follows:

$$\dot{w}_1 = a\ \dot{w}_{i_{new}} + (1 - a)\ \dot{w}_{i_{old}}$$

where:

a is an input quantity, usually 0.5,

(14) Steps (6) through (13) are then repeated until a pressure balance is obtained.

4.2.3 Component Description

The basic model of the TPR shown in Figure 4-1 consists of a system bypass valve, a regenerator, a regenerator bypass valve, a proportioning valve, two stagnation valves, two radiator panels and connecting tubing. This section will describe the assumed characteristics of the components which make up the system.

System Stagnation and Regenerator Bypass Valves

For each of the two bypass and two stagnation valves (valves 1, 2, 4, and 5) the user has the option to specify either rate limited valves or polynomial valves.

The rate limited valves are characterized by limiting the rate of opening or closing by the amount shown in Figure 4-3. The set point, deadband, $dX/d\Delta T$ and X_{max} shown on the figure are input values. The rate of opening for the valve is determined each iteration by the difference between the sensor lump temperature and the set point temperature. The amount of valve movement for each iteration is then the rate of opening times the time increment.

The polynomial valve flow distribution at a branch depends on the temperature of a specified lump (sensor lump) in the problem. The fraction bypassed is determined by a fourth order polynomial of valve position versus temperature. The coefficients of the polynomial are input.

Proportioning Valve (Valve 3)

The proportioning valve (Valve 3) is designed to respond in the direction of causing the flow in the two parallel paths to exhaust at the same temperature. This arrangement is utilized to provide maximum heat rejection when two sides of a radiator system operate in a significantly different incident heat environment. The equation describing the operation of the valve is:

$$X = X_{previous} + \frac{\Delta\tau}{\tau c}\left[(X_i - X_{previous}) + \text{valve gain } (T_{RT} - T_{LT})\right]$$

where:

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

$\Delta\tau$ = time increment

τc = valve time constant

X_i = initial valve position

X = present valve position

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

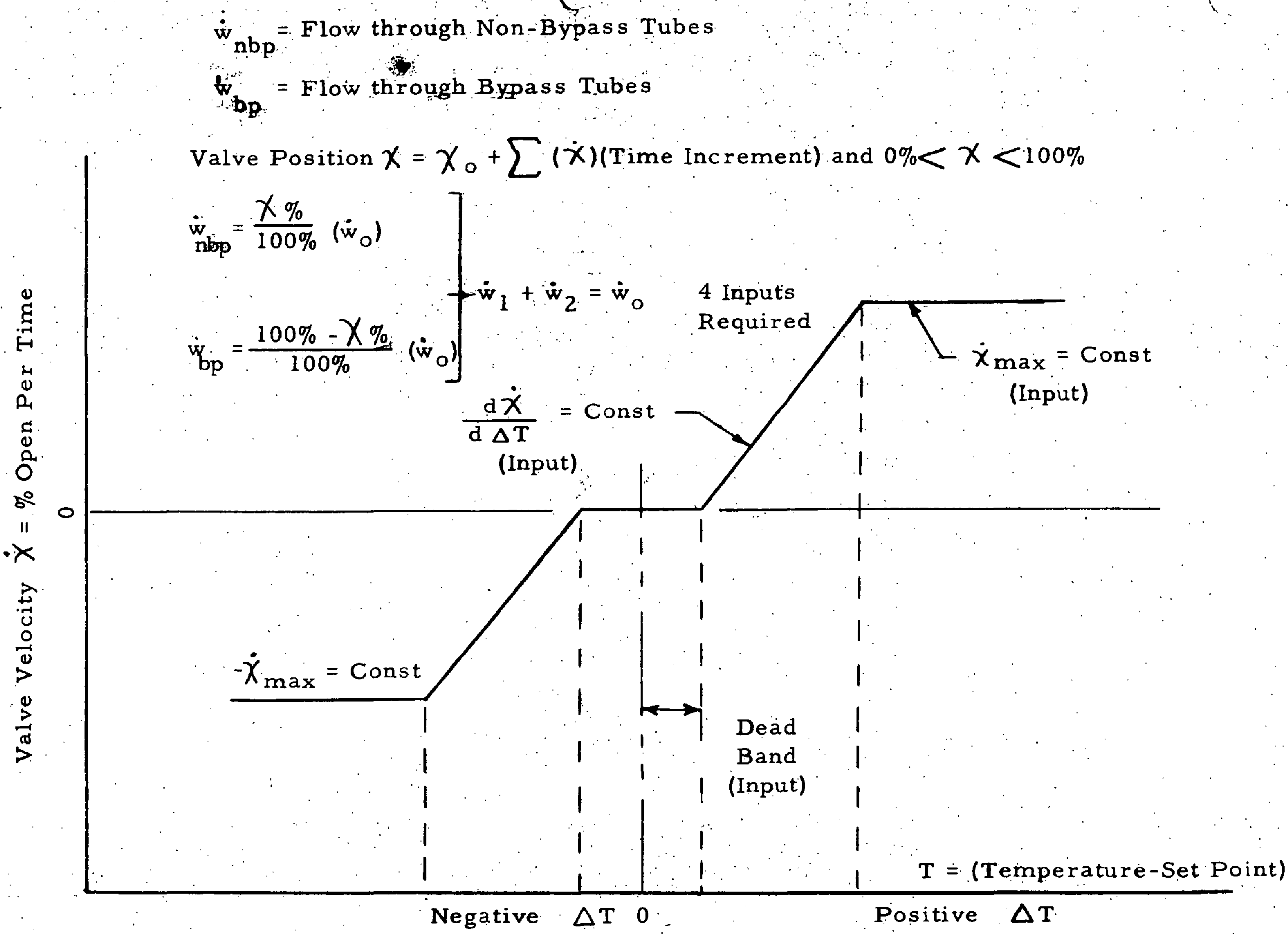


FIGURE 4-3 BYPASS VALVE OPERATION

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

$$\Delta P_{RT} = E\left[\frac{w_{RT}}{X_2}\right]^2$$

$$\Delta P_{LT} = E\left[\frac{w_{LT}}{X_1}\right]^2$$

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

w_{RT}, w_{LT} = right and left flow rates

X_1 = valve position from left

X_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:

$$K_{RT}\dot{w}_{RT} + E\left[\frac{\dot{w}_{RT}}{X_2}\right]^2 = K_{LT}\dot{w}_{LT} + E\left[\frac{\dot{w}_{LT}}{X_1}\right]^2$$

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 $w_{RT} = w_{TOT} - w_{LT}$.

$$E\left[\frac{1}{X_1^2} - \frac{1}{X_2^2}\right](\dot{w}_{LT})^2 + \left[K_{LT} + K_{RT} + \frac{2E\dot{w}_{TOT}}{X_2^2}\right]\dot{w}_{LT} = K_{RT}\dot{w}_{TOT} + \frac{E(\dot{w}_{TOT})^2}{X_2^2}$$

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

$$\dot{w}_{LT} = \frac{-b + \sqrt{b^2 - 4\ a\ c}}{2\ a}$$ (Step 10 of the preceeding flow and pressure balance description)

When X_1 and X_2 are different by less than a specified tolerance (VLVTOL, Card D, Columns 31-40, the value of (a) will be small and the approximation $\dot{w}_{LT} = c/b$ is used.

Regenerator

In the interest of low computer run times the regenerator effectiveness is determined using steady state equations. If tube 4 is assumed to be side 1 and tube 2 is side 2, the effectiveness is given by

$$\epsilon = \frac{1 - e^{-\frac{UA}{(mc)_1}\left[1 - \frac{mc_1}{mc_2}\right]}}{1 - \frac{(mc)_1}{(mc)_2}\, e^{-\frac{UA}{(mc)_1}\left[1 - \frac{(mc)_1}{(mc)_2}\right]}}$$

or when $mc_1 = mc_2$,

$$\epsilon = \frac{\frac{UA}{(mc)_1}}{1 + \frac{UA}{(mc)_1}}$$

where: UA is the overall heat transfer coefficient
$(mc)_1$ is the mass flow times specific heat for side 1
$(mc)_2$ is the mass flow times specific heat for side 2

The outlet temperature on side 1 of the heat exchanger is calculated based on the effectiveness as follows:

$$T_{out_1} = T_{in_1} - \epsilon\,(T_{in_1} - T_{in_2})$$

where:

T_{out_1} = outlet temperature of side 1

T_{in_1} = inlet temperature on side 1

T_{in_2} = inlet temperature on side 2

The outlet temperature on side 2 is determined by

(1) The enthalpy on side 2 is determined by:

$$h_{out_2} = h_{in_2} - \dot{w}_1/\dot{w}_2\,(h_{out_1} - h_{in_1})$$

where:

h_{out_2} = the fluid enthalpy at T_{out_2}

h_{out_1} = the fluid enthalpy at T_{out_1}

h_{in_1} = the fluid enthalpy at T_{in_1}

$\dot{w}_1$ = fluid flow rate on side 1

$\dot{w}_2$ = fluid flow rate on side 2

(2) T_{out_2} is then determined by reverse interpolation of the curves of enthalpy versus temperature for the fluid.

It should be stressed that this method gives the steady state outlet temperatures for the given inlet temperatures, overall heat transfer coefficient, and mc products for sides 1 and 2. However, an approximation of the regenerator transient performance may be obtained by putting 1/4 of the regenerator thermal capacitance into each inlet tube lump and the tube lump immediately downstream of each outlet lump.

Radiator Panels

The parallel flow radiator panels are each assumed to contain a bank of parallel tubes with one tube designated a high flow tube as shown in Figures 4-1 and 4-2. Between the high flow tube and the remaining tubes is a stagnation valve, either rate limited or polynomial, so that the flow is proportioned between the single high flow tube and the remaining tubes by the position of the valve. It is required that there exists at least 2 tubes per parallel flow panel; i.e., one tube on each side of the stagnation valve.

The TPR is setup to handle either radiators in parallel or in series since these are the types of systems which may be generated by the SSDR. Any combination of rectangular 1-D, rectangular 2-D, and circular panels in a parallel or series flow system can be analyzed by the TPR. Both parallel and serpentine flow radiators can be handled with the condition that all parallel flow panels must be located upstream of any series panels. To analyze a series flow system containing any number of parallel and series flow radiators the proportioning valve (Valve No. 3) should be locked by setting the valve of NOP (Parameter Card c of Users Manual) to 1 which will force all the flow to side No. 2 (Figure 4-2). The parallel flow panels should be placed upstream of the series flow panels and two nodes without external radiating area used for side 2.

The radiator panel nodal breakdown may be input by one of two ways.

(1) The user may input the nodal information directly

(2) The user may input overall radiator dimensions and call on the Automatic Nodal Subdivision Subroutines (SUBANS, SUB2D, and SUBRAD described in Section 4.3.1) to perform the nodal breakdown and generate input data automatically.

The user may also call on SUBANS, SUB2D or SUBRAD to perform the nodal breakdown on some panels and manually input the nodal breakdown for other panels. Only one run is required on the TPR to perform the nodal subdivision and the transient performance predictions.

4.3 ROUTINE OPTIONS

4.3.1 Automatic Nodal Subdivision Subroutines (SUBANS, SUB2D, and SUBRAD)

4.3.1.1 Purpose

The creation of data decks for the LTV Thermal Analyzer computer routines usually involves the tedious task of dividing a thermal model into its component nodes, numbering these nodes, specifying their dimensions and neighboring node numbers, loading the resulting values on keypunching sheets, and assembling the decks. The models being analyzed are usually so varied from node to node that no systematic method can be developed by which they may be broken into their components; there are, however, exceptions to this non-uniformity, viz., radiator panel models. Radiators usually involve large areas requiring many nodes to characterize them; but at the same time, their makeup is fairly simple, resulting in many nodes whose physical dimensions are the same, the only real difference being the unique number assigned to each node to distinguish it from the others.

4.3.1.2 Performance

Three subroutines (SUBANS, SUB2D, and SUBRAD) have therefore been written which, when supplied with overall radiator panel dimensions and when given an indication of the coarseness or fineness of the desired nodal breakdown, will provide all information necessary to input the model to the computer routine. SUBANS is capable of subdividing a 2-D rectangular panel, either parallel or serpentine flow, SUB2D handles 2-D rectangular panels and SUBRAD is capable of performing the nodal breakdown of a circular panel with parallel flow. More specifically the subroutines will divide the radiator panels into nodes, assign lump and type numbers to the nodes, identify conduction and/or flow neighbors (accounting for either parallel or serpentine flow), select the proper incident heat curves, and provide property curve numbers -- all on tape in the form of card images compatible with the EDIT subroutine. Thus, a user may provide nodal subdivision input cards for one or more radiator panels, followed by a data deck for the remainder of the model; and in one run the radiator panels will be automatically subdivided, the resulting tape will be combined with the input data deck, and the problem will be run to completion.

4.3.1.3 Input

As their major input, SUBANS, SUB2D, and SUBRAD require the overall panel dimensions. For a rectangular panel the length in the x-direction (see Figure 4-4) and the height in the y-direction are required input and for a circular panel the radius of the panel is a major input item. The panel thickness is input for both type panels. To keep the grid size flexible on a rectangular panel, the user specifies the number of nodes in the x-direction; and in the y-direction, he gives the typical tube lump width, the number of tubes, and the number of structure lumps between tubes. For a circular panel the user specifies the number of tubes and has an option of either specifying the number of lumps in each tube or a set of limits for the length of all tube lumps. Starting with n lumps for the first (inside) tube of a circular panel, each successive tube is required to have some multiple of n lumps; i.e., 1n, 2n, 3n, etc. Typical tube lump width and number of structure lumps between tubes are also input items for a circular panel. With reference to this latter number, SUBANS, SUB2D, and SUBRAD are restrained to put half as many structure lumps between the outside tubes and the panel edges, thus the number is required to be even.

Those quantities and numbers which do not enter into nodal subdivision calculations but which are required for input into the thermal analyzer routines are also SUBANS and SUBRAD input items; these include properties and property curve numbers, initial temperature, heat transfer and external radiation areas, cross-sectional area, wetted perimeter, and friction factor coefficient. These items are simply stored until the data tape is being written, at which time they are output exactly as they appeared on the input cards; no checks are made for correctness of either the formats or the values.

4.3.1.4 One Dimensional Rectangular Model Subdivision

The performance of SUBANS is best illustrated by showing what it will do with a sample data set. Assuming a panel length, x, of 120 inches (Figure 4-5); height, y, of 120 inches; and thickness, T, of 3 inches, we shall call for ten nodes in the x-direction, five tubes two inches wide in the y-direction, and two structure lumps between tubes, resulting in the nodal breakdown shown in Figure 4-6. Further, we shall specify four incident heat zones in both the x- and y-directions, from which SUBANS will set up the zone configuration shown in Figure 4-7.

Tube and Lump Type Numbering

For serpentine flow panels, only one tube is created; for parallel flow panels, n_{tube} tubes are set up, the lowest numbered tube being nearest the top of the panel. The single serpentine tube or the

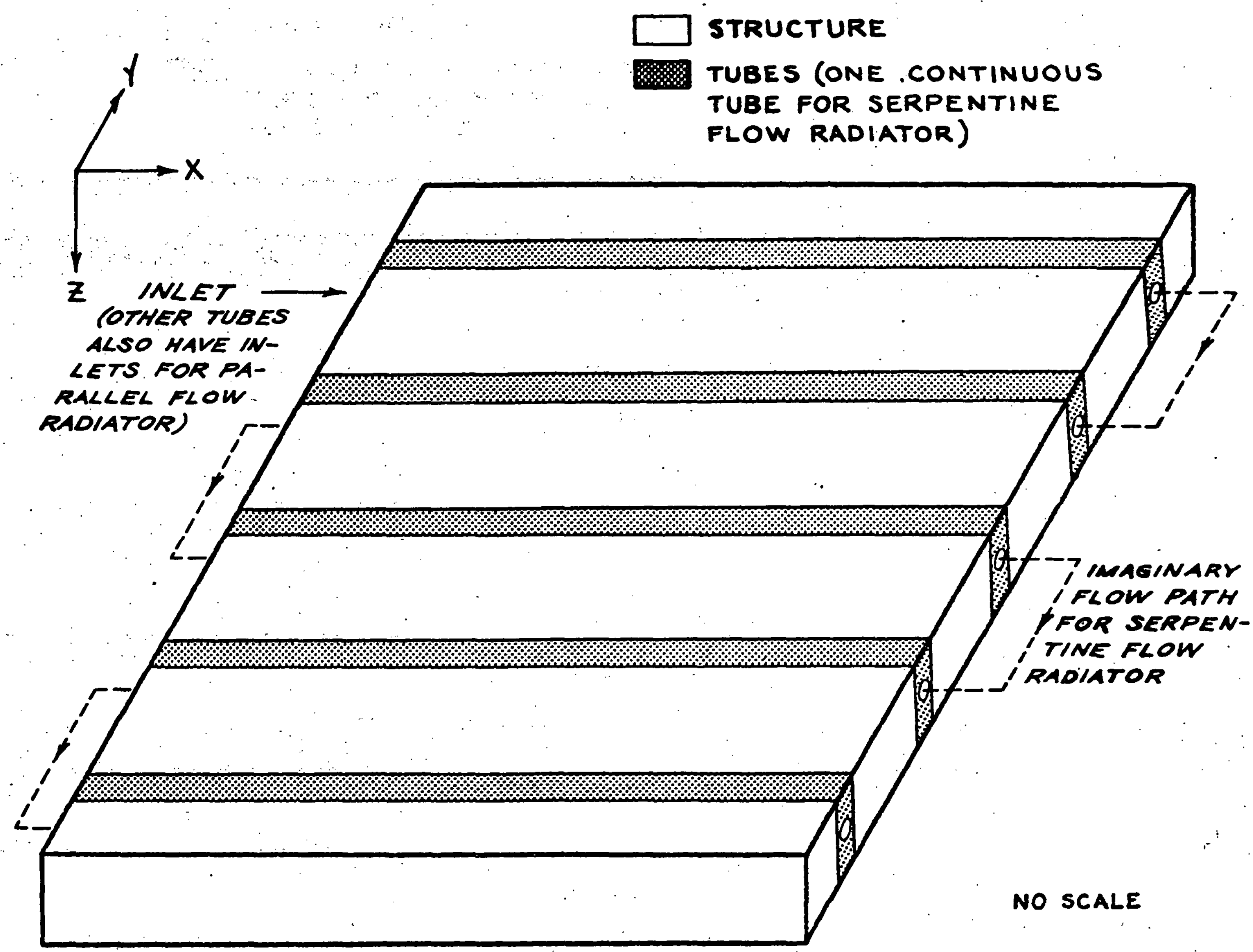


FIGURE 4-4 RECTANGULAR PANEL RADIATOR MODEL

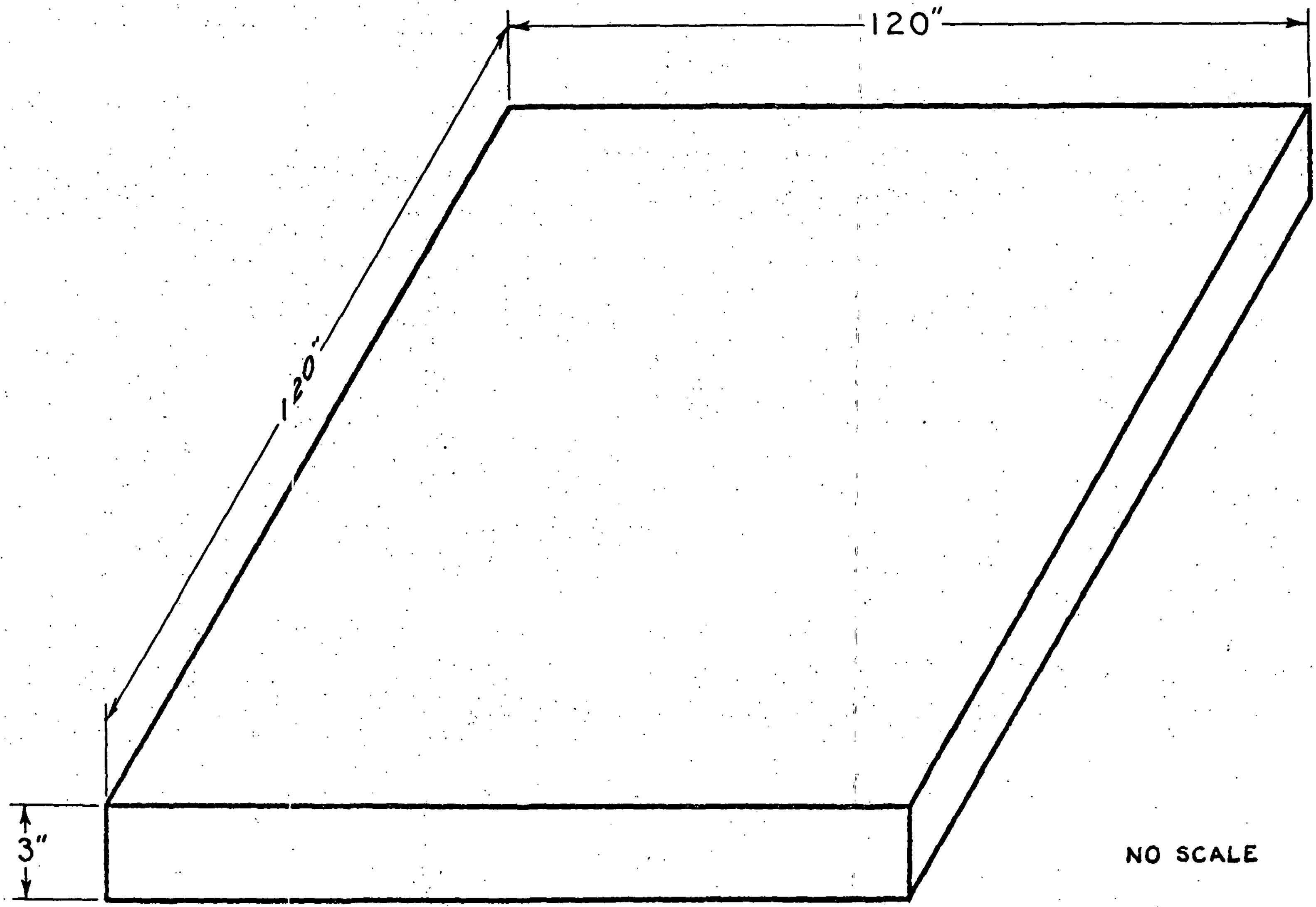


FIGURE 4-5 RECTANGULAR PANEL EXAMPLE PROBLEM - OVERALL DIMENSIONS

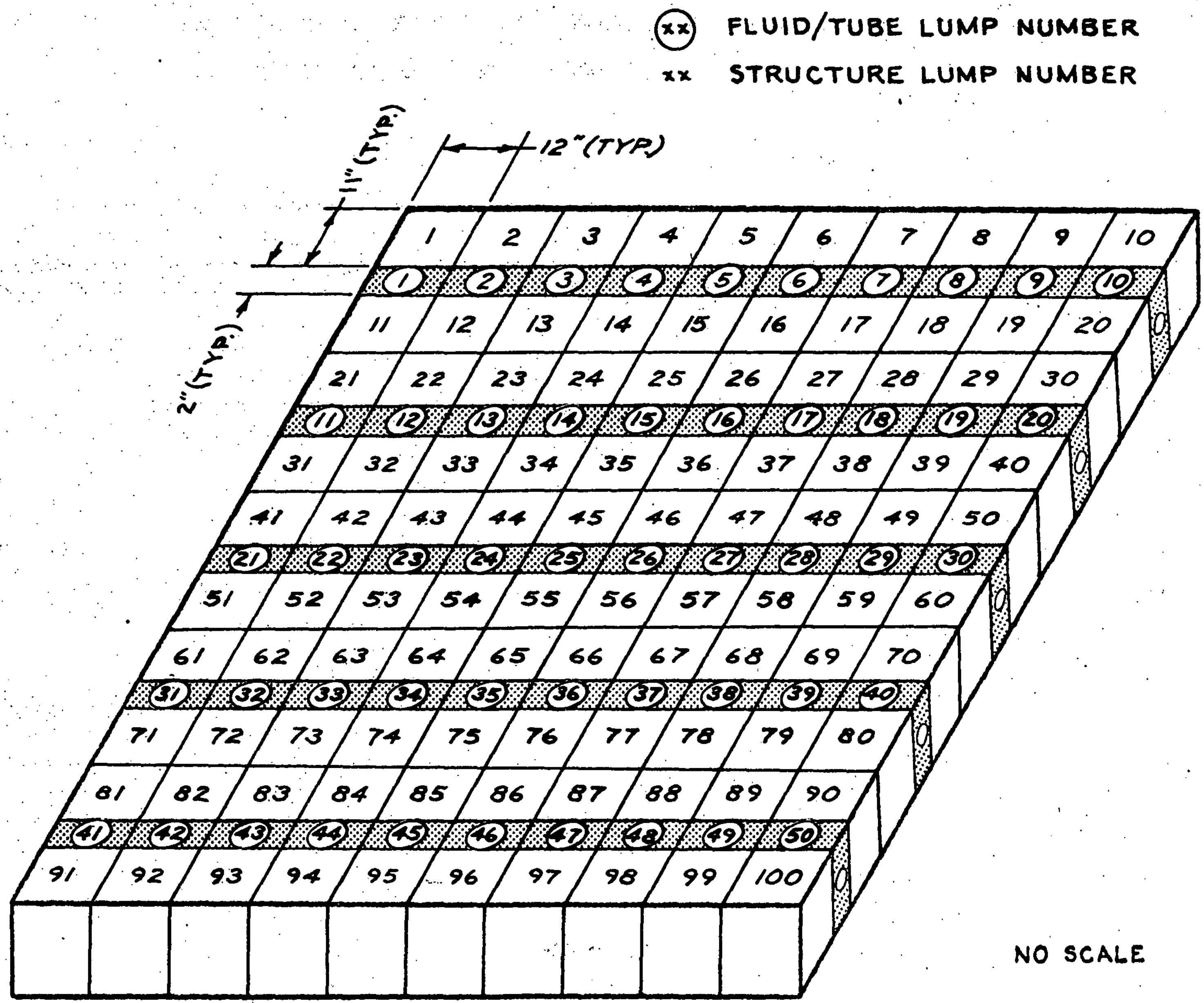


FIGURE 4-6 RECTANGULAR PANEL EXAMPLE PROBLEM - NODAL BREAKDOWN AND DIMENSIONS

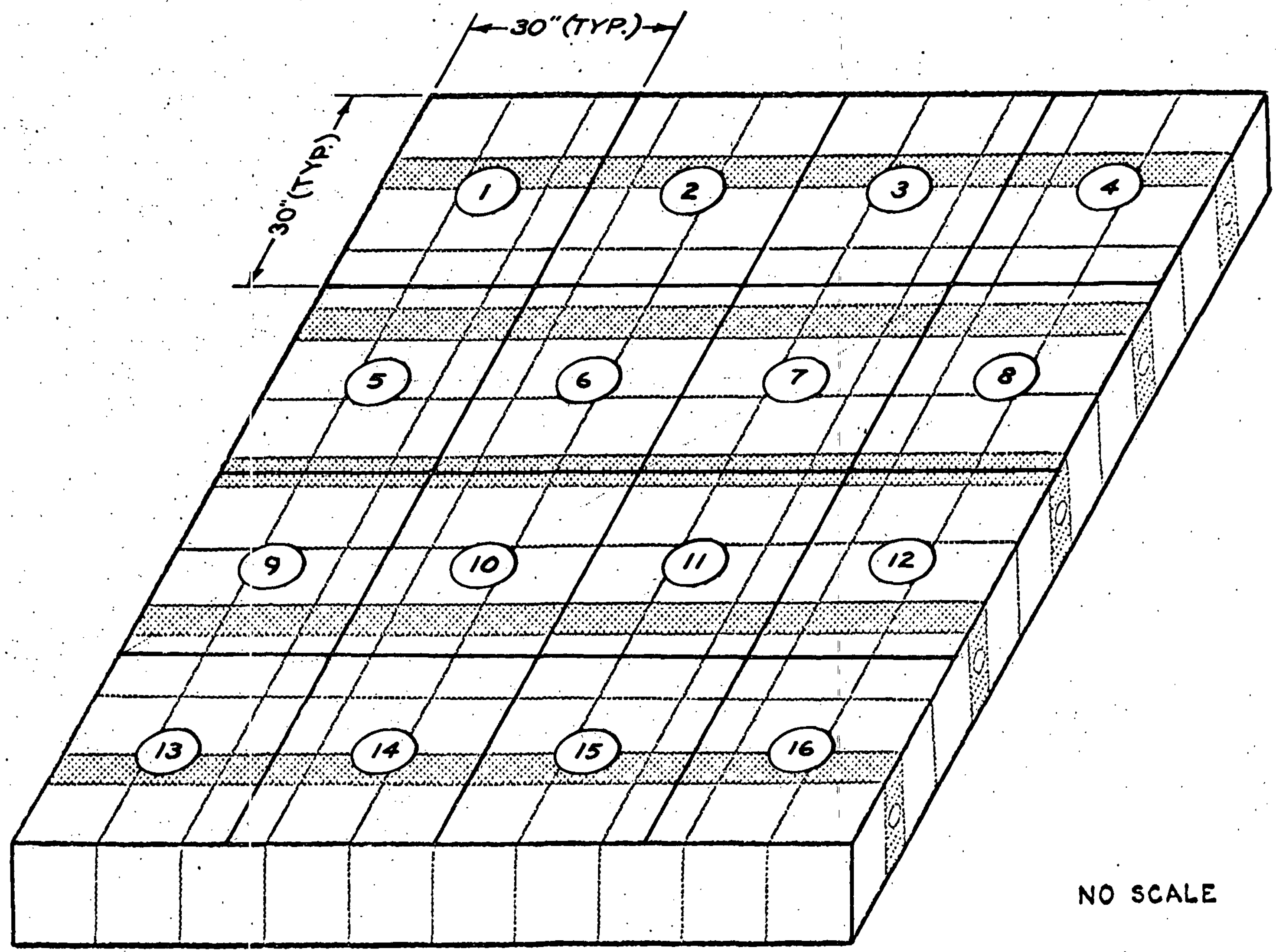


FIGURE 4-7 RECTANGULAR PANEL EXAMPLE PROBLEM - INCIDENT HEAT ZONE BREAKDOWN AND DIMENSIONS

first parallel flow tube in each panel will be numbered one greater than the last tube on the previous panel. For the first panel in the system the first tube will be Number 13.

For each panel being subdivided only one lump type is required for fluid and tube nodes. The latter calls for conduction to the structure lumps above and below, and an input code is provided whereby the user may call for inclusion of longitudinal conduction between tube lumps. Four structure lump types are created for each panel, the lowest type number being one greater than the last previous type for the system. The first of these types conducts to the structure lump immediately below (negative y-direction) and to the structure lump immediately to the right (positive x-direction); from the example problem, nodes of this type are 11-19, 31-39, 51-59, and 71-79. The second type conducts only to the structure lump below it (for our example, lumps 20, 40, 60, and 80); and the third type, only to the lump to the right (nodes 1-9, 21-29, 41-49, 61-69, 81-89, and 91-99). Finally, the fourth type conducts to no lumps, examples being lumps 10, 30, 50, 70, 90, and 100. The fluid and tube type numbers and the lowest of the structure lump type numbers will each be one greater than the last previous type for the system.

Lump Numbering

SUBANS will divide the panel described above into nodes numbered as shown in Figure 4-6. From this it may be seen that the total number of fluid/tube lumps created per panel is

$$n_{fluid/tube} = n_x \, n_{tube} \quad [= 10 \times 5 = 50]$$

where n_x is the number of nodes in the x-direction and n_{tube} is the number of tubes in the y-direction. Similarly, the total number of structure lumps is

$$n_{structure} = n_x n_y n_{tube} \quad [=10 \times 2 \times 5 = 100]$$

where n_y is the number of structure lumps between tubes.

Lump Size

In the x-direction, the size of all lumps will be

$$size_x = x/n_x \quad [=120 \text{ inches}/10 = 12 \text{ inches}]$$

where x is the panel length. In the y-direction, tube lumps are dimensioned by the input width, $size_{y_{tube}}$ [= 2 inches], while the size of structure dimensions is

$$size_{y_{structure}} = (y - n_{tube} \, size_{y_{tube}})/n_y$$

$$\left[= \frac{120 \text{ inches} - 5(2 \text{ inches})}{10} = 11 \text{ inches} \right]$$

where y is the panel height. The thickness of all tube and structure lumps is set to the same input value of thickness. The cross-sectional area of the fluid lumps is a direct input item, and as such is not calculated.

Upstream and Downstream Lump Numbers

For serpentine flow radiators, flow will be assumed to go from left to right in the first tube, to go from right to left in the second tube; and thence, to alternate in direction from one tube to the next. Accordingly, fluid upstream and tube downstream lump numbers are typically set up as shown in Table 4-1.

Incident Heat

To provide incident heat information, zones will be set up across the panel, with an incident heat curve number being specified for each zone. The number of zones in the x- and y-directions are also input; and to maintain generality, the incident heat zone boundaries need not coincide with node boundaries. When portions of more than one zone fall on a node, a single incident heat curve is selected according to the method described below.

The size of the incident heat zones in the x-direction is

$$size_{x_{zone}} = x/n_{x_{zone}} \qquad [= 120 \text{ inches}/4 = 30 \text{ inches}]$$

where $n_{x_{zone}}$ is the number of zones in the x-direction. Similarly, in the y-direction

$$size_{y_{zone}} = y/n_{y_{zone}} \qquad [= 120 \text{ inches}/4 = 30 \text{ inches}]$$

These sizes must be as large or larger than the maximum lump dimension in their respective direction. In the case where all of a tube or structure lump lies within a zone boundary, it takes the incident heat curve of that zone. When most of the area of a lump lies within a single zone boundary, it too takes the curve number of that zone. When the area of a lump is split equally between two zones, the following order of precedence is followed: if the two zones are side by side, the curve number for the zone to the left is assigned; if the zones are above and below each other, the curve for the uppermost zone is used. For a lump whose area is equally divided among four zones, the zone up and to the left prevails. As an example of the use of these rules, we shall select several lumps as follows. Structure lump 1, being entirely in zone 1, is assigned the incident heat curve number for zone 1. Seventy-two square inches of structure lump 21 are in zone 1 and sixty square inches are in zone 5; since zone 1 predominates, its curve number is chosen. Structure lump 3 has

TABLE 4-1

EXAMPLE (SERPENTINE) PROBLEM
TYPICAL UPSTREAM AND DOWNSTREAM LUMP NUMBERS

Fluid/Tube Lump	Upstream	Downstream
1	0	2
2	1	3
9	8	10
10	9	20
11	12	21
12	13	11
19	20	18
20	10	19
21	11	22
22	21	23
29	28	30
30	29	40
50	49	0

For parallel flow radiators, flow is assumed to flow from left to right in all tubes; accordingly, fluid upstream and tube downstream lump numbers are typically set up as shown in Table 4-2.

TABLE 4-2

EXAMPLE (PARALLEL) PROBLEM
TYPICAL UPSTREAM AND DOWNSTREAM LUMP NUMBERS

Fluid/Tube Lump	Upstream	Downstream
1	0	2
2	1	3
9	8	10
10	9	0
11	0	12
12	11	13
19	18	20
20	19	0
21	0	22
22	21	23
29	28	30
30	29	0
41	0	42
42	41	43
49	48	50
50	49	0

sixty-six square inches in zone 1 and sixty-six square inches in zone 2; therefore, the curve for the zone to the left -- zone 1 -- is assigned. Similarly, the area of tube lump 25 is exactly halved between zone 6 and 10; the former being uppermost, its curve is used. Finally, tube lump 23 has equally portions of its area in zones 5, 6, 9, and 10; the rule is to choose up and/or to the left, hence zone 5 is selected.

4.3.1.5 Circular Model Subdivision

The performance of SUBRAD will be illustrated by showing what it will do with a sample data set. Assuming a panel radius, R, of 20 inches (Figure 4-8); and thickness, T, of one inch, we shall call for four tubes two inches wide in the radial direction and two structure lumps between tubes. Furthermore we shall set the limits of tube lump length at a maximum of 5.0 and a minimum of 1.9 inches, resulting in the nodal breakdown shown in Figure 4-9. We shall specify four incident heat zones, from which SUBRAD will set up the zone configuration shown in Figure 4-10.

Tube and Lump Type Numbering

All tubes on a circular panel are assumed to flow in parallel with the innermost tube being the lowest numbered. For each panel being subdivided,the number of fluid and lump types will be equal to the number of tubes, with types being the same for a given tube. Tube lumps call for conduction to the structure lumps above and below, and an input code is provided whereby the user may call for inclusion of longitudinal conduction between tube lumps. The number of structure lump types created for each panel will be equal to the number of tubes times the number of structure lumps between tubes. Each type conducts to the adjoining structure lump in the negative θ direction (See Figure 4-8) and to the adjoining lump in the outward radial direction. Structure lumps adjacent to and inside the radius of a tube lump will therefore conduct to only one lump. From the example problem; type 1 conducts to only one lump (lumps 1-8), type 2 conducts to two lumps (9-16), type 3 conducts to only one lump (17-24), etc.

Lump Numbering

SUBRAD will divide the panel described above into nodes numbered as shown in Figure 4-9. From this it may be seen that the total number of fluid/tube lumps created per panel is:

$$n_{\text{fluid/tube}} = \sum_{t=1}^{NT} NL(t) \quad [\; = 8 + 16 + 16 + 32 = 72]$$

where NL(t) is equal to the number of lumps for tube number t. The values of NL(t) are either directly input into the program or calculated from a maximum node length specified by the user. The total number of structure lumps can be calculated as follows:

$$LDIV(i) = \frac{NTL(i)}{NTL(1)} \quad [\; = \frac{8}{8} = 1,\; = \frac{16}{8} = 2,\; = \frac{16}{8} = 2,\; = \frac{32}{8} = 4]$$

$$n_{\text{structure}} = NTL(1)\left\{(NS+1) + (NS-1)[LDIV(m)] + \sum_{j=i+1}^{m-1} NS[LDIV(j)]\right\}$$

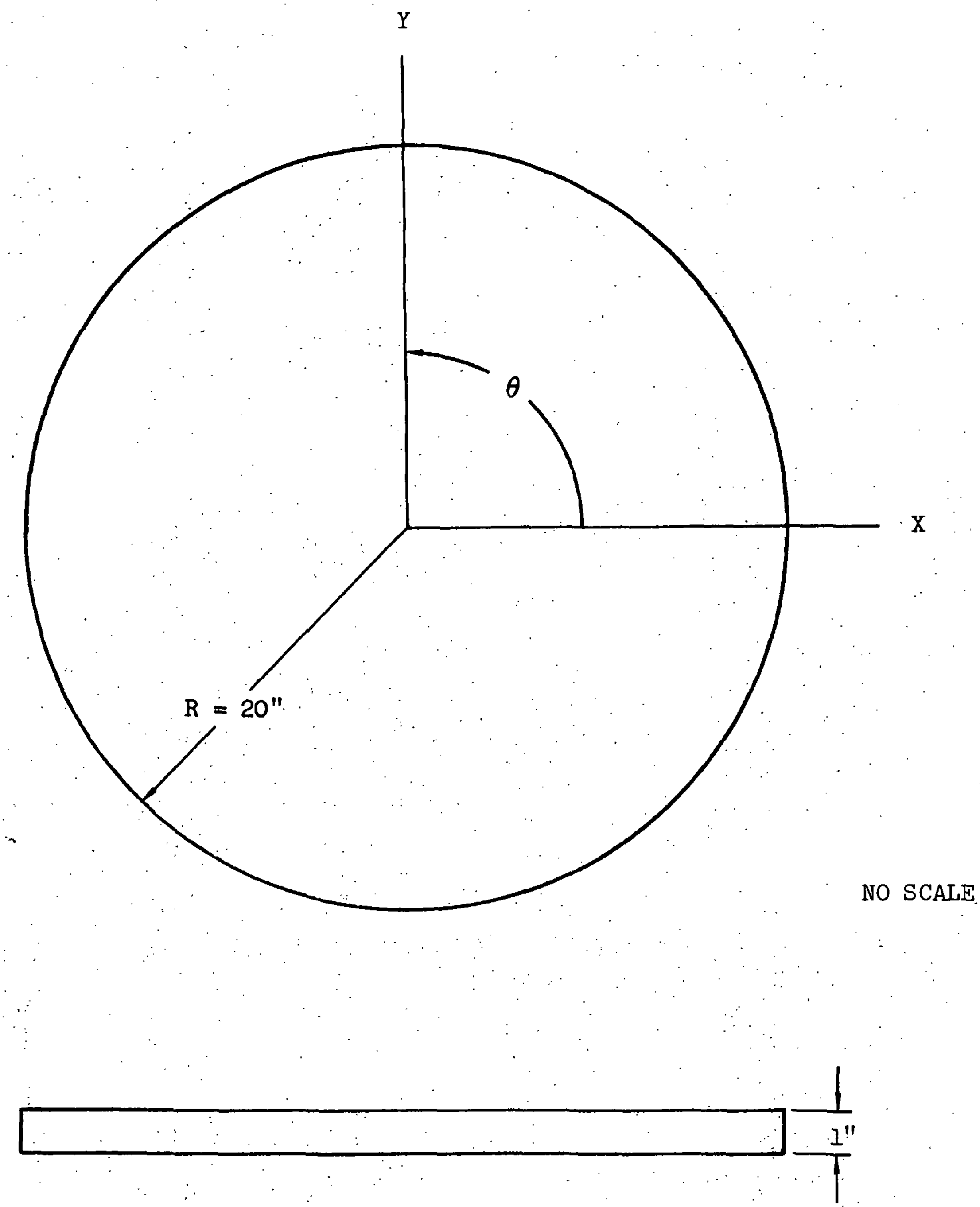


FIGURE 4-8. CIRCULAR PANEL EXAMPLE PROBLEM - COORDINATE SYSTEM AND OVERALL DIMENSIONS

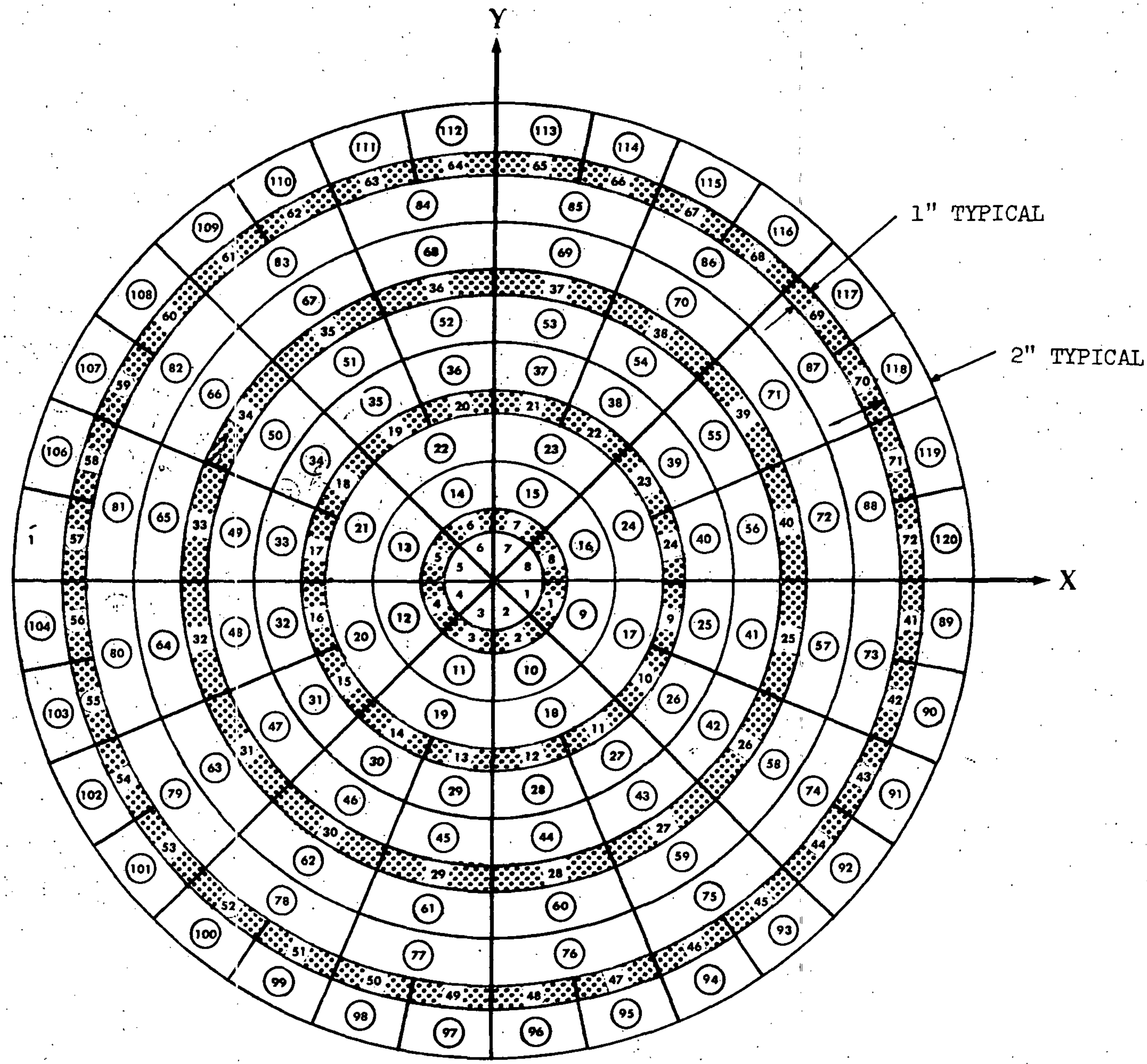


FIGURE 4-9 CIRCULAR PANEL EXAMPLE PROBLEM-
NODAL BREAKDOWN AND DIMENSIONS

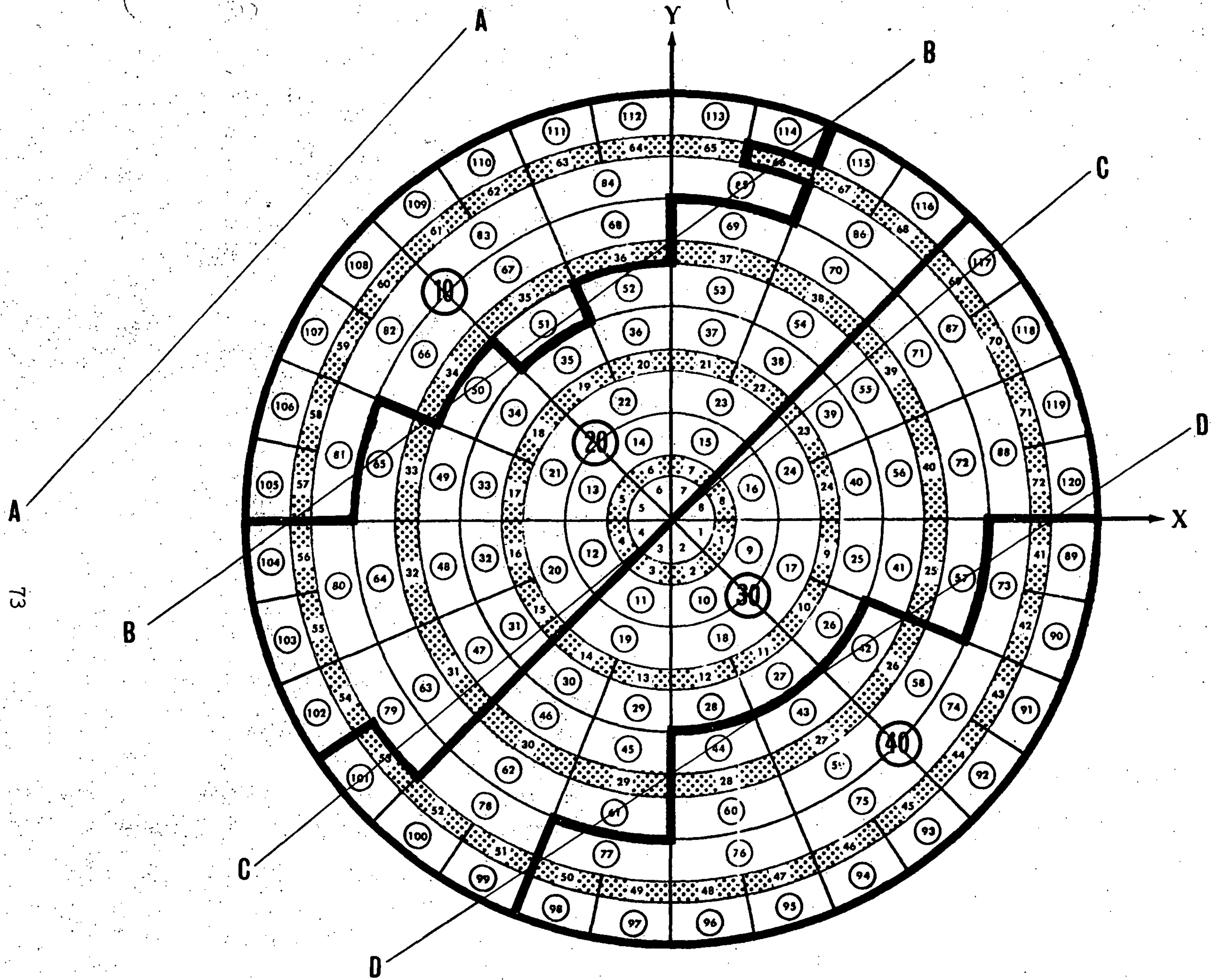


FIGURE 4-10 CIRCULAR PANEL EXAMPLE PROBLEM-
INCIDENT HEAT ZONES

$$= 8 \left\{ (2+1(1) + (2-1)(4) + 2\ (2+2) \right\} = 120$$

where:

i	= tube number
NTL(i)	= number of tube lumps for tube number i
NTL(1)	= number of tube lumps for first tube
NS	= number of structure lumps between tubes
m	= tube number for last tube

Lump Size

The size and number of nodes created for a circular panel are governed directly by the number of tube lumps in each tube. With reference to this latter number there are some basic groundrules for panel subdivision that SUBRAD follows. These include:

(1) The number of tube lumps per tube can be specified by the user or calculated by SUBRAD.

(2) User specification; starting with n lumps for the first (inside) tube, each successive tube is required to have some multiple of n lumps; i.e., 1n, 2 n, 3 n, etc.

(3) Automatic SUBRAD calculation; the user specifies a set of limits for tube lump length which SUBRAD will use to determine the number of lumps per tube,attempting to stay within the specified limits for each lump, while following the guideline as described above. If such a breakdown is not possible SUBRAD will override the maximum length specified by the user.

(4) Structure lumps inside the radius of the first tube coincide with the theta angle (Figure 4-8) of tube lumps in the first tube (See Figure 4-9).

(5) All other structure lumps coincide with the theta angle of the tube lump adjacent to and nearest the center of the panel.

Upstream and Downstream Lump Numbers

For circular radiator panels, flow is assumed to flow clockwise in all tubes; accordingly, fluid upstream and tube downstream lump numbers are typically set up as shown in Table 4-3.

Incident Heat

To provide incident heat information, zones will be set up across the panel, with an incident heat curve number being specified for

TABLE 4-3

CIRCULAR PANEL EXAMPLE PROBLEM
TYPICAL UPSTREAM AND DOWNSTREAM LUMP NUMBERS

FLUID/TUBE LUMP	UPSTREAM	DOWNSTREAM
1	0	2
2	1	3
7	6	8
8	7	0
9	0	10
10	9	11
23	22	24
24	23	0
25	0	26
26	25	27
55	54	56
56	55	0
57	0	58
58	57	59
87	86	88
88	87	0

each zone. The number of zones on the panel is input; and to maintain generality, the incident heat zone boundaries need not coincide with node boundaries. When portions of more than one zone fall on a node, the zone covering the greatest portion of the area will be assigned to the node. When the area of a lump is split equally between two zones the order in which the zones are specified determines which zone is assigned to the lump. The node will always fall in the zone with the highest order but will never fall in the last zone. To clarify this point, consider a panel with 6 zones, the first zone being of order 1 and the last of order 6. If a lump is split between zones 3 and 4, 4 will prevail; for a split between 1 and 6, 1 will prevail; for a split between 5 and 6, 5 will prevail.

For circular panels incident heat zones are determined by boundary lines, input by the user, by specifying the x and y-axis intercepts of the line. If a boundary line goes through the origin of the panel coordinates, a theta angle (see Figure 4-8) must be specified. Zones may be specified by any number of boundary lines, yielding the ability to describe almost any size, shape or form of zone by proper use of these lines. Boundary lines are input in sets of one or two along with an incident heat zone number.

SUBRAD's interpretation of these boundary lines can best be described by the groundrules built into the subroutine as listed below:

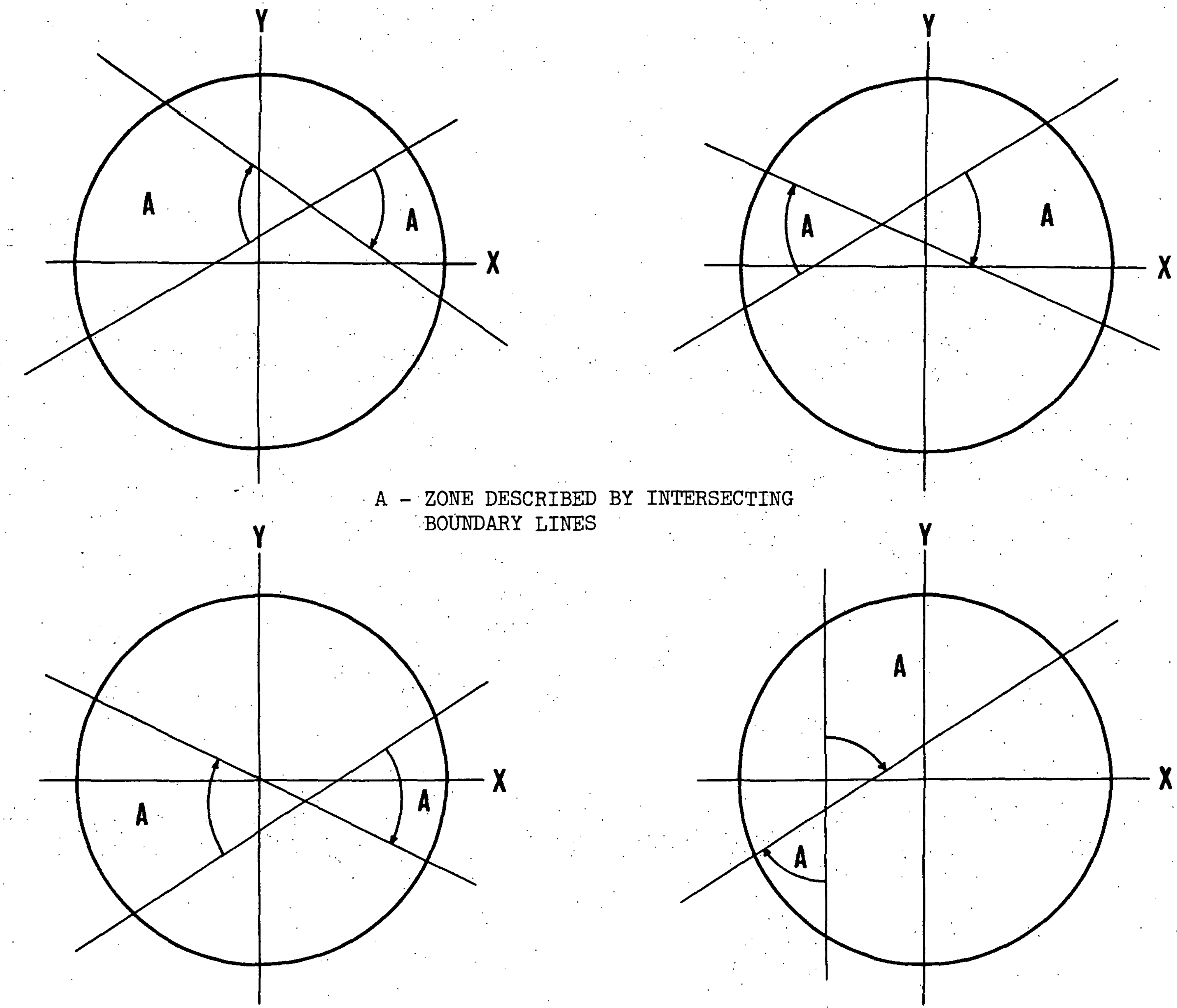
(1) For a panel with only one incident heat zone, boundary lines are not required.

(2) For a zone described by only one boundary line, that particular zone will be the larger of the two created by the boundary. If the panel is split into two zones of equal area, the zone which includes the lowest numbered node will be assigned to that particular incident heat curve number.

(3) For a zone described by two boundary lines, the nodes falling between the two boundaries will be assigned to the zone. If the two boundary lines intersect at some point, the zone described by these boundaries is determined as shown in Figure 4-11.

(4) For zones created by more than one set of boundary lines, the following procedure is followed; SUBRAD sets up preliminary zone numbers for the first set of boundary lines; any successive set of boundaries will override a previously assigned nodal zone number specified by a previous set of boundaries.

(5) Any nodes not falling within the prescribed boundary limits of any of the incident heat zones are assumed to lie in a zone with an incident heat curve number indicated for the last zone.



A - ZONE DESCRIBED BY INTERSECTING BOUNDARY LINES

FIGURE 4-11 INCIDENT HEAT ZONE DETERMINATION FOR TWO INTERSECTING BOUNDARY LINES

As an example of these rules, we will select several nodes as shown on Figure 4-10 of our example problem and describe how SUBRAD interprets the information supplied by the user. Three sets of boundary lines are necessary to describe the four incident heat zones on our example panel. Table 4-4 gives a description of the incident heat zone information supplied by the user. The first card being of order 1 describes lines AA and BB of Figure 4-10. All nodes falling between these lines are assigned incident heat curve number 10. Structure lumps 51, 81, and 85 do not lie entirely between the boundaries but over half of their area does, therefore these lumps are assigned to zone number 10. Boundary lines BB and CC describe zone number 20 having an order of 2, while CC and DD describe zone number 30 of order 3. Even though structure lumps 101 and 117 are split evenly between zones 20 and 30, both lumps are assigned to zone 30 since its order of 3 is higher than that of zone 20 whose order is 2. The remaining lumps which do not fall in any of the above 3 zones are assigned to the zone specified by the user as the last incident heat zone. For our example the zone is number 40, but could have been 10, 20, 30 or any number so desired by the user.

4.3.1.6 Two-Dimensional Model Subdivision

The performance of SUB2D will be illustrated by showing what it will do with a sample data set. We shall assume for the example a panel with four tubes and two structure lumps between tubes. Furthermore we shall set the number of tube lumps per tube and let SUB2D divide the model accordingly.

Figure 4-12 shows how the panel is subdivided into lumps. Lumps are created by lines originating from a central point and dividing each tube length into lumps of equal length. Twelve lumps were prescribed for the first two tubes and 24 lumps for the last two tubes. Subsequent divisions can be made in order to reduce the lump length for any tube past the first as in tube number three of the example

<u>Automatic Tube Length Option</u>

The number of lumps per tube can be prescribed by the program user, but in addition an automatic tube length option exists in SUB2D. This option allows the program user to specify a set of limits of tube lump length and SUB2D will automatically subdivide the panel accordingly. For this automatic division the user indicates the maximum length for a tube node in the first (innermost) tube whereupon the program sets this length at a value less than the prescribed value (XMAX1). An additional limit on node length (XMAX2) for the rest of the tubes is provided by the user also. XMAX2 is the maximum length for tube nodes past the first tube. With the divisions set up by the first tube, the routine checks the value of the tube node length for tube number two. If this length is greater than XMAX2, then a subsequent division is made making twice as many lumps in tube 2 as in tube 1. This process is continued for the entire panel.

For panels with a large number of tubes, the number of lumps can become excessive if very many subsequent divisions past the first tube are allowed. For this reason an additional check is made on the parameter NDIVA, another user input. This parameter is used to limit the number of lumps per

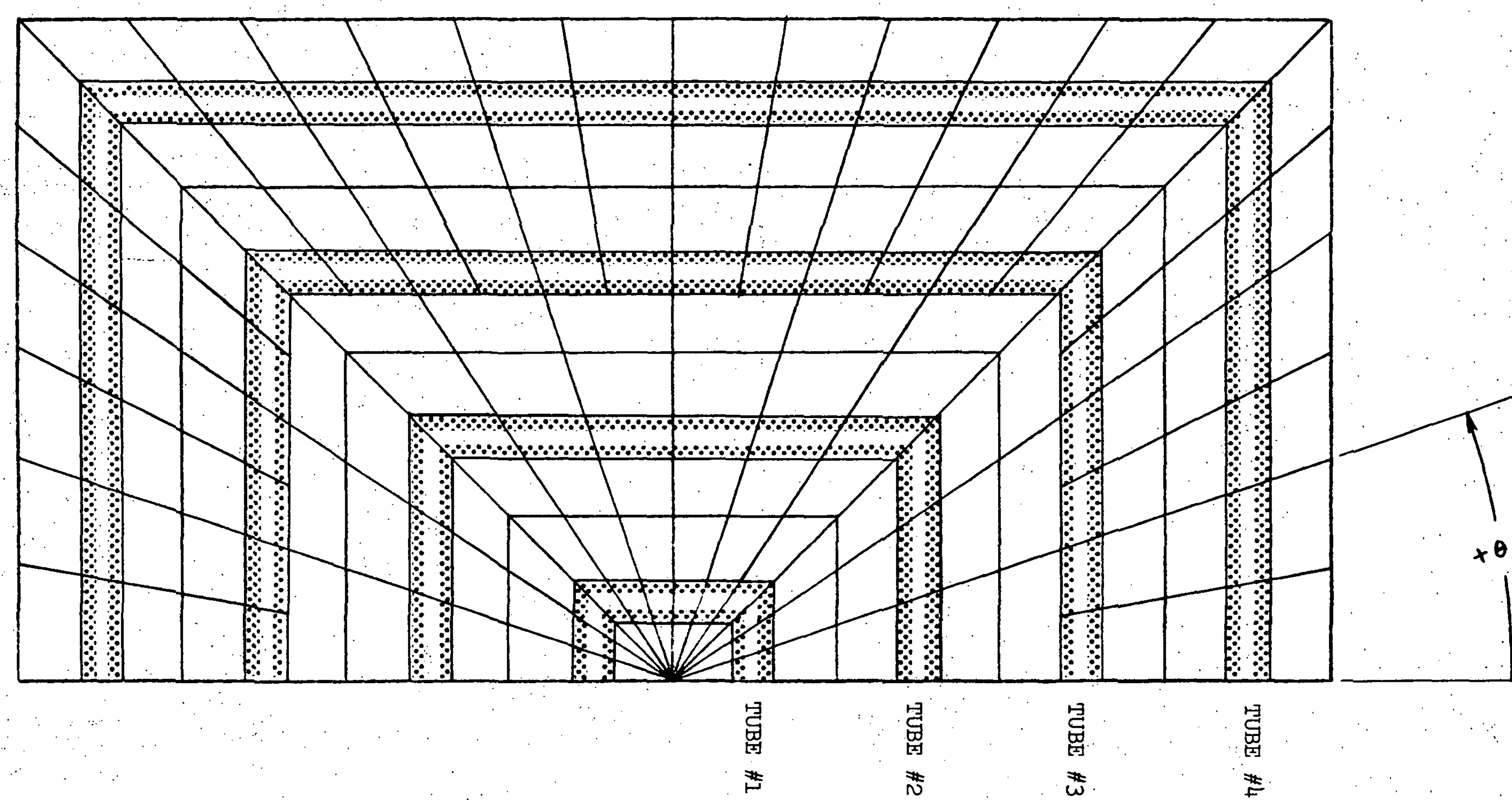


FIGURE 4-12 TWO-DIMENSIONAL PANEL NODAL BREAKDOWN

panel. This number represents the maximum number of subsequent divisions allowable past the division in the first tube. If after a test of tube lump length against XMAX2, another division is necessary, the routine checks to see if this would exceed the limits set up by NDIVA. If so, no further division in the panel is allowed.

Variable Tube Spacing Option

SUB2D has a variable tube spacing option whereby the tube spacing for the first tube can be different than that of the other tubes. By setting TSP1 (Card ANS-1D) to the desired value a unique tube spacing is set up for the first tube and the remaining tubes are spaced equally. If equal tube spacing is desired for the entire panel TSP1 should be set equal to zero or just left blank.

Tube and Lump Type Numbering

All tubes on a two-dimensional rectangular panel are assumed to flow in parallel with the innermost tube being the lowest numbered. Tube lumps call for conduction to the structure lumps above and below, and an input code is provided whereby the user may call for inclusion of longitudinal conduction between tube lumps. Each structure lump conducts to the adjoining structure lump in the outward radial direction and to the adjoining structure lump in the positive θ direction (See Figure 4-12). Structure lumps adjacent to and inside the radius of a tube lump will therefore conduct to no more than one lump.

Lump type numbering can best be understood by referring to Figure 4-13. Tube lump types start at $\theta = 0^\circ$ position and increase numerically to $\theta = 45^\circ$ position whereupon the type number decreases by one to $\theta = 90^\circ$ position. The process is then repeated for the rest of the panel.

Structure lump types also start at $\theta = 0^\circ$ position and then increase numerically to $\theta = 90^\circ$ position. This process is then repeated for the rest of the panel except for the last lump. Since the last lump does not conduct to any other lump it is assigned a new type number.

Lump Numbering

SUB2D will divide the panel described above into nodes numbered as shown in Figure 4-14. Lump numbers start at the $\theta = 0^\circ$ position and increase numerically around the panel. Tube lumps and structure lumps are allowed to have identical numbers since the identification of each is known internally in the program.

Lump Size

The size and number of nodes created for a two-dimensional panel are governed directly by the number of tube lumps in each tube. With reference to this latter number there are some basic ground rules for panel subdivision that SUB2D follows. These include:

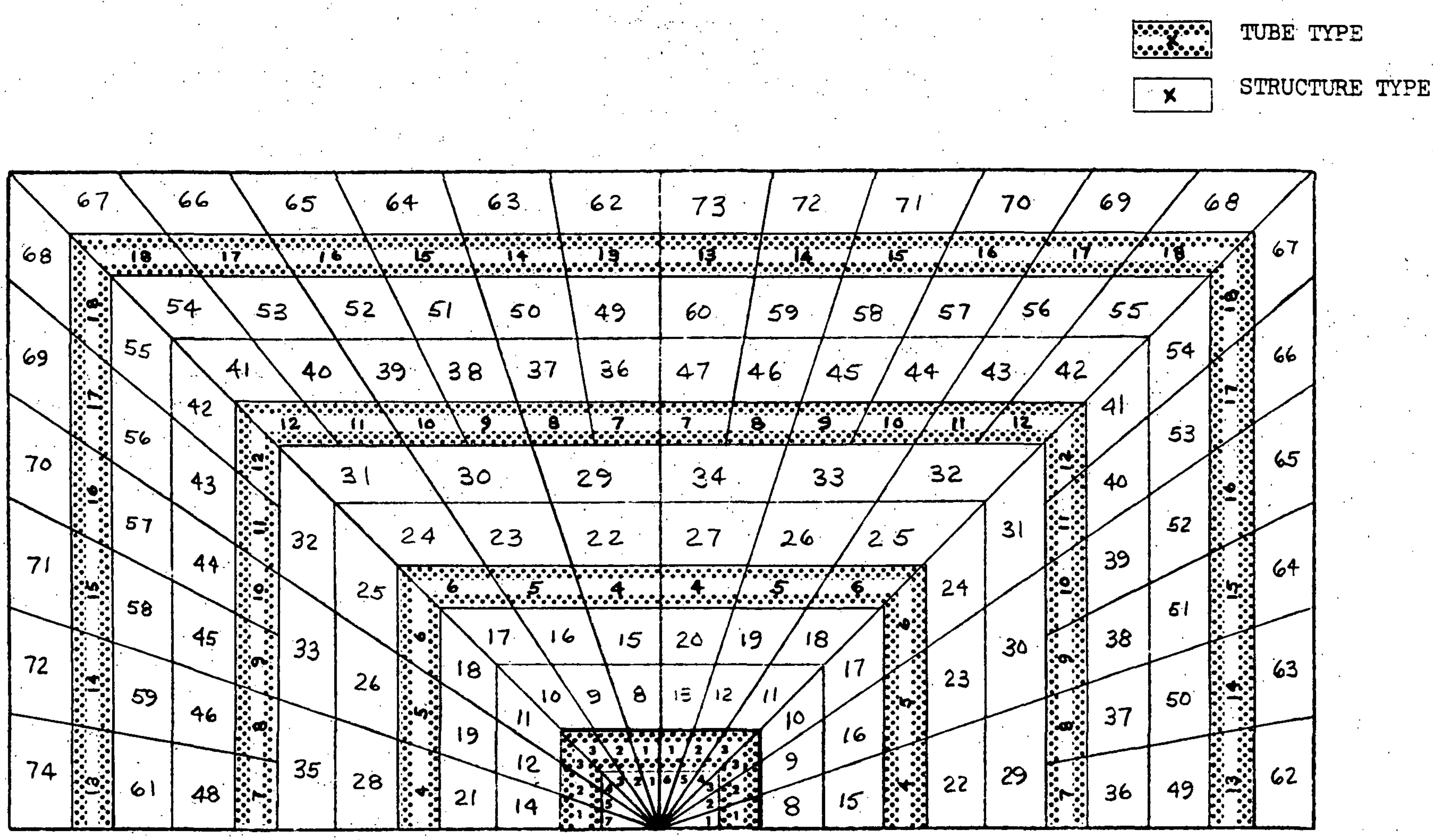


FIGURE 4-13 TWO-DIMENSIONAL PANEL LUMP TYPE CLASSIFICATION

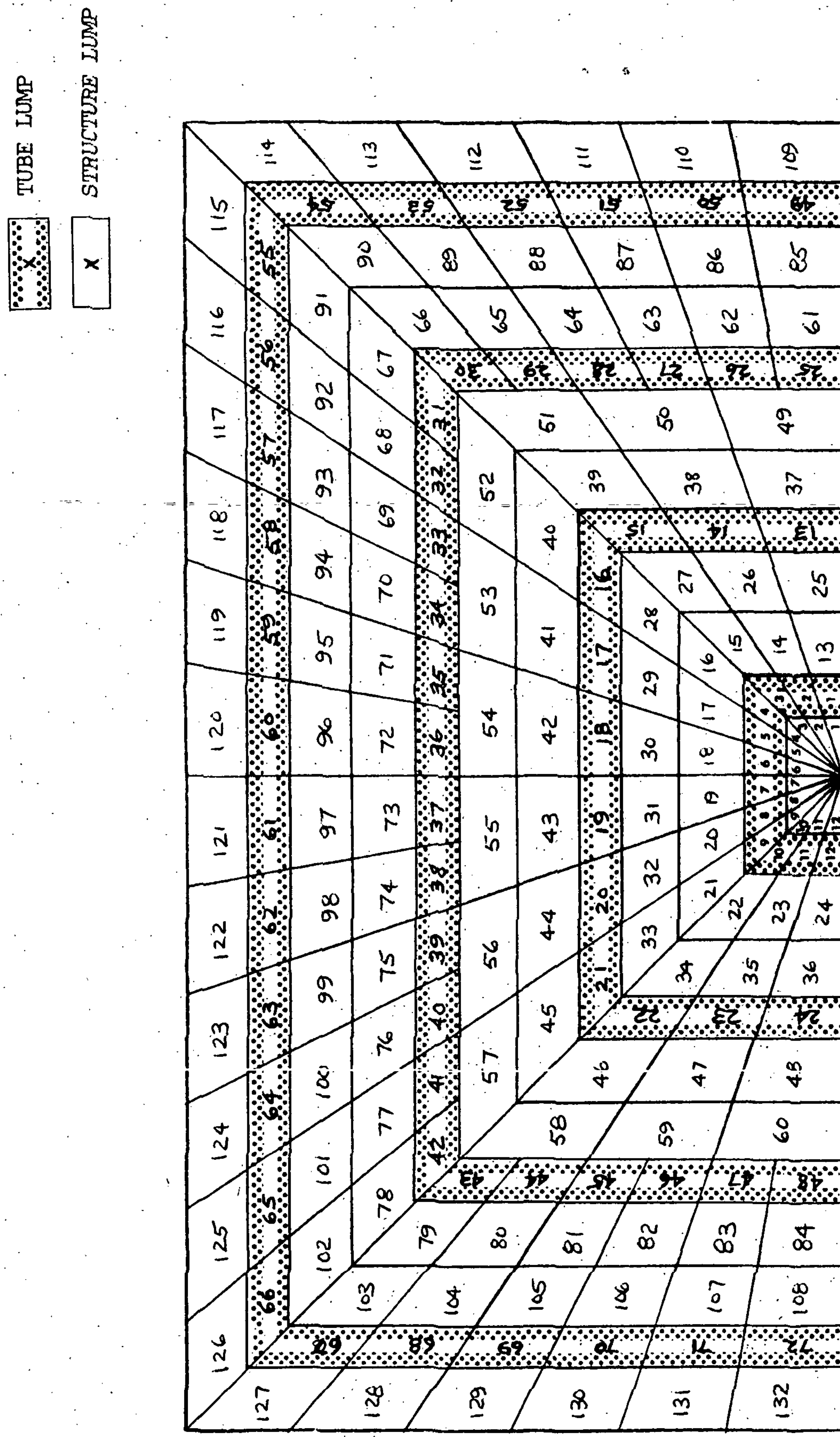


FIGURE 4-14 TWO-DIMENSIONAL PANEL LUMP NUMBERING

(1) The number of tube lumps per tube can be specified by the user or calculated by SUB2D.

(2) User specification; starting with n lumps for the first (innermost) tube, each successive tube is required to have some multiple of n lumps; i.e., 1n, 2n, 3n, etc.

(3) Automatic SUB2D calculation; the user specifies a set of limits for tube lump length whereupon SUB2D will determine the number of lumps per tube attempting to stay within the specified limits for each lump, while following the guidelines as described above.

(4) Structure lumps inside the radius of the first tube coincide with the theta angle of tube lumps in the first tube.

(5) All other structure lumps coincide with the theta angle of the tube lump adjacent to and nearest the origin of the panel.

Upstream and Downstream Lump Numbers

For 2-D radiator panels, flow is assumed to flow counter-clockwise in all tubes; accordingly, fluid upstream and tube downstream lumps numbers are typically set up as shown in Table 4-5

Incident Heat

Only one incident heat zone is allowed for the entire panel.

4.3.2 Plot Options

A positive integer punch in column 72 of parameter card 2 will cause the generation of a plot file. This tape will have all of the fluid, tube, and structure lump temperatures,plus other items indicated below. The plot file is generated on tape unit I.

The format of the plot tape is:

Record No. 1

Title (from title card, 12A6), 0, 0, 0, 0, 0, 0, 1, 0, 0, number of pressure drops, 1, number of flow rates, number of fluid temperatures, number of tube temperatures, number of structure temperatures.

Record No. 2

Time, total pressure drop, tube pressure drops, heat rejection, flow rates, fluid temperatures, tube temperatures, structure Temperatures.

ORDER	SUBRAD CARD NUMBER RAD-5									LINE
	YICEP1	XICEP1	BETA1	NQ	NL	YICEP2	XICEP2	BETA2	NCODE7	
1	13.0	-18.0		10	2	30.0	-30.0		0	AA and BB
2	13.0	-18.0		20	2			39.38	0	BB and CC
3			39.38	30	2	-12.0	18.0		1	CC and DD

TABLE 4-4 CIRCULAR PANEL EXAMPLE PROBLEM - INCIDENT HEAT ZONE SPECIFICATION

TABLE 4-5

TWO-DIMENSIONAL PANEL EXAMPLE PROBLEM
TYPICAL UPSTREAM AND DOWNSTREAM LUMP NUMBERS
(REFERENCE FIGURE 4-B)

Fluid/Tube Lump	Upstream	Downstream
1	0	2
2	1	3
7	6	8
11	10	12
12	11	0
13	0	14
14	13	15
19	18	20
23	22	24
24	23	0
25	0	26
26	25	27
37	36	38
47	46	48
48	47	0
49	0	50
50	49	51
61	60	62
71	70	72
72	71	0

Record No. 3

Time, etc. as on Record 2

The last record has a negative time to indicate end of output.

4.3.3 Checkout Print

It is possible to obtain a detailed print at each iteration (this is usually used in data checkout, and so is called checkout printing). This can be obtained by putting a "1" punch in column 60 of parameter card 2. The checkout print provides a direct, relatively simple check of the data input consistency, and indicates the minimum calculation time increments calculated for each lump. A survey of these time increments permits choice of a minimum time increment which will accurately characterize the transient and override only these lumps which can realistically be considered at steady state.

4.3.4 Restart

Requested Dump for Restarting

Any problem can be dumped and restarted at a later time. This is achieved by punching a "1" in column 58 on parameter card 2. This option is useful in data checkout in that a problem can be submitted for a short transient time, and, after examination of the results, restarted for a longer transient time. The computer request card must specify that the output tape is expected, and the proper set-up card must be included in the deck.

Restart Procedure

The procedure for restarting a problem which has been dumped is;

(1) Fill out the computer request card as in an initial run, except specify the previously dumped tape as an input tape on tape unit J.

(2) Submit only the first two of the data cards (that is, parameter cards 1 and 2) with a "1" punch in column 62 on Card 2 to indicate that data is to be read from a restart tape.

4.3.5 EDIT

The large number of data cards required for problems run on this routine presents three problems: (1) increased probability of operator and/or card reader error, (2) increased probability of a card reader jam, and (3) significant extra time required to read in data from the card reader when problem (2) occurs. For these reasons a routine was developed for reading input data from tape with the capability for modifying the data on read-in.

The EDIT routine is called by parameter INDATA input in columns 67 and 68 on parameter card 2. Possible inputs are:

(1) INDATA = 0, All data is supplied on cards.

(2) INDATA = 1, All data is supplied on cards and the card images are written on tape on Unit B. (Should be specified as an output tape on job card).

(3) INDATA = 2, Use data input on tape on unit D with desired changes on cards to write a new data tape on unit B. (D is input tape and B is output tape).

(4) INDATA = 3, Use the data read in from unit B without change. (B is input tape).

(5) INDATA = 4, List and use data read in from unit B without change. (B is input tape).

(6) INDATA = 5, Punch and use data read in from unit B without change. (B is input tape).

For INDATA = 3, 4, and 5, parameter cards 1 and 2 are read in from cards.

When INDATA = 2, the deck set-up consists of parameter cards 1 and 2, the EDIT control cards (described below), and the new data cards (with the same format as the cards being replaced).

The EDIT control cards, used only when INDATA has a value of 2, are:

Columns	Format	Nomenclature	Description
1-5	I5	K3	Card number K3 will be either removed or pushed down depending upon the contents of the next two fields (K4 and K5). If K3 is greater than the number of cards on the tape plus 10000, no edit will be performed.
6-10	I5	K4	K4 must be equal to or greater than K3 or must be left blank. If K4 $\geq$ K3, cards numbered K3 to K4 inclusive will not be transferred to the new data tape on unit B. If left blank no cards will be deleted.
11-15	I5	K5	If not blank or zero, K5 cards, which must immediately follow this edit control card will be inserted ahead of card K3 or in place of cards K3 through K4.

Giving K3 the value of 99999 will cause the continuing transfer of card images from Unit D to Unit B until a card image containing bbb13b (b = blank) in columns 1-6 is found. The Unit D tape is not altered in any way should there be errors in the edit deck which cause fatal errors in the LTV program. It is the responsibility of the user to maintain extra copies of the data tape and/or an up-to-date card deck.

If automatic nodal subdivision is used in a run, Unit C must be substituted for Unit B in the above discussion of the EDIT routine. The data on cards or Unit C is combined with output on Unit E from automatic nodal subdivision and resulting data is placed on Unit B.

4.3.6 Specified Temperature Nodes

If the mass-specific heat product for any node is zero, the temperature of that node will remain constant at the initial temperature throughout the duration of the problem.

A temperature history may be imposed on either structure or tube nodes for the duration of the problem. If a node has an imposed temperature variation, the prescribed temperature curve must be input for the node.

4.4 User's Manuals

4.4.1 Transient Performance Routine (TPR)

The user's instructions for the Transient Performance Routine are presented in this section.

Parameter Cards

Columns	Format	Nomenclature	Description
Parameter Card 1			
1-72	12A6	HEADER	Any 72 alphanumeric characters to be used for page heading.
Parameter Card 2			
1-10	F10.5	TIME	Transient start time, hr.
11-20	F10.5	TAU	Transient stop time, hr.
21-30	F10.5	TINCMN	Time increment, hr.
31-35	F5.0	DELTAU	Print interval, hr. If DELTAU < TINCMN, print interval = TINCMN.
36-40	F5.0	RTIME	Computer time requested, minutes.
41-45	F5.0	THETA	Convergence factor. Routine sets to .9 if left blank.
46-50	F5.0	DPTOL	Parallel flow path pressure drop balance tolerance (decimal fraction).
51-55	F5.0	SSTEST	Steady state tolerance, °F.
56-58	I2	IDUMP	= 0, No dump tape to be written. = 1, Dump data on UNIT I when either TAU or RTIME is exceeded.
59-60	I2	NCKOUT	= 0, No checkout print. = 1, Checkout print.
61-62	I2	ISTART	= 0, New data follows. = 1, Read data from restart tape.
63-64	I2	NVLVRS	Number of valves having parameter to be changed on restart.

Columns	Format	Nomenclature	Description
65-66	I2	NORAD	Number of radiator panels to be divided into nodes.
67-68	I2	INDATA	= 0, All data supplied on cards. = 1, Write data cards on UNIT B (UNIT C if NORAD > 0). = 2, Use data on UNIT D plus edit cards to create data on UNIT B (UNIT C if NORAD > 0). = 3, Use data on UNIT B (UNIT C if NORAD > 0). = 4, List and use data on UNIT B (UNIT C if NORAD > 0). = 5, Punch on cards and use data UNIT B (UNIT C if NORAD > 0).
69-72	I4	NPLOT	≠ 0, Plot file output will occur every NPLOT iteration on UNIT I. = 0, No plot file will be generated on UNIT I.

Parameter Card 3

Columns	Format	Nomenclature	Description
1-5	I5	NTUBE	Number of tubes.
6-10	I5	NFLT	Number of fluid lump types.
11-15	I5	NMLT	Number of tube lump types.
16-20	I5	NT	Number of structure lump types.
21-25	I5	NTFL	Number of fluid lumps.
26-30	I5	NTML	Number of tube lumps.
31-35	I5	NSL	Number of structure lumps.
36-40	I5	NPS1	Number of panels on Side 1.
41-45	I5	NPS2	Number of panels on Side 2.

Parameter Card 4 (Leave out for NORAD = 0)

Columns	Format	Nomenclature	Description
1-5	I5	NTYPE(1)	= 1, Rectangular panel. = 2, Circular panel. = 3, 2-D Rectangular panel.
6-10	I5	NTYPE(2)	Panel type for second panel on Side 1. or panel on side 2 if only 1 on side 1.

Columns	Format	Nomenclature	Description
11-15	I5	NTYPE(N)	Panel type for last panel on Side 1.
16-20	I5	NTYPE(N+1)	Panel type for first panel on Side 2.
21-25	I5	NTYPE(M)	Panel type for last panel on Side 2.

Insert ANS data cards here if NORAD > 0 (Parameter Card 2, Columns 65-66).

Parameter Card 5

Columns	Format	Nomenclature	Description
1-5	F5.0	HI1	Entry length heat transfer coefficient factor. Recommended value for circular tubes is 0.575.
6-10	F5.0	HI2	Fully developed heat transfer coefficient factor. Recommended value for circular tube is 1.0.
11-15	F5.0	ANEW	Fraction of new flow rate to use when averaging flow rates. Recommended value is 0.5.
16-20	I5	NCYCLE	Time dependent curve option. = 0, Non-cyclic. = 1, Cyclic.
20-25	I5	KLSDLP	Closed loop option = 0, Inlet temperature to tube 1 supplied on curve (Parameter Card 8, Cols. 31-35) = 1, Outlet temperature of tube 8 used as inlet temperature to tube 1 (Parameter Card 8, Cols. 31-35 may be left blank).

Parameter Card 6

Columns	Format	Nomenclature	Description
1-5	I5	NT1	*Number of tubes in panel 1.
6-10	I5	NT2	Number of tubes in panel 2.
11-15	I5	NT3	Number of tubes in panel 3.

Continue listing the number of tubes in each panel in five column fields.

* Set number of tubes to a minus quantity for circular and two-dimensional panels.

Parameter Card 7

Column	Format	Nomenclature	Description
1-5	I5	LMPIN1	Inlet lump for side 1 of the regenerator.
6-10	I5	LMPOT1	Outlet lump for side 1 of the regenerator.
11-15	I5	LMPIN2	Inlet lump for side 2 of the regenerator.
16-20	I5	LMPOT2	Outlet lump for side 2 of the regenerator.
21-30	F10.5	UA	Product of the overall heat transfer coefficient and the area of heat transfer (UA) for the regenerator, BTU/hr-°F.

Parameter Card 8

1-5	I5	NDENC	Fluid density curve number.
6-10	I5	NCONC	Fluid conductivity curve number.
11-15	I5	NSHC	Fluid specific heat curve number.
16-20	I5	NVISC	Fluid viscosity curve number.
21-25	I5	NFFC	Fluid friction factor curve number for turbulent flow.
26-30	I5	NFLOW	Inlet flow rate curve number.
31-35	I5	NTEMP	Inlet temperature curve number.

Ten cards are required to specify the valve parameters. Valve parameters for the radiator bypass valve (valve number 1) and the regenerator bypass (valve number 2) are specified on two pairs of Card A and Card B. Valve parameters for the proportioning valve (valve number 3) are specified on Cards C and D. Valve parameters for the two polynomial or rate limit stagnation valves (valve number 4 and valve number 5) are specified on two pairs of Card A and Card B. Valves do not need to be in numerical order.

Card A - Bypass and Stagnation Valves

Columns	Format	Nomenclature	Description
1-3	I3	NVN	Valve number.
4-5	I2	NOP	Operation mode, = 0, valve is operating. = 1, valve is locked in initial position. = 2, Valve is not considered; i.e. flow is distributed among all tubes on panel according to pressure drops (for valves 4 and 5 only).
6-10	I5	NSLN	Sensor lump number.
11-20	F10.5	FRMIN	Minimum fraction allowed through non-bypass tube.
21-30	F10.5	FRMAN	Maximum fraction allowed through non-bypass tube.
31-40	F10.5	FRIN	Initial fraction allowed through non-bypass tube.

Columns	Format	Nomenclature	Description
Card B			
1-5	I5	NTYPE	= -1, Bypass valve for solar absorber. = 1, Rate limit bypass. = 2, Polynomial bypass.
If NTYPE = 1,-1			
6-15	F10.5	SETPT	Set point temperature, °F.
16-25	F10.5	DBAND	Dead band, °F.
26-35	F10.5	RFACT	Rate factor. Units are fraction bypass per second per °F.
36-45	F10.5	RLIM	Rate limit. Units are fraction bypass per second.
If NTYPE = 2,-1			
6-15	F10.5	A_0	Coefficients in fraction bypass.
16-25	F10.5	A_1	$X = A_0+A_1T+A_2T^2+A_3T^3+A_4T^4$
26-35	F10.5	A_2	where T is sensor lump temperature (°F).
36-45	F10.5	A_3	
46-55	F10.5	A_4	
Card C Proportioning Valve			
1-3	I3	NVN	Valve number.
4-5	I2	NOP	Operating mode, = 0, Valve is operating. = 1, All the radiator flow is directed through side 2.
6-10			Blank
11-20	F10.5	POSMIN	Minimum allowable linear valve position from left, milli-inches.
21-30	F10.5	POSMAX	Maximum allowable linear valve position from left, milli-inches.

Columns	Format	Nomenclature	Description
31-40	F10.5	POSIN	Initial linear valve position from left, milli-inches (mils).
Card D - Proportioning Valve			
1-10	F10.5	FULOPN	Maximum linear valve position from left, mils.
11-20	F10.5	VLVGAN	Valve gain, milli-inches/°F.
21-30	F10.5	PPARA	Panel parameter. Enter 2.
31-40	F10.5	GFACT	Geometry factor. GFACT = $(2.92)(10^{-6})(D^2)$* where D is valve orifice diameter in mils. Units are $(\frac{lb}{hr})^2 \ (\frac{1}{mil})^2 \ (\frac{1}{1000\ psi})$
41-50	F10.5	VLVTOL	Null position tolerance, mils.
51-60	F10.5	TCON	Time constant, seconds.
	Fluid Data Cards		
Card 1			
1-12			Blank
13-36	4A6	ALPHA	FLUID b TYPE b DATA bbbbbbbb where b denotes a blank.
Card 2			
1-25			Blank
26-30	I5	NKPDC	Dynamic head loss, K. Factor curve number (leave blank if not needed).
31-40			Blank
41-50	F10.5	FLL	Fluid lump length, in.
51-60	F10.5	CSA	Cross-sectional area, sq. in.
61-67	F7.5	WP	Wetted perimeter, in.
68-72	F5.4	FRE	Factor for computing friction factor as a function of Reynold's number. Routine sets to 1.0 if left blank.

* Value for Apollo Block II Environmental Control System Valve.

Repeat Card 2 for every fluid type.

Card 3

Columns	Format	Nomenclature	Description
1-12			Blank
13-36	4A6	ALPHA	FLUID b LUMP b DATA bbbbbbbbb where b denotes a blank.

Card 4

Columns	Format	Nomenclature	Description
1-5	I5	LN	Lump number.
6-10	I5	NLU	Lump upstream. NLU=0 for first lump in every tube.
11-15	I5	NTB	Tube number.
16-20	I5	NTYP	Type number.
21-30	F10.5	TI	Initial temperature, °F.

Repeat Card 4 for every fluid lump. The lumps must be numbered 1 through NTFL and must be in numerical order.

Tube Data Cards

Card 1

Columns	Format	Nomenclature	Description
1-12			Blank
13-36	4A6	ALPHA	TUBE b TYPE b DATA bbbbbbbbb where b denotes a blank.

Card 2

Columns	Format	Nomenclature	Description
1-5	F5.2	DEN	Density, lb/ft^3.
6-10	I5	NCONC	Conductivity curve number.
11-15	I5	NSHC	Specific heat curve number.
16-20	I5	NABC	Absorptivity curve number.
21-25	I5	NEMC	Emissivity curve number.
26-30	I5	NTCT	Number of tube lumps conducted "to".
31-35	I5	NFCT	Number of structure lumps conducted "to".

Columns	Format	Nomenclature	Description
36-40	I5	LCC	= 0, Lumps of this type have longitudinal conduction. = 1, Lumps of this type do not have longitudinal conduction.
41-50	F10.5	X1	Dimensions, in. X1·X2·X3 = volume
51-60	F10.5	X2	X1/2 = longitudinal conduction distance.
61-70	F10.5	X3	X2·X3 = area for longitudinal conduction.

Card 3

Columns	Format	Nomenclature	Description
1-10	F10.5	AHT	Area for heat transfer to enclosed fluid lump, sq. in.
11-20	F10.5	AE	Surface area for external radiation, sq. in.
21-30	F10.5	FAC	Factor for dividing conduction distances and dimensions. Routine sets to 1.0 if left blank. Use when conduction dimensions do not fit into the five column fields.
31-35	F5.5	Y1	Conduction distance of this type of "from" lump to first "to" lump.
36-40	F5.5	Y2	Conduction distance for first "to" lump listed for this type of "from" lump.
41-45	F5.5	B	B x D is area for conduction for first "to" lump for this type of lump.
46-50	F5.5	D	
51-55	F5.5	Y1	Conduction data for second "to" lump.
56-60	F5.5	Y2	
61-65	F5.5	B	
66-70	F5.5	D	

If NTCT + NFCT > 2, follow with Card 4

Card 4

Columns	Format	Nomenclature	Description
1-10			Blank
11-15	F5.5	Y1	Conduction data for third "to" lump.
16-20	F5.5	Y2	
21-25	F5.5	B	
26-30	F5.5	D	

Columns	Format	Nomenclature	Description
31-35	F5.5	Y1	Conduction data for fourth "to" lump.
36-40	F5.5	Y2	
41-45	F5.5	B	
46-50	F5.5	D	
51-55	F5.5	Y1	Conduction data for fifth "to" lump.
56-60	F5.5	Y2	
61-65	F5.5	B	
66-70	F5.5	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

1-12			Blank
13-36	4A6	ALPHA	TUBE b LUMP b DATA bbbbbbbbb where b denotes blank.
37-80			Blank

Card 6 (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	I5	LN	Lump number.
6-10	I5	NDL	Lump number of tube lump downstream. = 0, for last lump in each tube.
11-15			Blank
16-20	I5	NTYPE	Type number of lump
21-30	F10.5	TI	Initial temperature, °F.
31-35	I5	NQIC	Incident heat curve number.
36-40	I5	NTWC	Prescribed temperature curve number (may be left blank)
41-45	I5	NTL1	First lump conducted "to".
46-50	I5	NTL2	Second lump conducted "to".

Columns	Format	Nomenclature	Description
51-55	I5	NTL3	Etc.
56-60	I5	NTL4	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	I5	NTL5	
66-70	I5	NTL6	

Card 7 (Continuation of list of lumps conducted "to". If the number of lumps conducted "to" is greater than 6, follow Card 6 with Card 7).

1-5	I5	NTL	Next lump conducted "to".
6-10	I5	NTL	Next lump conducted "to".
Etc. to			
66-70	I5	NTL	

Repeat Card 7 as needed to list all lumps.

Repeat Card 6 followed by Card 7 (if required) for every lump. The lumps must be given in increasing numerical order.

Structure Data Cards

Card 1

1-12			Blank
13-36	4A6	ALPHA	STRUCTURE b TYPE b DATE bbbbbbbbb where b denotes a blank
37-80			Blank

Card 2

1-5	F5.2	DEN	Density of fin material, lb/ft^3.
6-10	I5	NCONC	Conductivity curve number.
11-15	I5	NSHC	Specific heat curve number.
16-20	I5	NABC	Absorptivity curve number.
21-25	I5	NEMC	Emissivity curve number.

Columns	Format	Nomenclature	Description
26-30	I5	NFCT	Number of fin lumps conducted "to" by lumps of this type.
31-40	F10.5	X1	Dimensions of lump, inches.
41-50	F10.5	X2	X1·X2·X3 = Volume.
51-60	F10.5	X3	X1·X2 = External radiation area.

If NFCT > 0, enter Card 3.

Card 3

Columns	Format	Nomenclature	Description
1-10	F10.5	FAC	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	F5.5	Y1	Data for conduction to first lump conducted "to" by this type lump.
16-20	F5.5	Y2	
21-25	F5.5	B	
26-30	F5.5	D	
31-35	F5.5	Y1	Data for second lump conducted "to" by this type lump.
36-40	F5.5	Y2	
41-45	F5.5	B	
46-50	F5.5	D	
51-55	F5.5	Y1	Data for third lump conducted "to" by this type lump.
56-60	F5.5	Y2	
61-65	F5.5	B	
66-70	F5.5	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

Columns	Format	Nomenclature	Description
1-12			Blank
13-36	4A6	ALPHA	STRUCTURE b LUMP b DATA bbbbbbbbb where b denotes a blank
37-80			Blank

Card 5 (Structure Lump Cards) (One for each structure lump. The lumps must be numbered 1 through NSL and must be entered in numerical order)

Columns	Format	Nomenclature	Description
1-5	I5	LN	Lump number.
6-10	I5	LTYPE	Type number of lump.
11-20	F10.5	TL	Initial temperature of lump, °F.
21-25	I5	NQIC	Incident heat curve number.
26-30	I5	NTWC	Prescribed temperature curve number (may be left blank).
31-35	I5	NTL1	First lump conducted "to".
36-40	I5	NTL2	Second lump conducted "to".
41-45	I5	NTL3	Etc.
46-50	I5	NTL4	The order in which the lumps
51-55	I5	NTL5	conducted "to" are listed will
56-60	I5	NTL6	depend upon the order in which
61-65	I5	NTL7	the conduction data was given
66-70	I5	NTL8	on the type cards.

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

1-5	I5	NTL9	Ninth lump conducted "to".
6-10	I5	NTL10	Tenth lump conducted "to".
11-15	I5	NTL11	Eleventh lump conducted "to".
Etc. to			
66-70	I5	NTL22	Twenty-second lump conducted "to".

Repeat Card 6 if number of lumps conducted "to" is greater than 22.

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

Curve Data Cards

Card 1

1-12			Blank
13-36	4A6	ALPHA	Curve b Data bbbbbbbbbbbbbb where b denotes a blank

Columns	Format	Nomenclature	Description
Card 2 (Curve Header Card)			
4-5	I5	KCRV	Kind of curve code. Two curves may be the same number if kind of curve is different.
	0		K curve for pressure drop, dimensionless = $f(Re \times 10^{-3})$
	1		Density of fluid or liquid, $lb_m/ft^3 = f(°F)$.
	2		$(lb_m/ft\text{-}sec)(x\ 10^3) = (°F)$
	3		Friction factor for fluid, $f \times 10^3 = f(Re \times 10^{-3})$. (Used when Re 2000).
	4		Conductivity, BTU/hr-ft-°F = f(°F).
	5		Specific heat, BTU/lb_m-°F = f(°F)
	6		Absorptivity, dimensionless = f(°F)
	7		Emissivity, dimensionless = f(°F)
	9		Incident heat, $BTU/hr\text{-}ft^2$ = f(hours)
	10		Prescribed temperature, °F = f(hours)
	11		Total flow rate, lb_m/hr = f(hours)
	12		Fluid inlet temperature, °F = f(hours)
	13		This card signals the END OF CURVE DATA.
6-10	I5	NC	Curve number.
11-15	I5	NP	Number of points on curve.
16-72			May be used for curve title.
Cards 2 through 2 NP/7 (Curve Data Cards)			
1-10	FP F10.5	X1	Independent variable.
11-20		X2	

Columns	Format	Nomenclature	Description
21-30		X3	
Etc.			
	FP F10.5	Y1	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.

4.4.2 Automatic Nodal Subdivision (See Section 4.3.1) Cards

The Automatic Nodal Subdivision (ANS) cards are added if NORAD, the number of radiator panels to be subdivided, (Parameter Card 2, Columns 65-66) is not zero. One set of ANS cards are added for each radiator panel to be subdivided. That is, if NORAD = 1, one set of ANS cards are needed; if NORAD = 2, two sets of ANS cards are needed. There are two sets of ANS cards, one for rectangular panels and one for circular panels. Each panel to be subdivided must be represented by the proper set of cards; ANS-R cards for rectangular panels and ANS-C for circular panels. The location of the ANS cards relative to the other data cards depends on the value of INDATA (Parameter Card 2, Columns 67-68) which indicates where the data is to be found and whether it will be edited by the EDIT subroutine. The ANS cards for side 1 are placed first followed by the ANS cards for side 2. The following tabulation describes the location of the ANS cards relative to the other data for the various values of INDATA and output tape units required for each value of INDATA.

INDATA	LOCATION OF ANS CARDS 1 THRU 6	OUTPUT TAPE UNITS REQUIRED
0	After Parameter Card 4	B
1	After 13 cards	B & C
2	After last EDIT cards (99999 Card)	B & C
3 thru 5	After Parameter Card 2	B

A description of the ANS cards for rectangular and circular panels are given below.

Rectangular Panels

For all rectangular panels (NTYPE(N) = 1, Parameter Card 4) to be subdivided by the Automatic Nodal Subdivision Routine, six cards are necessary as described below.

Columns	Format	Nomenclature	Description
Card ANS-1R			
1-10	E10.3	X	Panel length, (x) in.
11-20	E10.3	Y	Panel height, (y) in.
21-30	E10.3	T	Panel thickness, in.
31-33	I3	NX	Number of nodes in the x-direction
34-35	I2	NTUBE	Number of tubes in the y-direction
36-37	I2	NY	Number of structure lumps between tubes.
38	I1	CODE	= 0, parallel flow = 1, serpentine flow
39-52			Blank - Starting lump, type and tube numbers furnished by TPR.
53-54	I2	NZX	Number of incident heat zones in the x-direction.
55-56	I2	NZY	Number of incident heat zones in the y-direction.
57-63	E7.3	TCSA*	Tube cross-sectional area, in^2.
64-70	E7.3	TUBWID*	Width of tube lumps in the y-direction, in.
71-76	A6	TINIT	Initial temperature of all lumps, °F.
77	I1	IN2D	= 1, 2-D panel. = 0, 1-D panel.

* Input of both these variables allows the user to distinguish between physical tube lump width (TUBWID) and the corresponding cross-sectional area.

Columns	Format	Nomenclature	Description
78	I1	IN2DC	= 1, Connect to following panel = 2, Connect to first of this series of 4 panels.
79	I1	IN2DD	= 1, Disconnect this panel on the diagonal.
80			Blank

Card ANS-2R (Information for Fluid Type Card)

Columns	Format	Nomenclature	Description
1-25			Blank - Fluid property curve numbers supplied by TPR.
26-30	5A6	NKPDC	Dynamic headloss factor (K) number.
31-50	Blank		
51-60		CSA	Fluid cross-sectional area, in^2.
61-67	3A6, A4	WP	Wetted perimeter, in.
68-72		FRE	Friction factor adjusting coefficient.

Card ANS-3R (Information for Tube Type Cards)

Columns	Format	Nomenclature	Description
1-5		DENM	Density, lb_m/ft.
6-10		NCONC	Conductivity curve number.
11-15	4A6, A1	NSHC	Specific heat curve number.
16-20		NABC	Absorptivity curve number.
21-25		NEMC	Emissivity curve number.
39-40	I2	LCC	Longitudinal conduction code = 0, lumps in this panel conduct longitudinally = 1, lumps in this panel do not conduct longitudinally

Card ANS-4R (More information for tube type cards)

Columns	Format	Nomenclature	Description
1-10	3A6, A2	AHT	Area for heat transfer to enclosed fluid lump, in^2.
11-20		AE	Area of surface for external radiator, in^2.
21-30	E10.3	YCTS	Conduction distance for tube to structure, in.

Columns	Format	Nomenclature	Description

Card ANS-5R (Information for Structure Type Cards).

1-5		DEN	Density, lb_m/ft^3
6-10		NCONC	Conductivity curve number
11-15	4A6, A1	NSHC	Specific heat curve number
16-20		NABC	Absorptivity curve number
21-25		NEMC	Emissivity curve number

Card ANS-6R

1-5	I5		Incident heat curve number for first zone.
6-10	I5		Incident heat curve number for second zone.
Etc. to			
46-50	I5		Incident heat curve number for tenth zone.

Repeat Card ANS-6R as many times as necessary to supply an incident heat curve number for each zone.

Repeat Card ANS-1R through Card ANS -6R for each rectangular radiator panel to be subdivided.

Circular Panels

For each circular panel (NTYPE(N) = 2, Parameter Card 4) to be subdivided by the Automatic Nodal Subdivision Routine, six cards are necessary as described below.

Card ANS-1C

1-10	F10.0	Radius	Panel radius, in.
11-15	F5.0	DELTA	Panel thickness, in.
16-20	F5.0	DIAMI	Inside tube diameter, in.
21-25	F5.0	LMAX	Maximum length of tube node desired, in. (may be left blank)
26-30	F5.0	LMIN	Minimum length of tube node allowed.

Columns	Format	Nomenclature	Description
36-37	I2	NT	Number of tubes on panel.
38-52			Blank - Starting lump, type and tube numbers furnished by TPR.
53-54	I2	NS	Number of structure lumps between tubes.
55-56	I2	NQL	Incident heat curve number for last zone.
57-63	F7.0	TCSA	Tube cross-sectional area, in^2.
64-70	F7.0	TW	Width of tube lumps in radial direction, in.
71-79	F9.0	TINIT	Initial temperature of all lumps, °F.
80			Blank

Card ANS-2C (Needed only if LMAX $\leq$ 0.0)

1-5	I5	NTBS(1)	Number of tube lumps for first tube.
6-10	I5	NTBS(2)	Number of tube lumps for second tube.
11-15	I5	NTBS(3)	Number of tube lumps for third tube.
Etc. to			
76-80	I5	NTBS(16)	Number of tube lumps for sixteenth tube.

Repeat card ANS-2C as many times as necessary to supply number of tubes lumps for each tube.

Card ANS-3C (Information for Fluid Type Card)

1-25			Blank - Fluid property curve numbers supplied by TPR.
26-30	I5	NKPDC	Dynamic head loss (K) factor number.
31-50			Blank
51-60	F10.0	CSA	Fluid cross-sectional area, in^2.

Columns	Format	Nomenclature	Description
61-67	F7.0	WP	Wetted perimeter.
68-72	F5.0	FRE	Friction factor adjusting coefficient.

Card ANS-4C (Information for Tube Type Cards)

1-5	F5.0	DENMT	Density, lb_m/ft^3
6-10	I5	NCONCT	Conductivity curve number.
11-15	I5	NSHCT	Specific heat curve number.
16-20	I5	NABCT	Absorptivity curve number.
21-25	I5	NEMCT	Emissivity curve number.
39-40	I2	LCC	Longitudinal conduction code = 0, lumps in this panel conduct longitudinally = 1, lumps in this panel do not conduct longitudinally

Card ANS-5C (Information for Structure Type Cards)

1-5	F5.0	DENS	Density, lb_m/ft^3
6-10	I5	NCONCS	Conductivity curve number.
11-15	I5	NSHCS	Specific heat curve number.
16-20	I5	NABCS	Absorptivity curve number.
21-25	I5	MENCS	Emissivity curve number.

Card ANS-6C

1-10	F10.0	YICEP1	Y-axis intercept for incident heat zone boundary line number 1.
11-20	F10.0	XICEP1	X-axis intercept for incident heat zone boundary line number 1.
21-30	F10.0	BETA1	Angle between incident heat zone boundary line and (+) x axis of panel, degrees, (Needed only if YICEP1 = XICEP1 = 0.0)
31-35	I5	NQCURV	Incident heat zone curve number.

Columns	Format	Nomenclature	Description
36-40	I5	NLINE	Number of boundary lines defining incident heat zone (1 or 2).
41-50	F10.0	YICEP2*	Y-axis intercept for incident heat zone boundary line number 2.
51-60	F10.0	XICEP2*	X-axis intercept for incident heat zone boundary line number 2.
61-70	F10.0	BETA2*	Boundary line angle (degrees).
75	I1	NCODE	= 0, Indicates more incident heat zone information follows. = 1, Indicates last incident heat zone data card. = 2, Indicates only one incident heat zone for this panel.

Repeat Cards ANS-6C as many times as necessary to supply incident heat zone data for each zone.

Repeat Cards ANS-1C through ANS-6C for each circular radiator panel to be subdivided.

---

* These parameters are needed only when NLINE = 2.

Two-Dimensional Rectangular Panels

For each 2-d panel (NTYPE (N) = 3, Parameter Card 4) to be subdivided by the Automatic Nodal Subdivision Routine, five cards are necessary as described below.

Card ANS-1D

Columns	Format	Nomenclature	Description
1-10	F1010	PANWID	Panel width, in.
11-20	F1010	TUBWID	Tube width, in.
21-25	F510	DELTA	Fin thickness, in.
26-30	F510	TCSA	Tube cross-sectional area, $in.^2$
31-35	F510	DIAM	Inside tube diameter, in.
36-40	F510	TSP1	Tube spacing for first tube (leave blank for equal tube spacing)
41-45	F510	XMAX1	Maximum length of tube nodes for first tube (may be left blank)
46-50	F510	XMAX2	Maximum length of tube nodes in remaining tubes (may be left blank)
51-60	F1010	TINIT	Initial temperature of all lumps
61-65	I5	NT	Number of tubes on panel
66-70	I5	NTRI	Number of triangles on panel (Must equal 4)
71-75	I5	NDIUA	Number of allowable subsequent tube divisions after first tube (overrides XMAX2 option, may be left blank)
76-80	I5	NQZONE	Incident heat zone number

Card ANS-2D (Use only when XMAX2 = 0.0)

Columns	Format	Nomenclature	Description
1-5	I5	NTL1	Number of tube lumps in first tube.

Columns	Format	Nomenclature	Description
6-10	I5	NTL2	Number of tube lumps in second tube.
76-80	I5	NTL16	Number of tube lumps in sixteenth tube.

Continue on another card if NT 16.

Card ANS-3D

1-5	I5	NKPDC	Curve number for N*PDC curve (May be left blank)
6-10			Blank
11-20	F1010	FCSA	Fluid cross-sectional area, in.^{2}.
21-30	F1010	WP	Wetted perimeter, in.
31-40	F1010	FRE	Friction factor adjusting coefficient (normally = 1.0)

Card ANS-4D (Tube type data)

1-10	F1010	DENT	Density of tube lumps, lb_m/ft^3
11-15	I5	KT	Conductivity curve number
16-20	I5	CPT	Specific heat curve number
21-25	I5	ALPHAT	Absorptivity curve number
26-30	I5	EMIST	Emissivity curve number
31-35	I5	LCC	Longitudinal conduction code = 0 considered = 1 not considered

Card ANS-5D (Structure type data)

Columns	Format	Nomenclature	Description
1-10	F10.0	DENS	Density of structure lumps, lb_m/ft^3
11-15	I5	KS	Conductivity curve number
16-20	I5	CPS	Specific heat curve number
21-25	I5	ALPHAS	Absorptivity curve number
26-30	I5	EMISS	Emissivity curve number

4.4.3 Plot Program

1. Control Cards

```
7/8 ASG A = PCF (Program tape)

7/8 ASG I = PLOT (History tape)

7/8 XQT CUR

    TRW A

    IN A

    TRI A

7/8 XQT PROG

Parameter cards and data cards, if any

7/8 XQT PLOT A

Plot data cards

7/8 EOF
```

2. Data Cards

Columns	Format	Name	Description
a. Case Title Card			
1-72	12A6	TITLEA	Title to be printed at the top of each grid.
b. Time Card			
1-10	F10.0	TA	First value of time to be plotted (hrs)
11-20	F10.0	TZ	Last value of time to be plotted (hrs)
21-30	F10.0	TPG	Time range for each grid (hrs)
c. Items Cards (Any quantity, followed by a blank card)			
1-5	I5	ITEM	The item number to be plotted. Use a negative value if this item is to start a new grid. A maximum of four curves may be plotted on one grid. Insert a blank card when the number of items exceeds

Columns	Format	Name	Description
			35,000 divided by the number of points between TA and TZ. More item cards may then follow this blank card if more curves are to be plotted.
6-7	A2	ITYPE	A two character item type code. (See 3 for definitions)
11-58	8A6	TITLES	Item description to be printed at the top of each grid, along with the plotting symbol which is generated and used by the program.

The next two values are optional on the cards whose item numbers are negative and are ignored on all other item cards.

61-70	F10.0	YLO	The minimum value of the y-axis.
71-80	F10.0	YHI	The maximum value on the y-axis.

3. Detail Type and Item Descriptions

Type	Item	Description
MP	1	Pressure drop in system
PR	1-N	Pressure drop of 1 through N tubes
BT	1	Heat rejection of system 1
FR	1-N	Flowrate of 1 through N tubes
FT	1-N	Fluid temperature of 1 through N lumps
TT	1-N	Tube temperature of 1 through N lumps
ST	1-N	Structure temperature 1 - through N lumps

5.0 COMPUTER INCIDENT HEAT ROUTINE

The Computer Incident Heat Data Routine (CIHR) was developed to reduce the large amount of user time required to generate incident heats for use in LTV thermal analyzers for orbital missions. Prior to the availability of this routine this task consisted of (1) running the Midwest Research Institute (MRI) Routine to obtain the incident heats, (2) selecting the number of points required to describe the curves, and (3) filling out data sheets for key punching the curves in a format compatible with LTV routines. Using the CIHR, only the first step is required. The remaining steps required to obtain the incident curves on cards are performed by the computer including (1) surveying the points to determine the minimum number needed to define the curves and (2) punching the cards in a format compatible to LTV routines.

The CIHR was created by modifying the Midwest Research Institute's Heat Rate Routine described in Reference 4 to: (1) survey the data points of each heat rate curve generated by it and select only the points necessary to describe the curve for linear interpolation, (2) punch an output curve generated from the selected points on cards with the appropriate curve number in LTV curve format, and (3) plot the curve created by the selected points with original curve on the same grid and the output curve on another grid. The method used to select points along with the additions to the data preparation described in Reference 5 are given below.

Method

Points to describe a heat rate curve are selected from the points of the curve itself such that the heat rate difference between the original curve and curve created by the selected points is never greater than a tolerance. In Figure 5-1, points A, B, C, and D are the data points of the original curve. Points A, C, and D are selected to describe the curve. Point B is eliminated because D1 is less than the tolerance and C is selected because D2 is greater than the tolerance.

Data Preparation

The data preparation for the computer incident heat routine is given in Reference 5 except for the following new values on the low altitude planet temperature card and element card.

A list is given on the following pages summarizing the various data that might be punched as program input data. For each type of card a description is given of all applicable fields. Page numbers referencing additional information in this manual are also given. If the entry under "Applicability" is blank, the field in question may pertain to all kinds of cases. If there is an entry under "Applicability", however, the field is pertinent only for the type of case designated. For all other types of cases the field is not applicable, i.e., it can be left blank.

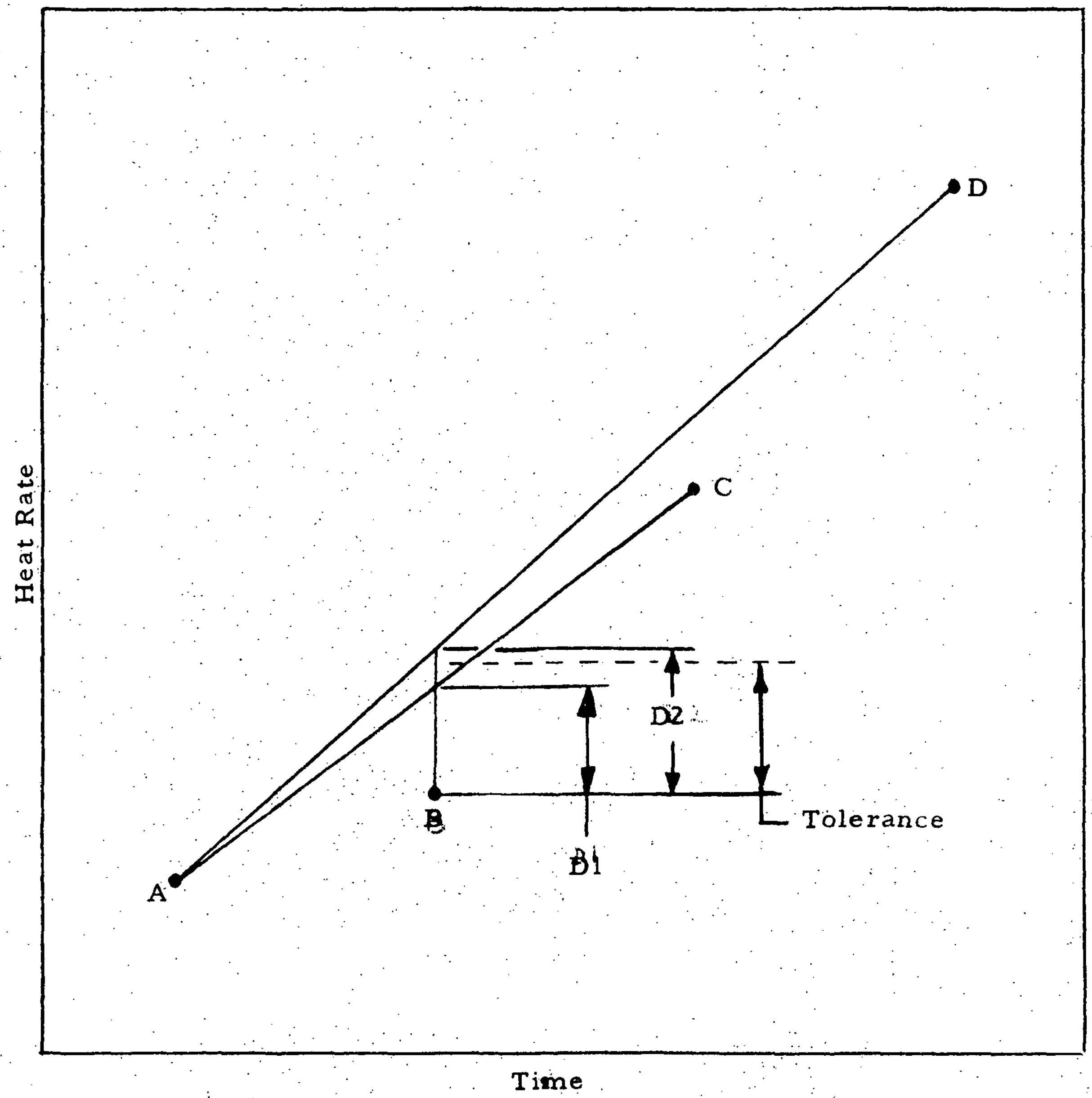


FIGURE 5-1 ILLUSTRATION OF METHOD USED TO SELECT POINTS

Note that the entire 05 card is not applicable to trajectory tape missions and can be omitted in such cases. Likewise the 08 card is not applicable to orbital missions.

The formats listed are those used by the program; however, for all fields specified as E8.1 it is advisable to punch the number with a decimal point but with no exponent unless the magnitude of the number is so large or so small as to require exponents. For example, one (1) in this format could be punched as "0.1E 01", but fewer errors would be made if it were simply punched as "1.0" anywhere in the eight-column field. Numbers in I format must be right justified in their appropriate fields.

CASE NUMBER AND CONTROL INFORMATION (01 CARD)

Columns	Format	Applicability	Description	Ref. 5 Page
1-2	I2		Card code (=01).	
3-5	I3		Case number.	
9-12	I4		Number of elements to be analyzed ($1 \leq n \leq 1000$).	
13-20	E8.1	Orbital	ϕ_o, the initial value for true anomaly.	49
21-28	E8.1	Orbital	ϕ_o, the increment of true anomaly at which heat fluxes are calculated.	
37-44	E8.1	Traj. tape	First time (min.) in which program parameters are to be instantaneously changed.	
78	I1		Configuration number (1-6) if Apollo shadow factors stored on tape are required for this case. (Shadow tape must be mounted when a valid configuration number is used.) Blank or 0 is used when no shadow factors are used.	
79	I1		For 0 or blank, only absorbed heated are printed out. For 1, incident and absorbed heats are printed out.	
80	I1		For 0 or blank, fluxes in BTU/hr-ft^2 are printed out. For 1, products of fluxes and element areas in BTU/hr are printed out.	

ORIENTATION AND ROTATION (02 CARD)

Columns	Format	Applicability	Description	Ref. 5 Page
1-2	I2		Card code (=02).	
3-5	I3	Rotating	Ω_r(°), one of angles describing axis of vehicle rotation.	53
6-8	I3	Rotating	Λ_r(°), one of angles describing axis of vehicle rotation.	53
9-12	I4		For 1, vehicle is planet oriented. For 0, vehicle spins rapidly about random axes. For -1, vehicle is sun-oriented. For -2, vehicle is star-oriented.	
13-20	E8.1		(°), vehicle roll angle.	52
21-28	E8.1		ρ(°), vehicle pitch angle.	52
29-36	E8.1		Ψ(°), vehicle yaw angle.	52
37-44	E8.1		η_r(rph), rate of vehicle rotation. Blank or 0 is used when vehicle is not rotating.	
45-52	E8.1	Star-Oriented	X-component of a vector pointing to orientation star.	
53-60	E8.1	Star-Oriented	Y-component of a vector pointing to orientation star.	
61-68	E8.1	Star-Oriented	Z-component of a vector pointing to orientation star.	

PLANET (03 CARD)

Columns	Format	Applicability	Description	Ref. 5 Page
1-2	I2		Card code (=03).	
3-5	I3		For 1 to 9, number is taken as planet code.	60
8	I1		0 for constant surface temp.	
			1 for variable temp.	
			For 0 or blank, planet data are read from columns 13-52.	
13-20	E8.1	Unknown planet	Distance from planet to sun in nautical miles.	
21-28	E8.1	Unknown planet	Planet radius in nautical miles.	
29-36	E8.1	Unknown planet	Planet albedo.	
37-44	E8.1	Unknown planet	GM_p (ft^3/sec^2), gravitational constant times planet mass.	
45-52	E8.1	Unknown planet	Adjusted cold side temperature (°R).	

MISSION (04 CARD)

Columns	Format	Applicability	Description	Ref. 5 Page
1-2	I2		Card code (=04).	
3-5	I3		For 0 or blank, trajectory tape mission is to be run. For 1, orbital mission is to be run.	
6-8	I3	Orbital	Number of degrees of true anomaly for which program computes.	49
9	I1	Traj. tape	Planet code of first trajectory tape planet of reference.*	
10	I1	Traj. tape	Planet code of second trajectory tape planet of reference.*	
13-20	E8.1	Orbital	Apogee in nautical miles.	
21-28	E8.1	Orbital	Perigee in nautical miles.	

---

* Unless new routines are written to manipulate the trajectory tape (see Appendix I of Reference 5-1) the planet codes are 1 and 2, respectively.

SUN POSITION (05 CARD)

Columns	Format	Applicability	Description	Ref. 5 Page
1-2	I2	Orbital	Card code (=05).	
3-5	I3	Orbital	A code to specify sun position input option. Value must be 1, 2, 3 or 5. The code instructs the program how to interpret data in 13-76.	
6-8	I3	Orbital	For 1, sun-shade points ϕ_{in} and ϕ_{out} are read from columns 61-76. Otherwise they are computed.	
13-20	E8.1	Orbital	Angle i(°) if column 5 contains 1 or 5.	51
			Angle Σ(°) if column 5 contains 2.	50
			Angle α(°) if column 5 contains 3.	50
21-28	E8.1	Orbital	Angle ω(°) if column 5 contains 1 or 5.	51
			Angle β(°) if column 5 contains 2 or 3.	50
29-36	E8.1	Orbital	Angle Ω(°) if column 5 contains 1 or 5.	51
			Angle γ(°) if column 5 contains 3. Otherwise blank.	50
37-44	E8.1	Orbital	Angle RA(°) if column 5 contains 5.	50
			Year if column 5 contains 1. Otherwise blank.	
45-52	E8.1	Orbital	Angle DEC(°) if column 5 contains 5.	50
			Month if column 5 contains 1. Otherwise blank.	

SUN POSITION (05 CARD) (Concluded)

Columns	Format	Applicability	Description	Ref. 5 Page
53-60	#8.1	Orbital	Day of month if column 5 contains 1. Otherwise blank.	
61-68	E8.1	Orbital	Hour of day (0 to 23) if column 5 contains 5.	
			ϕ_{in} (°) if column 8 contains 1. Otherwise blank.	
69-76	E8.1	Orbital	Minute of hour (0. to 60.) if column 5 contains 5.	
			ϕ_{out} (°) if column 8 contains 1. Otherwise blank.	

REDEFINITION (06 CARD)

Columns	Format	Applicability	Description	Ref. 5 Page
		(Subcase with 3, 4, 5, or 6 in column 12)		
1-2	I2		Card code (=06).	
3-5	I3		Index of first table entry on card.	
6-8	I3		Index of last table entry on card.	
9-12	I4		Code describing type of table being defined. Code 3 indicates f_s versus t. Code 4 indicates f_p versus t. Code 5 indicates g versus δ. Code 6 indicates b_m versus T.	
13-76	8E8.1		Table entries to be stored as index ranges from first to last value.	
77-78	I2		Number of table being defined (from 1 to 16).	
		(Subcase with 7, 8, or 9 in column 12)		
1-2	I2		Card code (=06).	
3-5	I3		Material code (from 1 to 16).	
6-8	I3		Corresponding table numbers (from 1 to 16).	
9-12	I4		Code describing type of table assignment. Code 7 indicates assignment of f_p versus t table. Code 8 indicates assignment of f_s versus t table. Code 9 indicates assignment of g versus δ table.	

REDEFINITION (06 CARD) (Concluded)

Columns	Format	Applicability	Description	Ref. 5 Page
		(Subcase with 10 in columns 11 - 12)		
1-2	I2		Card code (=06).	
9-12	I4		Subcode (=10) indicating solar constant is redefined.	
13-20	E8.1		New value of solar constant.	
		(Subcase with 11 in columns 11 - 12)		
1-2	I2		Card code (=06).	
3-5	I3		Code of first material referenced on this card.	
6-8	I3		Code of last material referenced on this card.	
9-12	I4		Subcode (=11) indicating that this card redefines values of α_m for one or more materials.	
13-76	8E8.1		Values of α_m for materials with codes ranging from first to last as shown in columns 3-5 and 6-8.	

LOW ALTITUDE PLANET TEMPERATURE (07 CARD)

Columns	Format	Applicability (or Name)	Description	Ref. 5 Page
1-2	I2		Card code (=07).	
3-5	I3	NSELC	=0, No output curves requested. =1, Output curves requested for specified elements.	
9-12	I4	NTOL	Type of tolerance code for CIHR = 0, Absolute. = 1, Relative.	
13-20	E8.1		Altitude (n.m.) below which planet temperatures computed by the program are superseded by temperature in columns 21-28 of this card. For blank or 0. the program always uses computed temperatures. This altitude is understood to be zero unless an 07 card is read to redefine it.	
21-28	E8.1		Planet temperature (°R) used by the program when the altitude is below the value in columns 13-20 of this card.	
29-36	E8.1	TOL	Tolerance for CIHR (BTY/hr if NTOL= 0 and percent if NTOL = 1).	
37-44	E8.1	START	Start time for output curves (hr)	
45-52	E8.1	STOP	Stop time for output curves (hr)	
53-60	E8.1	TIMADD	Time adjustment to the original curve (hr)	
61-68	E8.1	QADD	Heat rate adjustment to the original curve (BTU/hr).	
77-78	I2	NORBIT	Number of cycles of selected data points to be in output curves.	
79	I1	NPUNCH	= 0, No punched output = 1, Punch output curve on cards	
80	I1	NPLOT	= 0, No plot output = 1, Plot output	

If no 07 card is read, no output curves are generated. If NSELC equals zero, the other variables described above are not used. If START is less than the time of the first data point, the output curves have zero heat rate from START to the first data point. The output curves end at STOP or after NORBIT cycles of the selected data points whichever is greater. If STOP is greater than the time of the last data point, the selected data is cycled until STOP is reached.

TRAJECTORY CONTINUATION (08 CARD)

Columns	Format	Applicability	Description	Ref. 5 Page
1-2	I2	Traj. tape	Card code (=08).	
13-20	E8.1	Traj. tape	Cutoff time (min.) for next segment of trajectory. When a time exceeding this value is read from the trajectory tape, the case will be interrupted to read parameters being instantaneously changed.	

ELEMENT (09 CARD)

Columns	Format	Applicability	Description	Ref. 5 Page
1-2	I2		Card code (=09).	
3-5	I3		Sequence number of element for this problem. The number must be no greater than the number of elements to be analyzed. Elements to be lumped together require adjacent sequence numbers.	
6-8	I3		If any of the internally stored element data are needed, the node number for the element must be punched. If this field does not contain a valid node number area, Λ_n and Ω_n are read from this card, and shadow factors cannot be referenced.	
9-12	I4		This field contains a nonzero numerical label which will identify the element in the output listing. If this field is blank or 0 the program uses node number in columns 6-8 as label.	
13-20	E8.1		Angle Λ_n (°) for the element in case values from internal tables are not used.	49
21-28	E8.1		Angle Ω_n (°) for the element in case values from internal tables are not used.	49
29-36	E8.1		Element area (ft^2) in case values from internal tables are not used.	
37-44	E8.1		For all elements which are to be lumped with succeeding elements, i.e., with elements having succeeding sequence numbers, this field must contain the same label punched in columns 9-12 unless they are blank, in which case it must contain the node number from columns 6-8. Note that the format here requires a decimal point.	

ELEMENT (09 CARD) (Concluded)

Columns	Format	Applicability	Description	Ref. 5 Page
45-52	E8.1		For 1.0 the value of Λ_n in 13-20 supersedes the value stored in internal tables. For blank or 0. the value from the internal table is used if a valid node number is given.	
53-60	E8.1		For 1.0 the value of Ω_n in 21-28 supersedes the value stored in internal tables. For blank or 0. the value from the internal table is used if a valid node number is given.	
61-68	E8.1		For 1.0 the value of area in 29-36 supersedes the value stored internally. For blank or 0. the value from internal tables is used if a valid node number is given.	
69-76	E8.1	NCURVE	0, Curve number of output curve for this element. 0, No output curve for this element. Note that the format here requires a decimal point.	
77-78	I2		Coating material number.	
79	I1		For 1, shadow factors for this node are loaded from the shadow tape and shadow logic is used to find heat fluxes. For 0, shadow logic is suppressed and factors are not loaded.	
80	I1		For 1, heats will be plotted for this element. For 0, plots will be suppressed.	

COMMENT (10 CARD)

Columns	Format	Applicability	Description	Ref. 5 Page
1-2	I2		Card code (=10).	
3-80	13A6		Alphameric comment.	

6.0 REFERENCES

1 Dietz, J. D., et.al., "Development of Computer Programs In Support of Radiator Analysis", VSD Report No. 00.1091, 11 December 1968.

2 Eckert, E. R. G. and Drake, R.M., <u>Heat and Mass Transfer</u>, McGraw-Hill Book Company, 1959.

3 Mackay, D. B., Hubler, V. A., "Digital Programs For Establishing Steady-State Space Radiator Performance", ASD-TDR-63-222, Flight Dynamics Laboratory, Wright-Patterson Air Force Base, October 1963.

4 Gaddis, J. L., "Explicit Finite Difference Heat Transfer Program, LVVM25", LTV Astronautics Report No. 00.823, dated 29 July 1966.

5 Finch, H. L., Sommerville, D., "Development of a Computer Program for Determining External Radiation Absorbed by the Apollo Spacecraft", MRI Project Number 2846-E Final Users Manual, 21 June 1966.

6 Chambers, R. L., and Somers, E. V., "Radiation Fin Efficiency for One-Dimensional Heat Flow in a Circular Fin", <u>Journal of Heat Transfer</u>, November 1959.

7 Lieblein, S., "Analysis of Temperature Distribution and Radiant Heat Transfer Along a Rectangular Fin of Constant Thickness", NASA TN D-196, November 1959.

8 Anderson, A. F., et al, "Radiator Design for Space Vehicles", AiResearch Manufacturing Company, Los Angeles, 1963.

APPENDIX A

DETERMINATION OF RADIAL FIN EFFECTIVENESS IN A NON-ZERO SINK TEMPERATURE ENVIRONMENT

1.0 SUMMARY AND INTRODUCTION

This Appendix presents the method and results of an analysis which was conducted to determine the fin effectiveness for circular radiating fins in a non-zero sink temperature environment. The second order nonlinear differential equation which describes the heat flow within the fin along with the associated boundary conditions were derived from the physical laws of heat transfer. The solution of the governing equation had been determined prior to this study for a limited range of design parameters, (Ref. 1A), but had not previously been determined for non-zero sink temperatures. In this study a numerical technique was devised whereby values of radial fin effectiveness could be determined from the governing equation for sink temperatures greater than or equal to zero. A computer program, Radial Fin Effectiveness Routine (RFER), was written incorporating this numerical technique and the solution was obtained for a wide range of design parameters with the use of a NASA-MSC Univac 1108 computer. A detailed discussion of the method and results is presented below.

2.0 DISCUSSION

The governing differential equation for a circular radiating fin can be derived as follows. Consider a heat balance on the surfaces of the differential element of a radial fin shown in Figure A-1.

On surface 1:

$$Q_r = -kA \frac{\partial T}{\partial r} \qquad A = \delta r d\theta$$

$$Q_r = K \delta r d\theta \frac{\partial T}{\partial r}$$

On surface 2:

$$Q_{r+dr} = Q_r + \frac{\partial}{\partial r} (Q_r)\, dr$$

On surface 3:

$$Q_{rad} = \epsilon \sigma A_r (T^4 - T_S{}^4) \qquad A_r = r d\theta dr \cdot Ns$$

$$Q_{rad} = Ns\, \epsilon\, \sigma\, r d\theta\, dr\, (T^4 - T_S{}^4)$$

where:

- Q = heat flux
- Ns = number of sides radiating
- ϵ = thermal emissivity
- δ = fin thickness
- K = thermal conductivity
- σ = Steffan-Boltzman constants

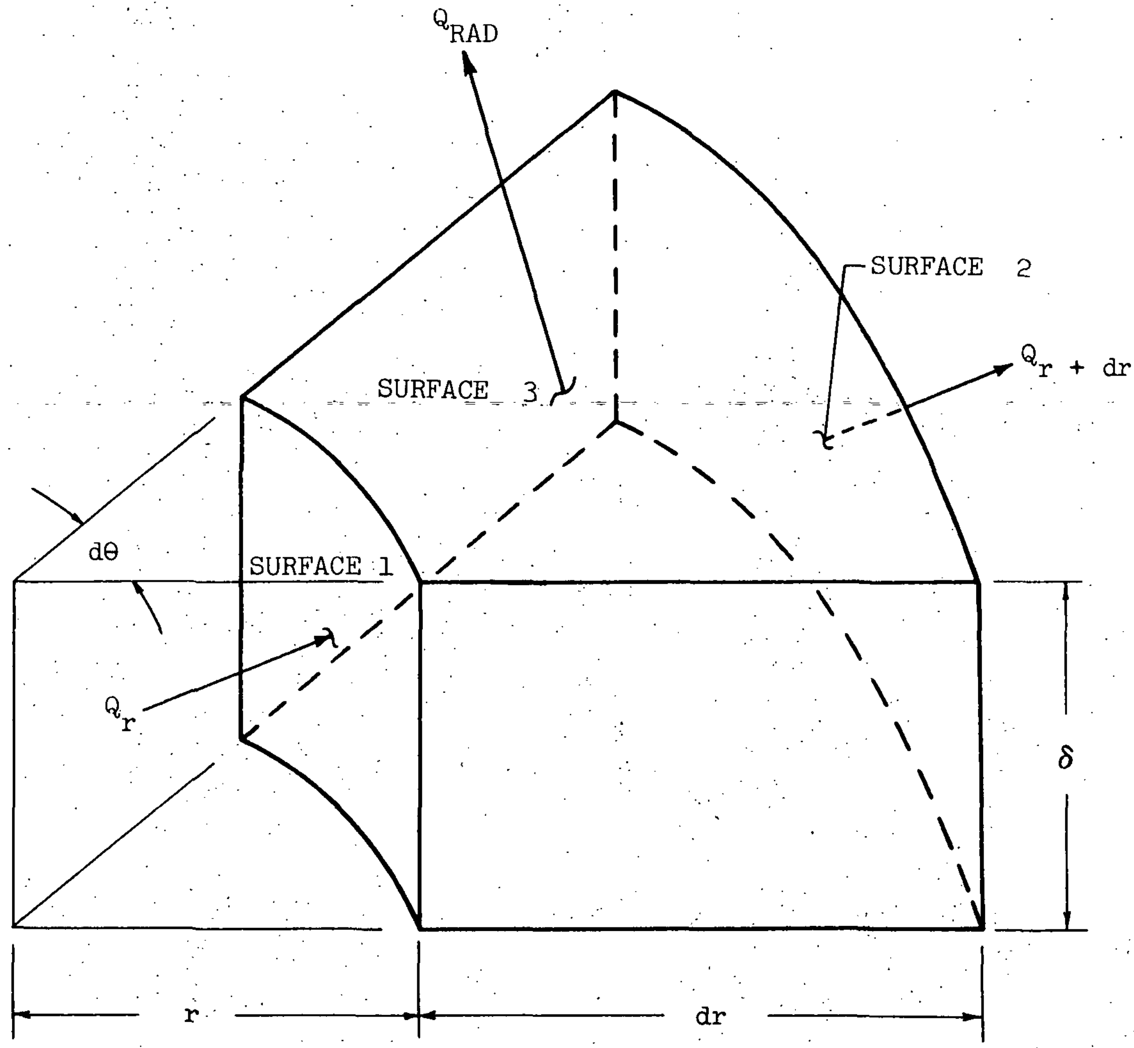


FIGURE A-1 - DIFFERENTIAL ELEMENT OF A RADIAL FIN

Assuming one dimensional radial heat flow, a heat balance gives:

$$Q_{in} = Q_{out}$$

$$Q_r = Q_{r+dr} + Q_{rad}$$

$$Q_{r+dr} - Q_r + Q_{rad} = 0$$

$$\frac{\partial Qr}{\partial r} dr + \epsilon\sigma r d\theta dr\ (T^4 - T_S)Ns = 0$$

$$\frac{\partial}{\partial r}[-K\delta r d\theta \ \frac{\partial T}{\partial r}] dr + \epsilon\sigma r d\theta dr (T^4 - T_S^{\ 4})Ns = 0$$

$$-K\ \delta\ 2\pi \frac{\partial}{\partial r}[r \frac{\partial T}{\partial r}] dr + 2\pi\epsilon\sigma r dr\ (T^4 - T_S^{\ 4})\ Ns = 0$$

$$-K\delta[\frac{\partial T}{\partial r} + \frac{r\,\partial^2 T}{\partial r^2}] + \epsilon\sigma r(T^4 - T_S^{\ 4})Ns = 0$$

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\ \frac{\partial T}{\partial r} - \frac{Ns\,\epsilon\sigma}{\delta K}(T^4 - T_S^{\ 4}) = 0 \qquad \text{Eq. 1}$$

If we let:

1) $\theta = T/Ti$ Ti = Temperature at r = ri

2) $R = \frac{r-ri}{ro-ri}$

3) $\theta s = Ts/Ti$

4) $\zeta = \frac{Ns\,\epsilon\,\sigma\ Ti^3(r_o - r_i)^2}{K\,\delta}$

5) $\gamma = \frac{r_i}{r_o - r_i}$

6) $\phi = \frac{r_o}{r_i}$

$r = ri + R(r_o - r_i)$

$T^4 = \theta^4 T_i^{\ 4}$

$T_S^{\ 4} = \theta_S^4\ T_i^{\ 4}$ $(T^4 - T_S^{\ 4}) = T_i^{\ 4}(\theta^4 - \theta_s^{\ 4})$

$$\frac{dT}{dr} = \frac{T_i d(T/T_i)}{(r_o - r_i)\ d(\frac{r-r_i}{r_o-r_i})} = \frac{T_i}{(r_o-r_i)}\ \frac{d\theta}{dR}$$

$$\frac{dT}{dr} = \frac{T_i}{(r_o - r_i)} \quad \frac{d\theta}{dR}$$

$$\frac{d^2T}{dr^2} = \frac{T_i}{(r_o - r_i)} \quad \frac{d}{dr} \left[\frac{d\theta}{dR}\right] = \frac{T_i}{(r_o-r_i)} \quad \frac{d(d\theta)}{(r_o-r_i)d\left(\frac{r-r_i}{r_o-r_i}\right)[dR]}$$

$$\frac{d^2T}{dr^2} = \frac{T_i}{(r_o-r_i)^2} \quad \frac{d^2\theta}{dR^2}$$

Substituting the above values of $\frac{dT}{dr}$, r, $(T^4-T_S^4)$ and $\frac{d^2T}{dr^2}$ into equation 1 gives:

$$\frac{T_i}{(r_o-r_i)^2} \quad \frac{d^2\theta}{dr^2} + \left[\frac{1}{r_i + R(r_o-r_i)}\right] \frac{T_i}{(r_o-r_i)} \quad \frac{d\theta}{dR} - \frac{Ns\,\epsilon\,\sigma\,T_i^4 (\theta^4-\theta s^4)}{K\,\delta} = 0$$

$$\frac{d^2\theta}{dR^2} + \frac{1}{(R + r_i/r_o-r_i)} \quad \frac{d\theta}{dR} - \frac{Ns\,\epsilon\,\sigma\,T_i^3(r_o-r_i)^2(\theta^4-\theta s^4)}{K\,\delta} = 0$$

$$\frac{d^2\theta}{dR^2} + \frac{1}{(R + \gamma)} \frac{d\theta}{dR} - \zeta\,(\theta^4-\theta s^4) = 0 \qquad \text{Eq. 2}$$

Equation 2 is the governing differential equation for the temperature of a one-dimensional radial fin in dimensionless form.

Calculation of Q from fin:

$$Q = \eta\,\epsilon\,\sigma\,Ns\,\pi\,(r_o^2-r_i^2)\,(T_B^4-T_S^4) \qquad \text{Eq. 3}$$

Calculation of Q conducted from tube:

$$Q = -KA \left(\frac{dT}{dr}\right)_{r=r_i} = -K\,\delta\,2\,\pi\,r_i\left(\frac{dT}{dr}\right)_{r=r_i} \qquad \text{Eq. 4}$$

Setting $T_i = T_B$

$$\theta = \frac{T}{T_B} \quad ; \quad d\theta = \frac{dT}{T_B}$$

$$R = \frac{r-r_i}{r_o-r_i} \quad ; \quad dR = \frac{dr}{(r_o-r_i)} = \frac{dr}{r_i}$$

$$(R)_{r=r_i} = 0$$

$$\frac{d\theta}{dR} = \frac{dT}{dr} \frac{r_o - r_i}{T_B}$$

$$\left(\frac{dT}{dr}\right)_{r=r_i} = \frac{T_B}{(r_o - r_i)} \left(\frac{d\theta}{dR}\right)_{R=0}$$

Setting equation 3 = equation 4

$$\eta \epsilon \sigma Ns \pi \; (r_o^2 - r_i^2)\,(T_B^4 - T_S^4) = \frac{-K \delta \, 2 \pi \, r_i T_B}{(r_o - r_i)} \left(\frac{d\theta}{dR}\right)_{R=0}$$

$$\left(\frac{d\theta}{dR}\right)_{R=0} = \frac{- \eta \epsilon \sigma Ns \pi \; (r_o^2 - r_i^2)(r_o - r_i)(T_B^4 - T_S^4)}{K \delta \, 2 \pi r_i T_B}$$

$$\left(\frac{d\theta}{dR}\right)_{R=0} = - \frac{\eta \epsilon \sigma Ns (r_o - r_i)^2 T_B^3 (1 - \theta_S^4)(r_o + r_i)}{2K \delta r_i}$$

$$\left(\frac{d\theta}{dR}\right)_{R=0} = - \frac{\eta \zeta (1/2 + \nu)(1 - \theta_S^4)}{\gamma} \qquad \text{Eq. 5}$$

From Eq. 2:

$$\left(\frac{d^2\theta}{dR^2}\right)_{R=0} = \zeta (1 - \theta_S^4) - \frac{1}{(0 + \gamma)} \left(\frac{d\theta}{dR}\right)_{R=0}$$

$$\left(\frac{d^2\theta}{dR^2}\right)_{R=0} = \zeta (1 - \theta_S^4) - \frac{1}{\gamma} \left(\frac{d\theta}{dR}\right)_{R=0} \qquad \text{Eq. 6}$$

Now with the values of $d\theta/dR$ and $d^2\theta/dR^2$ at the fin base, (R=0) known the differential equation can be integrated in step-wise manner. The only parameter which is not known is η or fin effectiveness. The procedure for obtaining the correct value of η is outlined in following section.

3.0 PROCEDURE FOR CALCULATING RADIAL FIN EFFECTIVENESS

Governing differential equation in dimensionless form:

$$\frac{d^2\theta}{dR^2} + \frac{1}{(R+\gamma)} \frac{d\theta}{dR} - \zeta (\theta^4 - \theta_s^4) = 0 \qquad \text{Eq. 7}$$

Boundary Conditions:

1) $\theta (0) = 1$

2) $\theta' (1) = 0$

3) $\theta (1) > 0$

Radial fin effectiveness is obtained by a step-wise integration of equation 7.

Calculate for each R_i; $R_i = 0, 1$

$$\theta_{i+1} = \theta_i + \left(\frac{d\theta}{dR}\right)_i (\Delta R) \qquad \text{Eq. 8}$$

$$\left(\frac{d\theta}{dR}\right)_{i+1} = \left(\frac{d\theta}{dR}\right)_i + \left(\frac{d^2\theta}{dR^2}\right)_i (\Delta R) \qquad \text{Eq. 9}$$

$$\left(\frac{d^2\theta}{dR^2}\right)_{i+1} = \zeta (\theta^4 - \theta_s^4) - \frac{1}{(R_{i+1} + \gamma)} \left(\frac{d\theta}{dR}\right)_i \qquad \text{Eq. 10}$$

Calculate constants and θ_o', θ_o''

1) γ

2) ζ

3) $\left(\frac{d\theta}{dR}\right)_{R=0}$

4) $\left(\frac{d^2\theta}{dR^2}\right)_{R=0}$

5) Make an initial guess of η and go through equations 8-10.

6) Check $d\theta/dR$ against zero at the end of the fin (R=1).

7) If not within small tolerance decrease η and repeat process until $d\theta/dR$ approaches zero.

One must be very careful in arriving at the initial guess of η. If initial η is chosen below the actual value then of course the process will not converge on the correct answer.

There are four values of η that will yield a $d\theta/dR = 0$ at $R = 1$. The correct value of fin effectiveness will satisfy boundary condition 3 while the other η's yield negative values of θ at the end of the fin.

A computer routine was written capable of computing values of radial fin effectiveness for nearly the entire range of design parameters. The numerical technique described above was programmed into the Radial Fin Effectiveness Routine (RFER) and used to calculate values of η over the range shown below:

1) $\theta_s = 0., .5, .6, .7, .8, .9$

2) $\zeta = 0.1 - 200.0$

3) $\phi_R = 1.5, 2.0, 3.0, 6.0, 10.0, 15.0, 50.0$

Curves of the results are shown in Figures A2-A13.

The curves of radial fin effectiveness were curve fit for addition into SSDR. The curve fit was based on a modification of the value of η of a one-dimensional fin at the same value of ζ and θ_s. This method provides a simple curve fit since SSDR already had 1-D fin effectiveness capability.

$0 < \zeta < 1.0$	$X = -.0724 \ln(\zeta) - .248$
$1.0 < \zeta < 4.0$	$X = -.075 \ln(\zeta) - .248$
$4.0 < \zeta < 15.0$	$X = -.04786 \ln(\zeta) - .215$
$15.0 < \zeta < 200.0$	$X = -.0539 \ln(\zeta) - .334$

η_{1D} = fin effectiveness for a 1-D fin

$\eta = \eta_{1D}(\phi_R)^X$ - Curve fit equation programmed into SSDR.

4.0 REFERENCES

1-A Chambers, R. L., and Somers, E. V., "Radiation Fin Efficiency For One-Dimensional Heat Flow in a Circular Fin", Journal of Heat Transfer, November 1959.

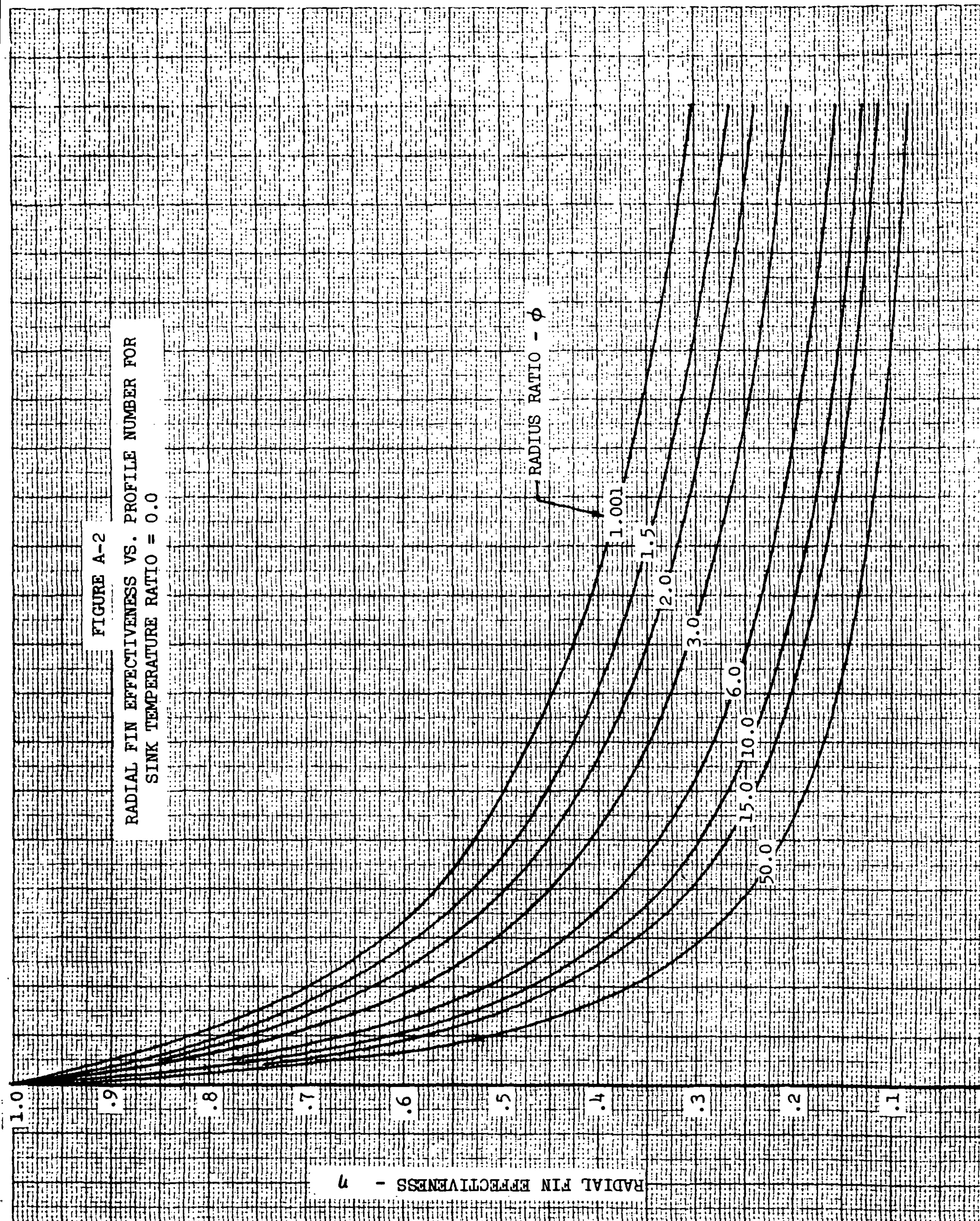


FIGURE A-2

RADIAL FIN EFFECTIVENESS VS. PROFILE NUMBER FOR SINK TEMPERATURE RATIO = 0.0

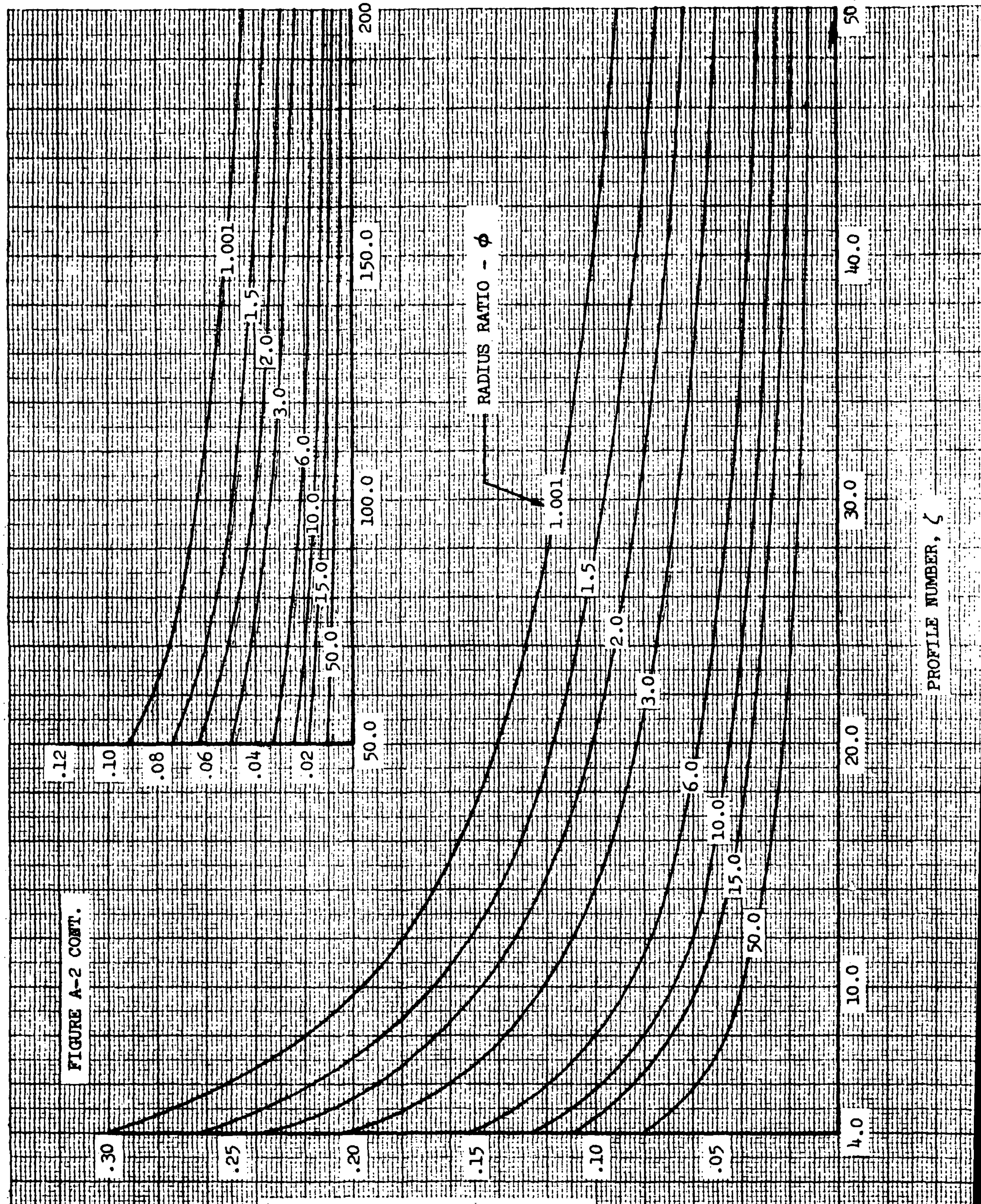
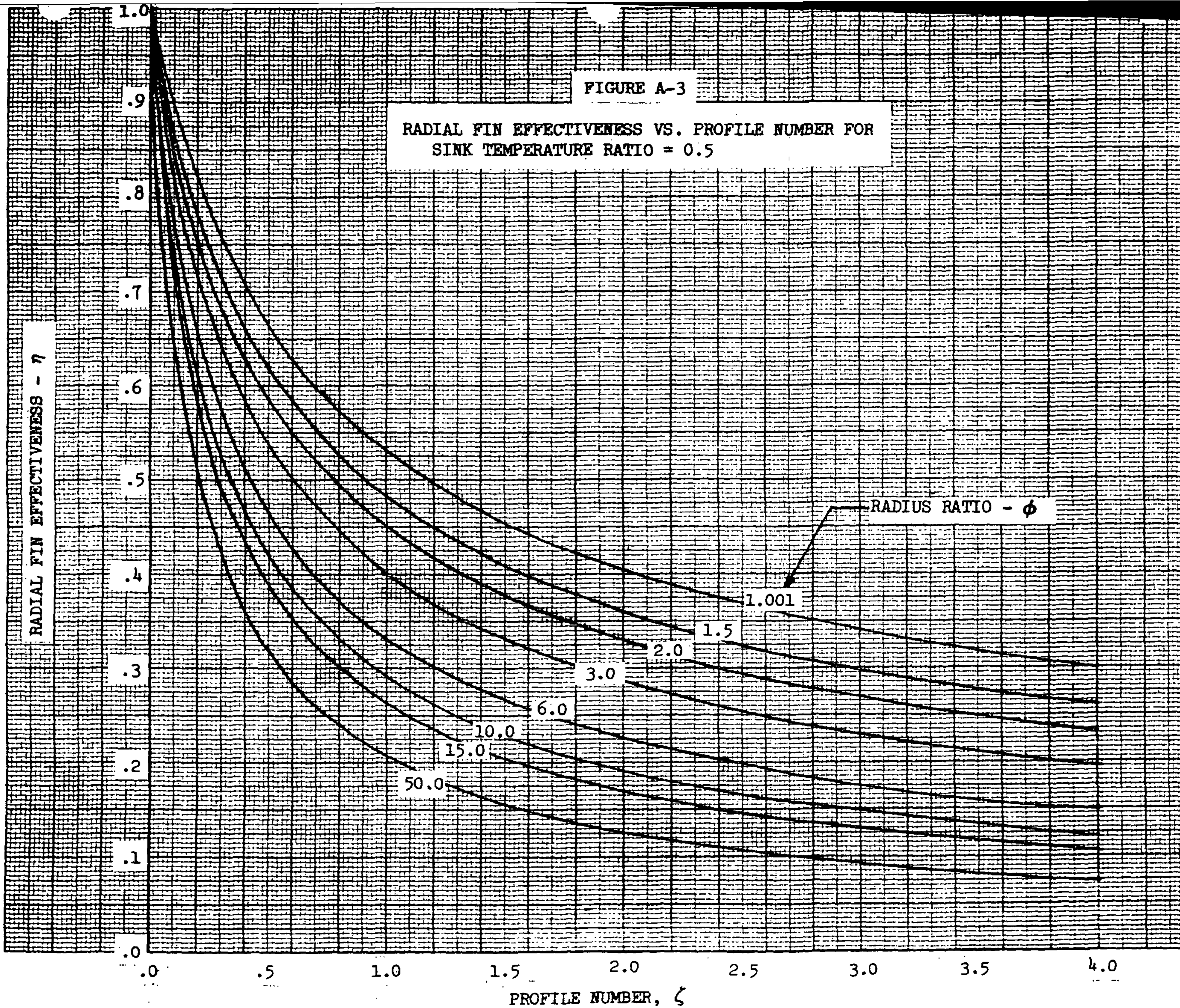


FIGURE A-2 CONT.

FIGURE A-3

RADIAL FIN EFFECTIVENESS VS. PROFILE NUMBER FOR SINK TEMPERATURE RATIO = 0.5



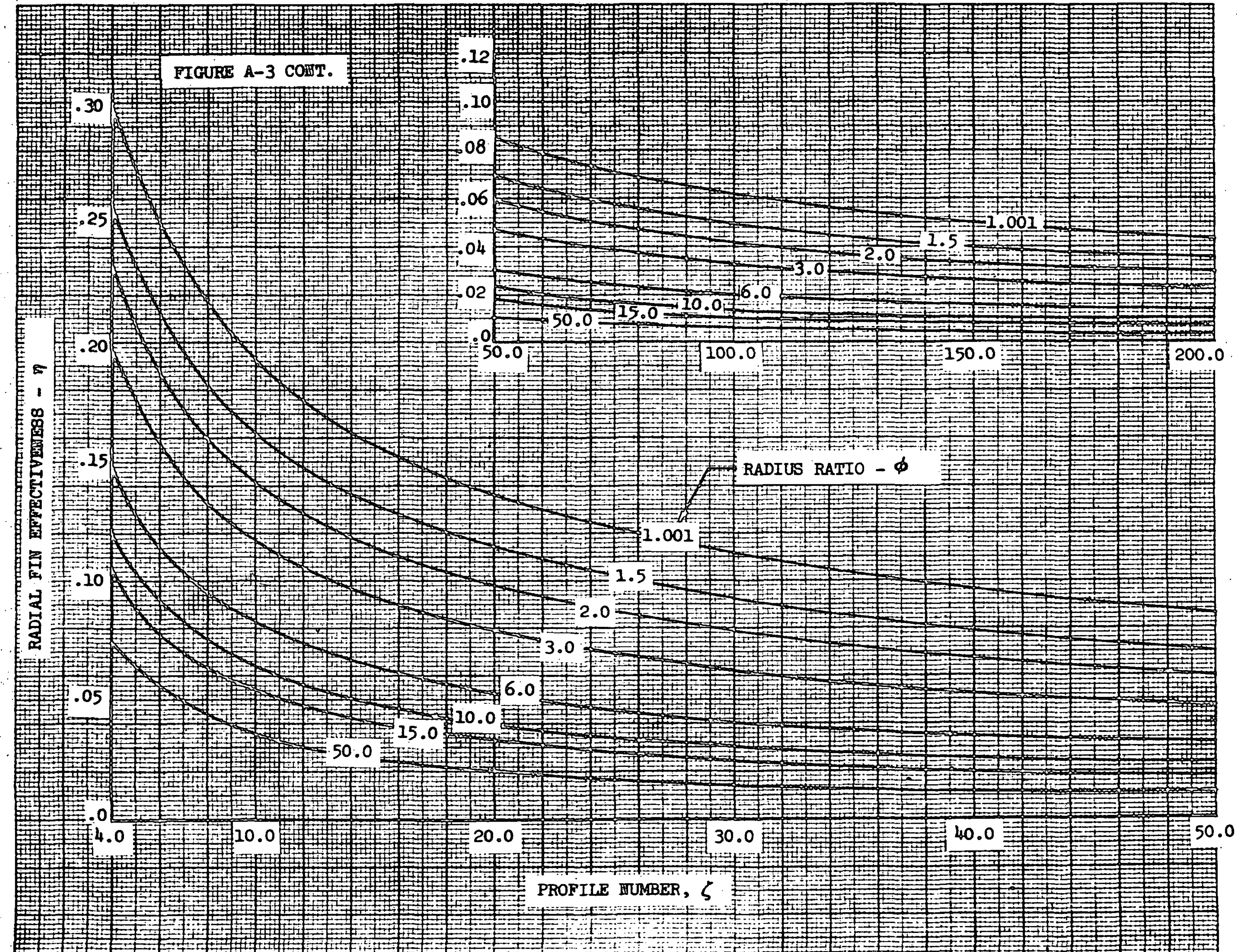


FIGURE A-3 CONT.
RADIAL FIN EFFECTIVENESS - η
PROFILE NUMBER, ζ
RADIUS RATIO - ϕ
.30
.25
.20
.15
.10
.05
.0
4.0
10.0
20.0
30.0
40.0
50.0
1.001
1.5
2.0
3.0
6.0
10.0
15.0
50.0
.12
.10
.08
.06
.04
.02
.0
50.0
100.0
150.0
200.0

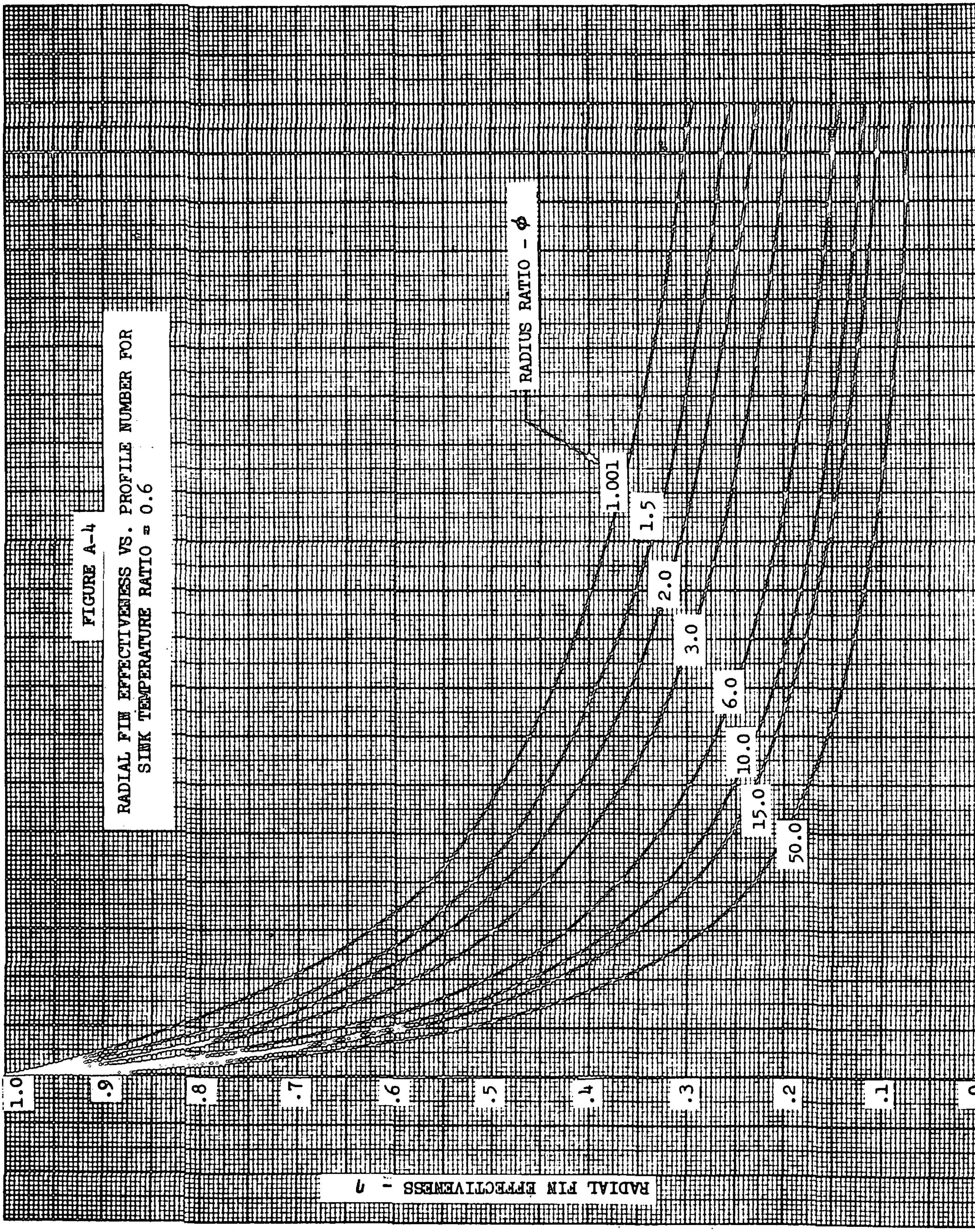


FIGURE A-4

RADIAL FIN EFFECTIVENESS VS. PROFILE NUMBER FOR SINK TEMPERATURE RATIO = 0.6

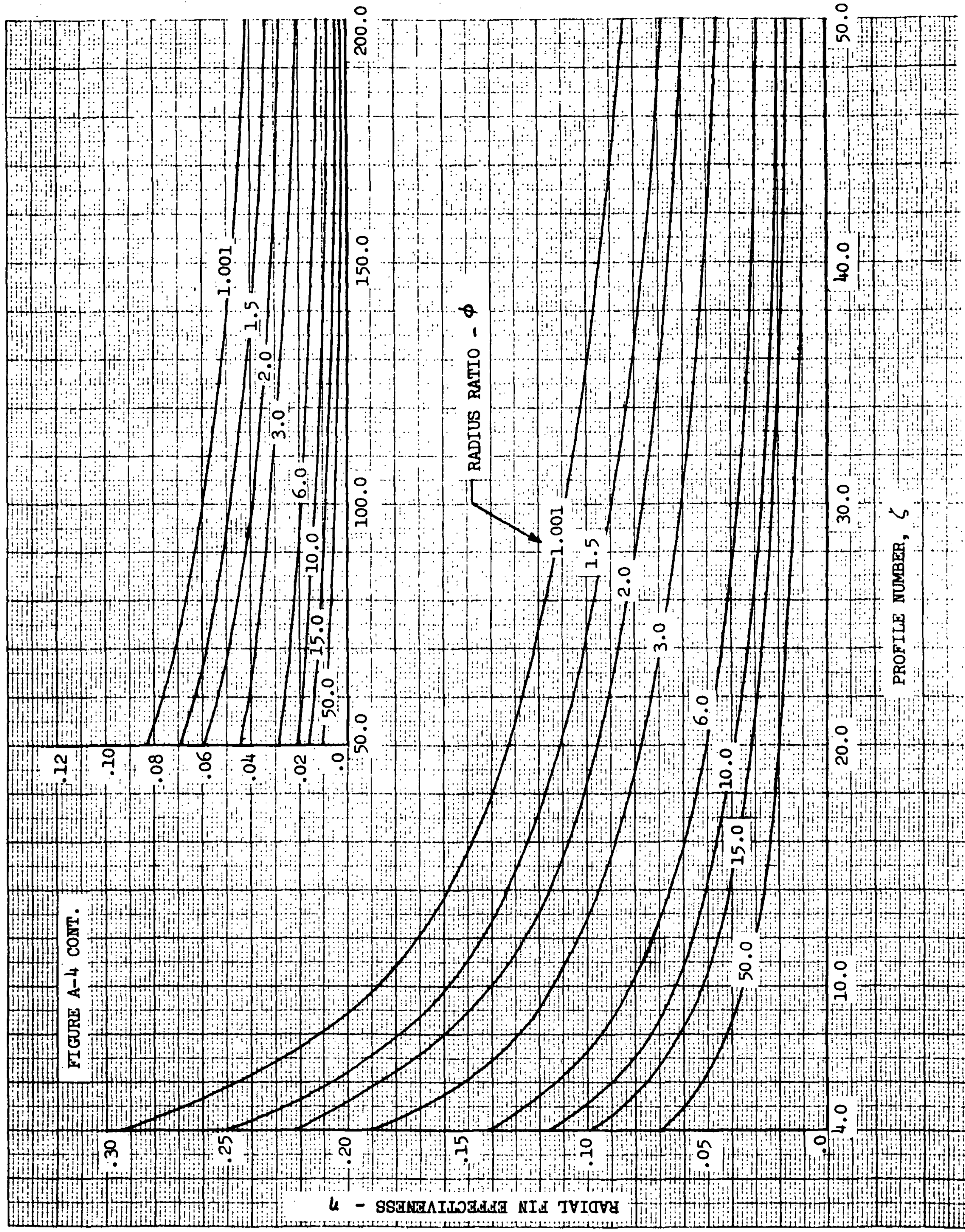


FIGURE A-4 CONT.
RADIUS RATIO - φ
1.001
1.5
2.0
3.0
6.0
10.0
15.0
50.0
RADIAL FIN EFFECTIVENESS - η
PROFILE NUMBER, ζ
.30
.25
.20
.15
.10
.05
.0
4.0
10.0
20.0
30.0
40.0
50.0
.12
.10
.08
.06
.04
.02
.0
50.0
100.0
150.0
200.0

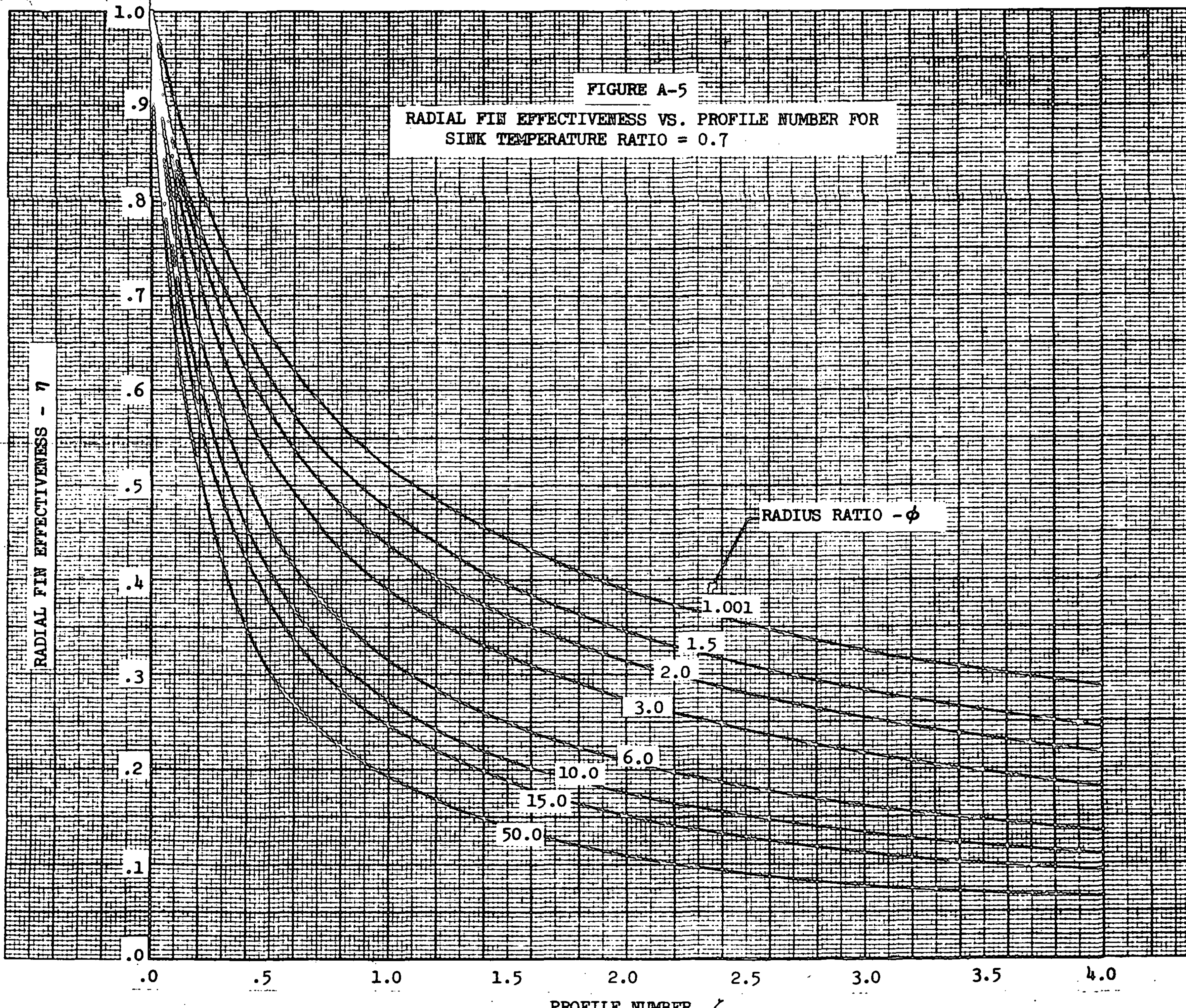


FIGURE A-5
RADIAL FIN EFFECTIVENESS VS. PROFILE NUMBER FOR
SINK TEMPERATURE RATIO = 0.7
RADIUS RATIO - ϕ
1.001
1.5
2.0
3.0
6.0
10.0
15.0
50.0
RADIAL FIN EFFECTIVENESS - η
PROFILE NUMBER, ζ
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

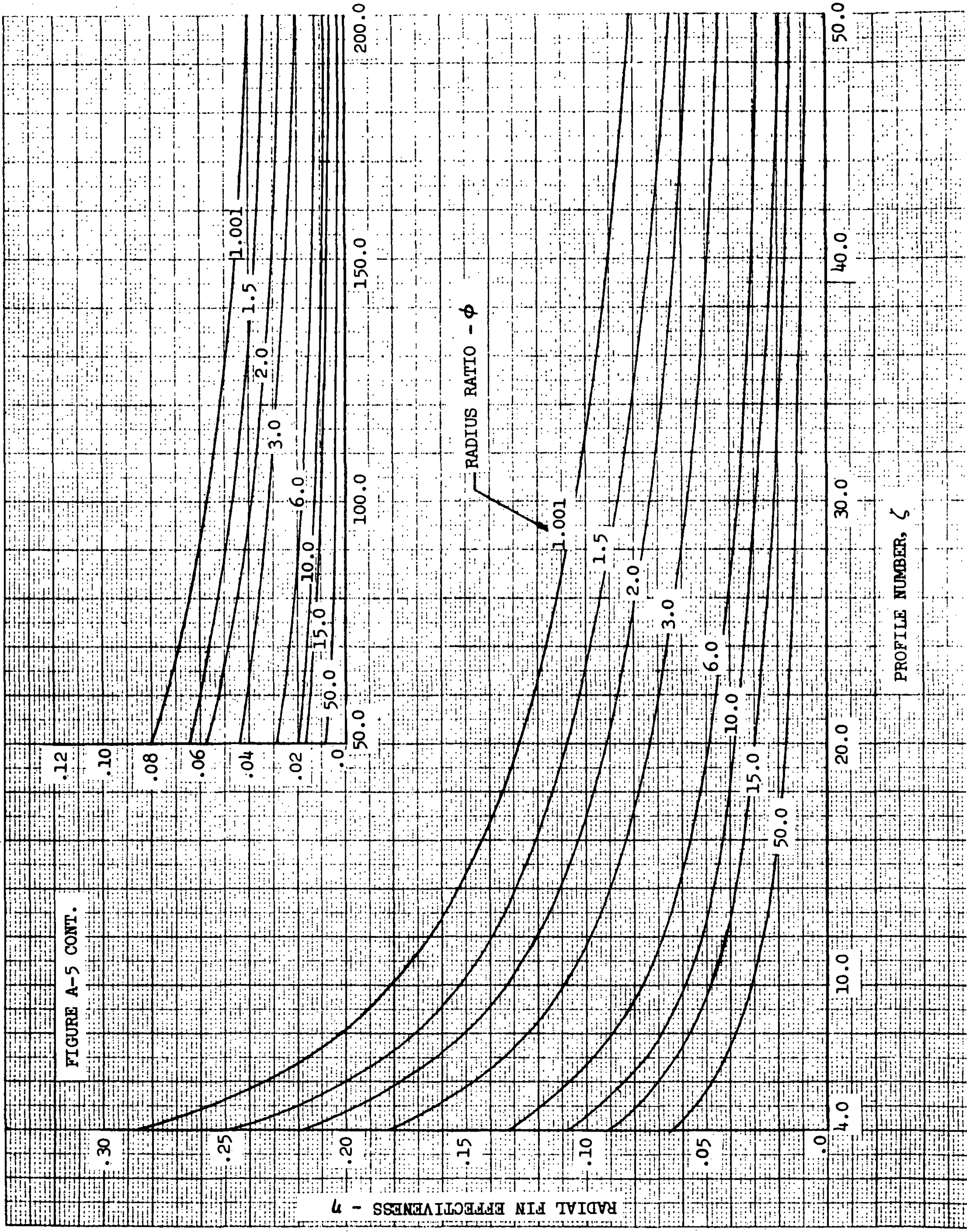


FIGURE A-5 CONT.

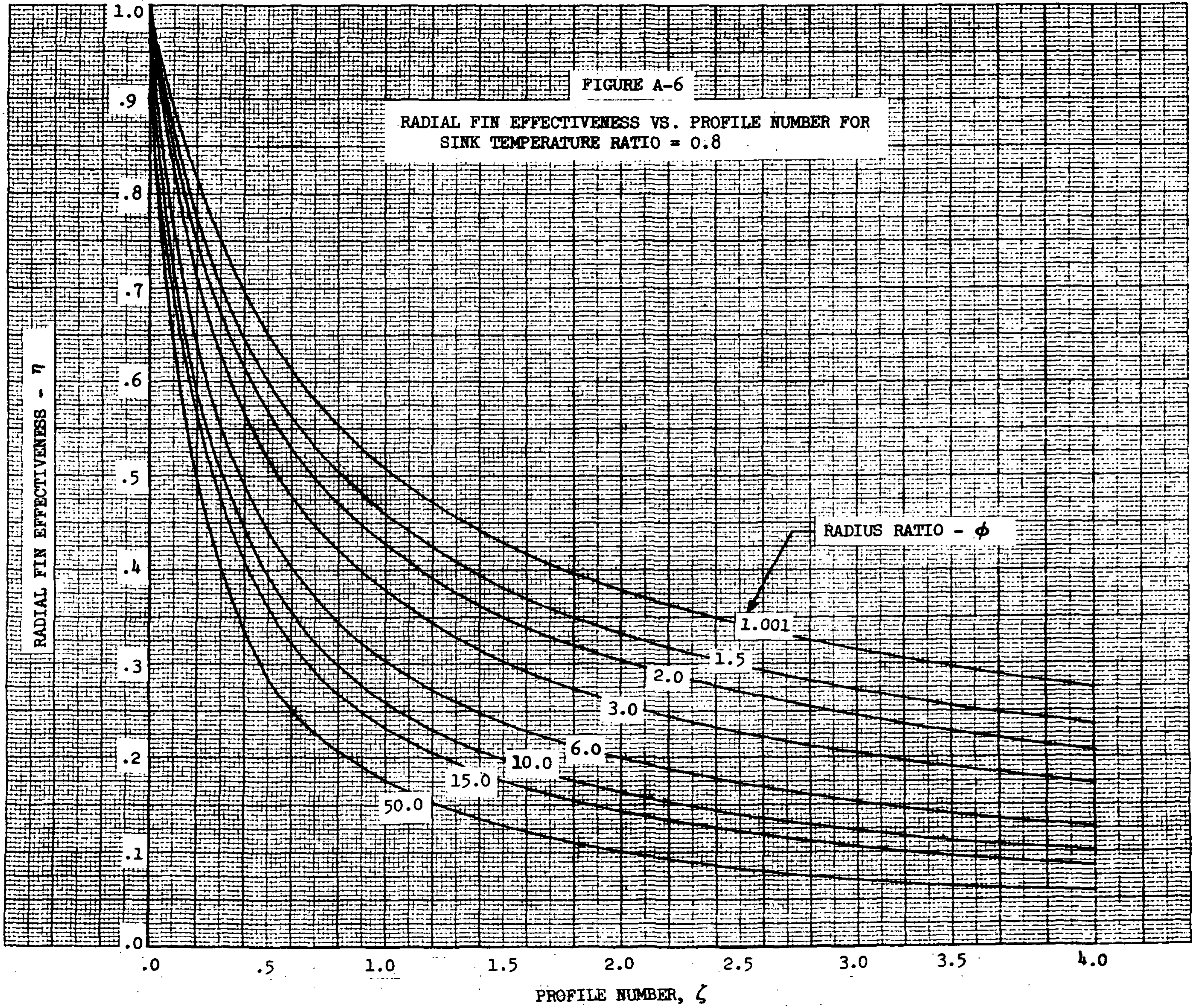


FIGURE A-6
RADIAL FIN EFFECTIVENESS VS. PROFILE NUMBER FOR SINK TEMPERATURE RATIO = 0.8
RADIUS RATIO - ϕ
1.001
1.5
2.0
3.0
6.0
10.0
15.0
50.0
RADIAL FIN EFFECTIVENESS - η
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
.0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
PROFILE NUMBER, ζ

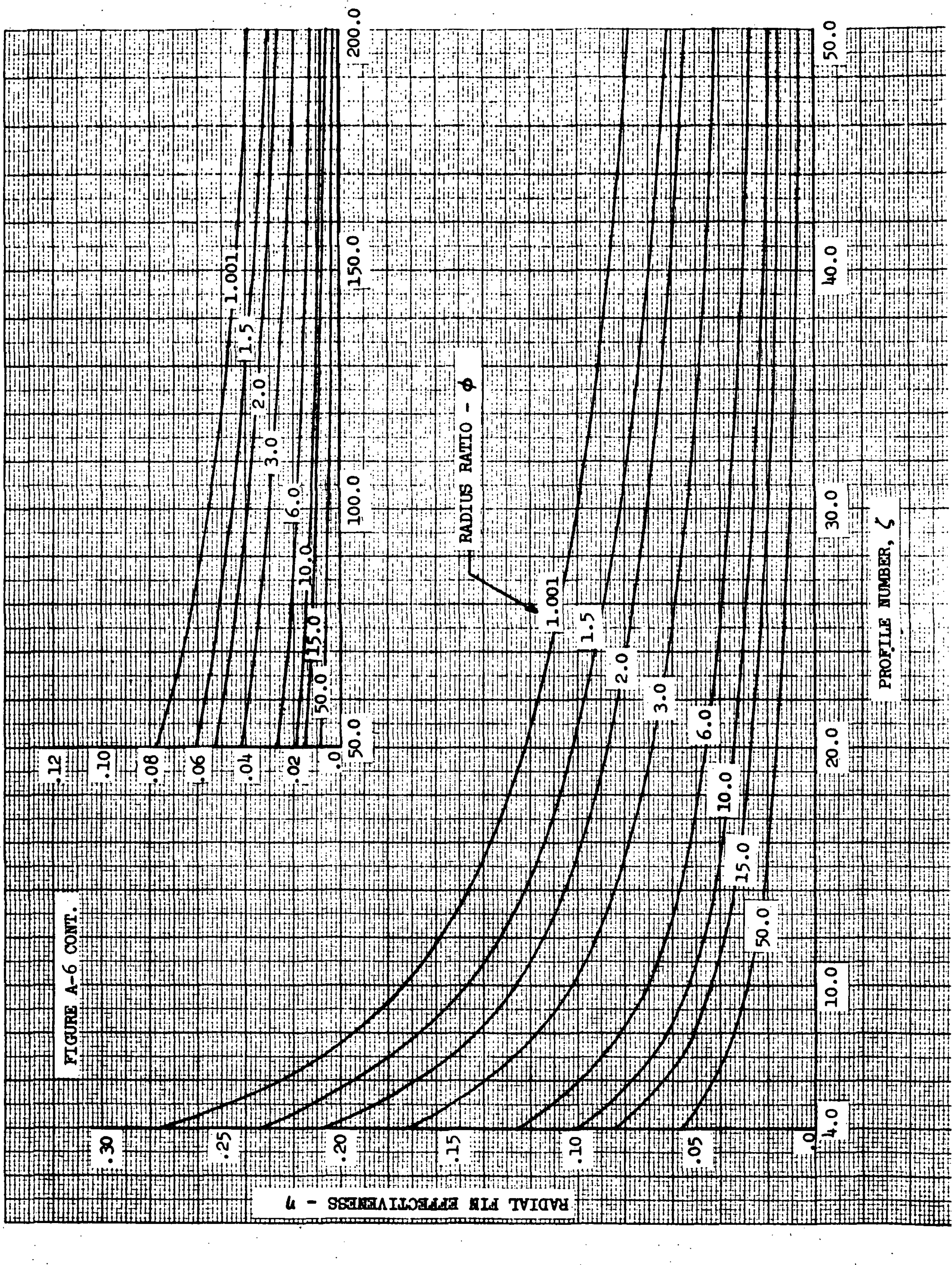


FIGURE A-6 CONT.
RADIAL FIN EFFECTIVENESS - η
PROFILE NUMBER, ζ
RADIUS RATIO - φ
.30
.25
.20
.15
.10
.05
.0
4.0
10.0
20.0
30.0
40.0
50.0
.12
.10
.08
.06
.04
.02
.0
50.0
100.0
150.0
200.0
1.001
1.5
2.0
3.0
6.0
10.0
15.0
50.0

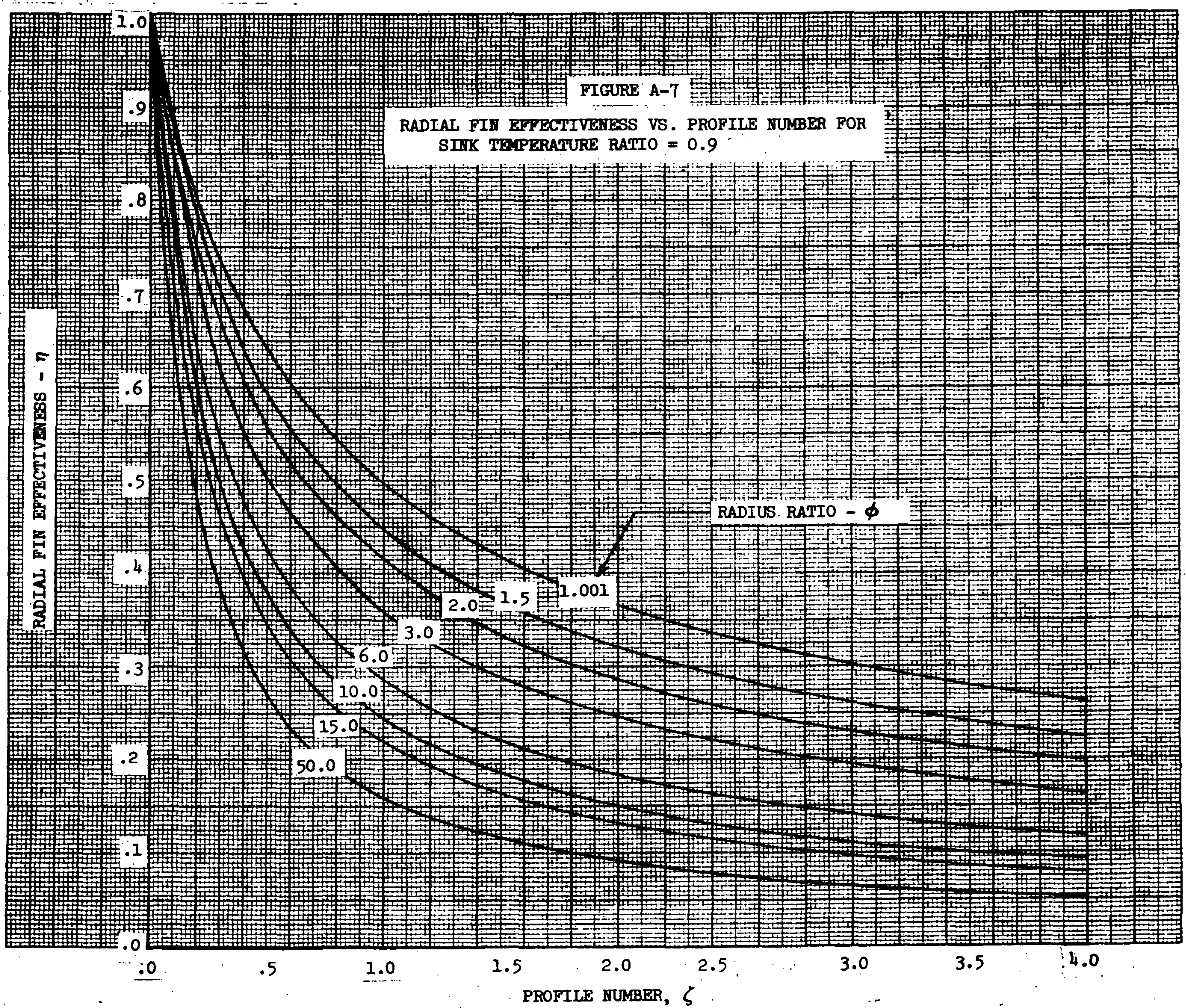


FIGURE A-7
RADIAL FIN EFFECTIVENESS VS. PROFILE NUMBER FOR SINK TEMPERATURE RATIO = 0.9
RADIUS RATIO - ϕ
1.001
1.5
2.0
3.0
6.0
10.0
15.0
50.0
RADIAL FIN EFFECTIVENESS - η
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
.0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
PROFILE NUMBER, ζ

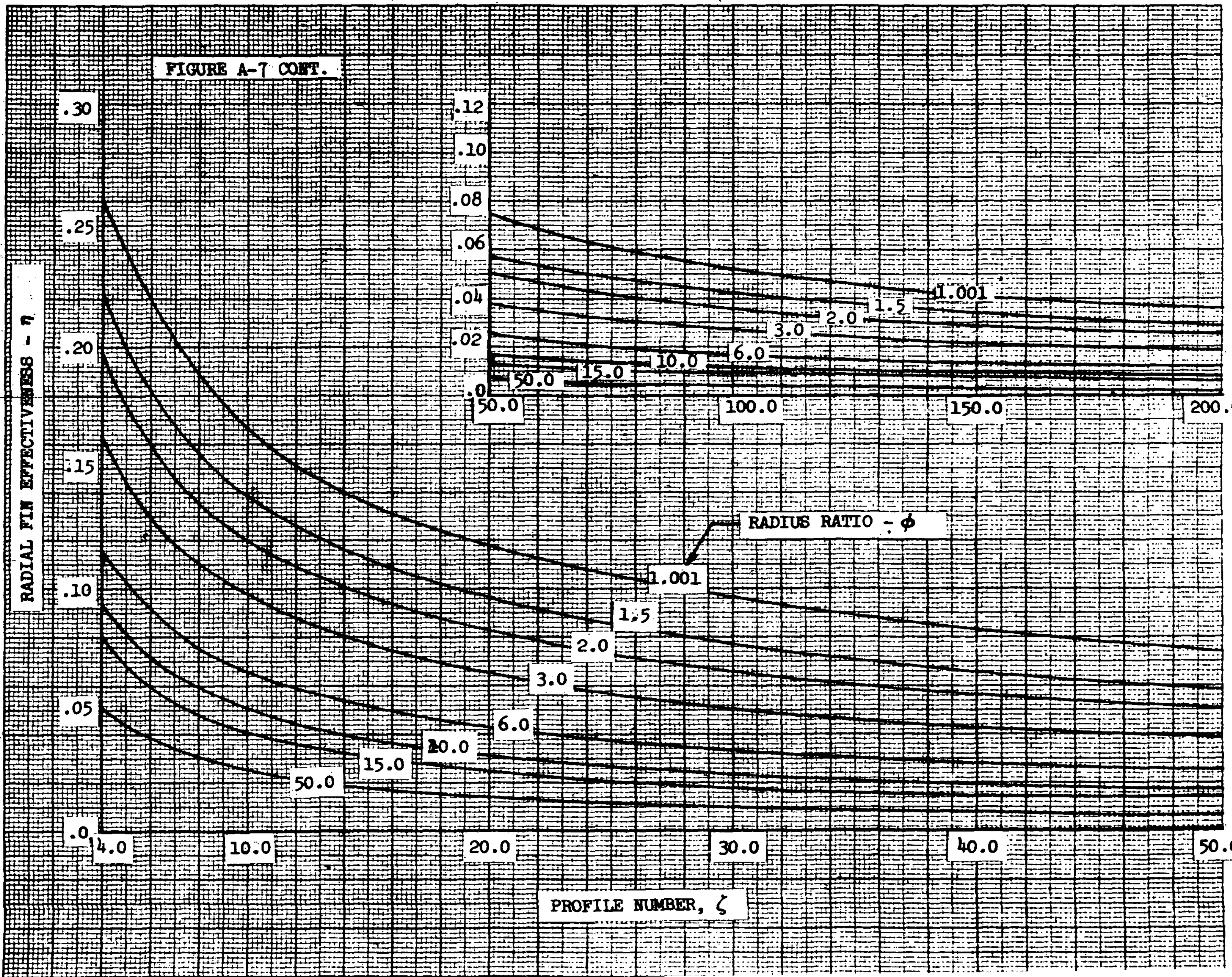


FIGURE A-7 CONT.
RADIAL FIN EFFECTIVENESS - η
PROFILE NUMBER, ζ
RADIUS RATIO - φ
.30
.25
.20
.15
.10
.05
.0
4.0
10.0
20.0
30.0
40.0
50.0
.12
.10
.08
.06
.04
.02
.0
50.0
100.0
150.0
200.0
1.001
1.5
2.0
3.0
6.0
10.0
15.0
50.0

APPENDIX B

DETERMINATION OF FIN EFFECTIVENESS FOR
A HEAT ABSORBING FIN

1.0 SUMMARY AND INTRODUCTION

This appendix presents the method and results of an analysis which was conducted to determine values of fin effectiveness for an absorbing fin. The differential equation describing the heat flow in a one-dimensional radiating fin was integrated for a reasonable range of boundary conditions to obtain effectiveness for values of sink temperature greater than the fin base temperature. A curve fit of the information was performed and the results programmed into SSPR. An equation was derived that results in effectiveness values with a ±1% degree of accuracy for sink to base temperature ratios under a prescribed boundary.

2.0 DISCUSSION

Steady state analysis of a radiating fin can be accomplished by the use of the radiating fin effectiveness where the effectiveness is defined by:

$$\eta = \frac{\text{Actual heat radiated}}{\text{Heat radiated at the fin base temperature}}$$

$$\eta = \frac{(Q/A)\ rej}{\epsilon\ \sigma\ (T_b^{\ 4} - T_s^{\ 4})} \qquad \text{(Eq. 1)}$$

where:

η = radiating fin effectiveness

$(Q/A)rej$ = heat flux radiated by fin

T_b = fin base temperature

T_s = equivalent sink temperature of the environment

ϵ = emissivity

σ = Stefan-Boltzman constant

For a heat absorbing fin such as a solar absorber the values of η are needed for T_s/T_b greater than 1.0. The procedure for obtaining these is discussed below.

The fundamental differential equation for the temperature distribution of a radiating one dimensional rectangular fin can be derived (Ref.1B) and is given by:

$$\frac{d^2T}{dx^2} = \frac{\epsilon\ \sigma}{k\ \delta}\ (T^4 - T_s^{\ 4}) \qquad \text{(Eq. 2)}$$

where:

T = fin temperature which is a function of x

x = the distance along the fin perpendicular to the edge which is at $T = T_b$

δ = the fin thickness

The value of η can be determined as a function of T_s/T_b, and Nc by integration of the basic differential equation where Nc is given by:

$$Nc = \frac{L^2 \sigma \epsilon T_b^3}{k \delta}$$

L = the length from the fin base to the end of the fin

k = the conductivity of the fin material

δ = the fin thickness

This was accomplished (Ref. 1B) for values of T/T_b betweem 0 and 0.9. An exact solution can be derived for $T_s/T_b = 1.0$ (Ref. 2B) and is given by:

$$\eta_{1.0} = \frac{\tanh (2\sqrt{Nc})}{2\sqrt{Nc}} \qquad \text{(Eq. 3)}$$

$$T_s = \sqrt[4]{(\alpha Q_s + \epsilon Q_i)/\epsilon \sigma}$$

α = solar absorptance of the fin surface

Q_s = incident solar and albedo radiant flux

Q_i = incident IR radiant flux

This equation can be written in the form:

$$\frac{d\theta}{dx} = - \sqrt{2/5} \sqrt{\theta^5 - \theta_L{}^5 - 5(\theta_s)^4(\theta - \theta_L)} \qquad \text{(Eq. 4)}$$

by defining:

$$\theta = T/T_b$$

$$X = x\sqrt{\frac{\epsilon \sigma T_b^3}{k \delta}}$$

$\theta_s = T_s/T_b$

$\theta_L = T_L/T_b$

T_b = temperature at x = 0

T_L = temperature at x = L

and one integration.

From equation 1, the fin effectiveness is:

$$\eta = \frac{(Q/A)\ rej}{\epsilon\,\sigma\,(T_b^4 - T_s^4)}$$

Using equation 4, this equation can be reduced to:

$$\eta = \frac{\sqrt{2/5}}{\sqrt{Nc}\ (1 - \theta_s^4)} \sqrt{1 - (\theta_L)^5 - 5(\theta_s)^5(1 - \theta_L)} \qquad \text{(Eq. 5)}$$

where:

$$Nc = \frac{\epsilon\,\sigma\,T_b^3\,L^2}{k\,\delta}$$

The values of η were calculated as a function of Nc, and θ_s by a step wise integration of equation (4) to determine values of θ_L (as a function of Nc and θ_s) and substituting these values into equation (5).

If θ_L is assumed to equal θ_s equation (5) reduces to:

$$\eta = \frac{2/5}{Nc\ (1 - \theta_s^4)} \sqrt{(4\theta_S^5 - 5\theta_S^4 + 1)} \qquad \text{(Eq. 6)}$$

Equation (6) was found to result in effectiveness values with a $\pm1\%$ degree of accuracy for sink to base temperature ratios under a prescribed boundary. This boundary is shown in Figure 1-B along with values of fin effectiveness.

3.0 REFERENCES

1-B Lieblein, S., "Analysis of Temperature Distribution and Radiant Heat Transfer Along a Rectangular Fin of Constant Thickness", NASA TN D-196, November 1959.

2-B Anderson, A. F., et.al., "Radiator Design for Space Vehicles", AiResearch Manufacturing Company, Los Angeles, 1963.

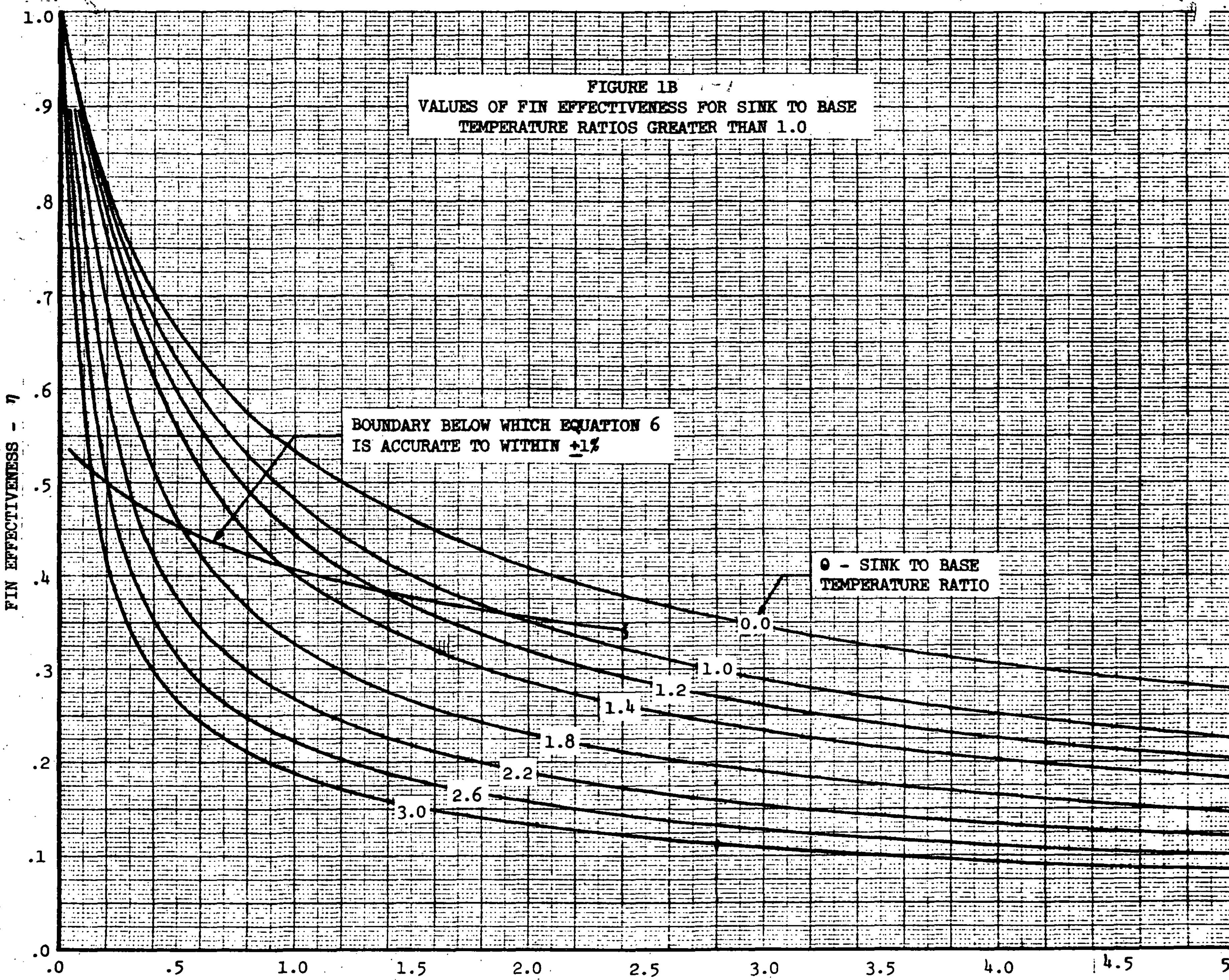


FIGURE 1B
VALUES OF FIN EFFECTIVENESS FOR SINK TO BASE TEMPERATURE RATIOS GREATER THAN 1.0
BOUNDARY BELOW WHICH EQUATION 6 IS ACCURATE TO WITHIN ±1%
θ - SINK TO BASE TEMPERATURE RATIO
0.0
1.0
1.2
1.4
1.8
2.2
2.6
3.0
FIN EFFECTIVENESS - η
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
.0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

Page Intentionally Left Blank

LTV AEROSPACE CORPORATION

VOUGHT MISSILES
AND SPACE COMPANY
TEXAS DIVISION