NASA CR-170563

USER'S MANUAL

FOR

THERMAL ANALYSIS PROGRAM OF AXIALLY GROOVED HEAT PIPE

(HTGAP)

Prepared for

NASA Goddard Space Flight Center

Contract No. NAS5-24144

September, 1978

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(NASA-CR-170563) USER'S MANUAL FOR THERMAL ANALYSIS PROGRAM OF AXIALLY GROOVED HEAT PIPE (HTGAP) (Case Western Reserve Univ.) 64 p HC A04/MF A01 CSCL 20D

N83-33102

Unclas

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The computer program HTGAP described in this user's manual was prepared under NASA Contract NAS5-24144, "Axially Grooved Heat Pipe". The contract was administered by Goddard Space Flight Center, Greenbelt, Maryland, with Mr. Stanford Ol.endorf serving as technical monitor.

Dr. Y. Kamotani was responsible for the development of the analytical model and computer program.

1. INTRODUCTION

HTGAP is a computer program that numerically predicts the steady state temperature distribution inside an axially grooved heat pipe wall for a given groove geometry and working fluid under various heat input and output modes. The program computes both evaporator and condenser film coefficients. The program is able to handle both axisymmetric and non-axisymmetric heat transfer cases. Non-axisymmetric heat transfer results either from non-uniform input at the evaporator or non-uniform heat removal from the condenser, or from both. The presence of a liquid pool in the condenser region under one-g condition also causes non-axisymmetric heat transfer, and its effect on the pipe wall temperature distribution is included in the present program.

The hydrodynamic aspect of an axially grooved heat pipe is studied in the Groove Analysis Program (GAP). The present thermal analysis program assumes that the GAP program (or other similar programs) is run first so that the heat transport limit and optimum fluid charge of the heat pipe are known a priori. The performance of an under-charged heat pipe is not considered in the present program.

2. ANALYSIS

2.1 Problem Statement

Figure 1 shows a typical axially grooved heat pipe. Each groove is designed to operate as an isolated liquid passage. Under steady state conditions the rates of condensation and evaporation must be equal for each groove. For uniform heating at the evaporator and uniform cooling at the condenser (axisymmetric case) all the grooves are subject to identical boundary conditions so that the performance of the heat pipe can be deduced from the behavior of any one groove (assuming no excess liquid). For non-uniform heating and cooling, however, the rates of condensation and evaporation of a groove may be different from those of .ther grooves so that it is necessary to study the behaviors of all the grooves in order to predict the performance of the heat pipe.

The pipe wall temperature distribution is governed by a steady state heat conduction equation together with the exterior boundary condition (i.e., the way heat is applied to the evaporator and removed from the condenser) and the interior boundary condition (i.e., the rates of evaporation and condensation). Using cylindrical coordinates (Fig. 1) the governing equation is written as

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \psi^2} + \frac{\partial^2 T}{\partial Z^2} = 0 \tag{1}$$

The boundary condition describing the thermal interaction between the groove and the liquid in it, and between the liquid and the vapor is very complicated because of the complex geometry of the groove. To avoid an unnecessary complicated solution in the present analysis, the inner surface thermal behavior is modelled as that shown in Fig. 2. An equivalent heat transfer coefficient ($h_{eq,e}$ or $h_{eq,c}$) is used to describe the thermal interaction between a hypothetical inner surface (radius R_i) and the vapor. This approach was initially used by Schneider and Yovanovich [1]. The computations of $h_{eq,e}$ and $h_{eq,c}$ are explained in the following section. The region covered by a liquid pool is assumed to be thermally insulated.

The exterior boundary condition is determined by a specified (by the user) heater-cooler combination. Three different boundary conditions can be specified in the regions covered by the heater and cooler as explained in section 2.3. The rest of the pipe wall surface is assumed to be thermally insulated, or the user can specify parasitic heat loss or gain. The heat conduction through the pipe end caps is neglected in the present analysis.

Equation (1) together with the above mentioned boundary conditions is solved numerically using the successive-over-relaxation method.

2.2 Problem Formulation

To solve Eq. (1) numerically the heat pipe wall is divided into a number nodes as shown in Fig. 3. The cylindrical wall is divided into L nodes radially (r-direction), M nodes (equal to the number of grooves) circumferentially (Ψ-direction), and N nodes axially (z-direction). An energy balance applied to every node yields a system of finite difference equations representing the heat conduction equation (1). The following finite difference formulation follows Schneider and Yovanovich [1].

For the (i,j,k) th node the finite difference equation is written as

$$
\begin{aligned}
C_5 T_{i,j,k} = {} & C_1 T_{i-1,j,k} + C_2 T_{i+1,j,k} \\
& + C_3 T_{i,j-1,k} + C_4 T_{i,j+1,k} \\
& + C_5 T_{i,j,k-1} + C_6 T_{i,j,k+1}
\end{aligned}
\tag{2}
$$

where
$$C_{1,2} = \frac{k_w (r_i \mp \delta r^{\mp}/2) \Delta\psi \Delta Z}{\delta r^{\mp}}$$

$$C_{3,4} = \frac{k_w \Delta Z}{\delta\psi^{\mp}} \ln \left[\frac{r_i + \delta r^{+}/2}{r_i - \delta r^{-}/2} \right]$$

$$C_{5,6} = \frac{k_w \Delta\psi}{\delta Z^{\mp}} \left[\frac{(r_i + \delta r^{+}/2)^2 - (r_i - \delta r^{-}/2)^2}{2} \right] \tag{3}$$

The heat transfer rate at the hypothetical inner surface (Fig. 2) of the pipe wall is determined by the equivalent heat transfer coefficient h_{eq}. h_{eq} represents the total thermal conductance between the pipe inner surface (radius Ri) and the vapor. Then, the interior boundary condition is incorporated into the above formulation by putting

$$C_1 = \frac{\frac{h_{eq}}{k_w} \frac{\Delta r}{2}}{1 + \frac{h_{eq}}{k_w} \frac{\Delta r}{2}}$$

$$T_{i-1,j,k} = T_v \tag{4}$$

for those nodes contacting the vapor. In the present analysis the vapor region is modeled as one node with a uniform temperature T_v.

If the pipe inner surface temperature is lower than T_v, condensation takes place. In Ref. 2 Kamotani suggested a numerical method to compute the condenser film coefficient of a grooved heat pipe. However, the method is too complex to be included in the present program. After some calculations using the method under various conditions, it was found that the following expression for the equivalent heat transfer coefficient expresses well the computed as well as experimental values.

$$h_{eg,c} = \frac{N k_\ell}{2\pi R_i} \frac{1}{.02 + \frac{k_\ell}{k_w} \frac{D}{S}} \tag{5}$$

If the pipe inner surface temperature is larger than T_v, evaporation takes place. After studying several experimental and analytical investigations on the evaporator film coefficient of a grooved heat pipe (Ref. 3 - 7), the following expression for the equivalent heat transfer coefficient is suggested.

$$h_{eg,e} = \frac{N k_\ell}{2\pi R_i} \frac{1}{.07 + \frac{k_\ell}{k_w} \frac{D}{S}} \tag{6}$$

The boundary condition at the exterior surface of the heat pipe is discussed in the following section.

2.3 Modes of Heat Input and Removal

The exterior boundary condition is determined by the way heat is applied to the evaporator and removed from the condenser. Three typical boundary conditions are considered in the present analysis. They are shown schematically in Fig. 4, and discussed below.

Type 1 Boundary Condition

Total heat flux Q and vapor temperature T_v are given. This boundary condition is incorporated into Eq. (2) by adding a source (or sink) term

$$S = \pm q R_{OUT} \Delta\psi \Delta Z$$

to the right hand side of Eq. (2) for those nodes contacting the heater or cooler. q is heat flux per unit area (Q divided by heating or cooling area). + sign is for heat input, and - sign for heat removal.

Type 2 Boundary Condition

Total heat flux Q at the evaporator and condenser surface temperature $T_{w,c}$ are given. For those nodes contacting the heater the treatment is the same as above. The surface temperatures of those nodes contacting the cooler are set equal to $T_{w,c}$. The vapor temperature is computed from the relation

$$\sum_{\text{inner surface}} h_{eq} (T_{s_i} - T_v) = 0$$

where T_{s_i} is the inner surface temperature.

Tyep 3 Boundary Condition

Both evaporator and condenser surface temperatures $T_{w,e}$ and $T_{w,c}$ are given. The specification of this boundary condition and the computation of T_v are the same as above.

If there is parasitic heat loss or gain from the heat pipe to the environment, it is accounted for by putting

$$C_2 = \frac{\frac{h_{par}}{k_w} \frac{\Delta r}{2}}{1 + \frac{h_{par}}{k_w} \frac{\Delta r}{2}}$$

$$T_{i+1,j,k} = T_{amb}$$

for the nodes on the pipe outside surface. h_{par} is the heat transfer coefficient between the pipe and the environment, and T_{amb} is the ambient temperature.

2.4 Puddle Effect Treatment

At the user's option the program investigates the effect of a liquid pool on the pipe wall temperature distribution in one-g and under an over-charged condition. The excess liquid forms a liquid pool at the bottom of the heat pipe, which influences the pipe performance (puddle effect). The hydrodynamic aspect of the puddle flow is studied in GAP. The present program considers mainly the thermal aspect.

The free surface of the liquid pool is assumed to be flat in the present analysis. The assumption is not valid when the heat pipe is operating at a small tilt angle under a high heat load, or when the ratio $\rho_\ell g R_v^2/\sigma$ (Bond number) is on the order of one or less. Therefore to avoid a complex combined hydrodynamic and thermal analysis, the puddle effect at zero tilt angle is not considered in the present program.

Depending on a given tilt angle and amount of excess fluid, the puddle shape is classified into one of four shapes depicted in Fig. 5. To simplify the numerical analysis the following approximate relation between the puddle volume and the puddle depth H_1 at the condenser end is used,

$$VOL = \frac{\pi}{\tan\alpha} R_v^3 \left(\frac{H_1}{2R_v}\right)^2$$

The pipe inner surface submerged in the pool is assumed to be thermally insulated. Numerically C_1 is set equal to zero for the submerged nodes on the pipe inner surface. At a given z location the submerged region is specified by the angle θ (Fig. 5). The angle θ is related to the puddle depth H by the equation

$$\theta = \cos^{-1}\left(1 - \frac{H}{R_v}\right)$$

2.5 Method of Solution

A set of finite difference equations (2) together with the aforementioned boundary conditions are solved by successive-over-relation to determine the pipe wall temperature distribution. Recognizing the fact that the heat transfer in the pipe wall is predominantly in the radial direction, the temperature distribution in the r-direction is determined first to reduce the convergence time (Schneider and Yovanovich [1]), that is, at a given (ψ,z) location, L equations in the r-direction are solved simultaneously.

Once the temperature distribution in the pipe wall is determined, the program computes the evaporator and condenser over-all film coefficients which are defined as

$$h_e = \frac{Q}{2\pi R_v L_e (\bar{T}_{w,e} - T_v)} , \quad h_c = \frac{Q}{2\pi R_v L_c (T_v - \bar{T}_{w,c})} \tag{7}$$

Notice that the coefficients are based on the vapor core diameter ($2R_v$) and the difference between the vapor temperature and the average evaporator or condenser surface temperature.

The program also computes the heat load of each groove. In case of non-axisymmetric heat transfer each groove transports different amounts of heat so that all the grooves do not dry-out at the same time. The program checks whether the heat load of any of the grooves exceeds the heat transport limit of a single groove. To compute the single groove transport limit the user must specify the heat transport limit of the heat pipe in zero-g (or under zero tilt without the puddle effect) and under axisymmetric heat transfer conditions, which can be determined either from GAP or from similar hydrodynamic analyses. If the transport limit is not known, it can be set equal to an arbitrary large value, but in that case it is noted that the program does not predict partial dry-out condition. In zero-g or for horizontal operations without the puddle effect in one-g, the single groove transport limit is simply equal to the heat pipe transport limit divided by the total number of grooves. Under tilt conditions in one-g without the puddle effect the single groove transport limit is calculated as

$$q_{limit} = \frac{Q_{limit}}{N}\left(1 - \frac{ELV}{X_{ST}}\right) \tag{8}$$

In the above relation the static height of the pipe (X_{ST}) must be specified by the user. X_{ST} can be determined from GAP or from the relation

$$X_{ST} = \frac{2\sigma}{\rho_\ell g W_{min}}$$

When the puddle effect is included, the single groove transport limit is calculated as (Ref. 8)

$$q_{limit} = \frac{Q_{limit} L_{eff}}{N L'_{eff}}\left(1 - \frac{L'_{eff}\tan\alpha}{X_{ST}}\right) \tag{9}$$

where

$$L'_{eff} = \begin{cases} \frac{1}{2}L_e + L_a + \frac{1}{2}(L_p - L_c) & \text{if} \quad L_p \le L_c \\ \frac{1}{2}L_e + (L_p - L_c) & \text{if} \quad L_c < L_p \le L_c + L_a \\ \frac{1}{2}(L_p - L_a - L_c) & \text{if} \quad L_p > L_a + L_c \end{cases}$$

If the heat load of any of the grooves exceeds the transport limit, the program writes-out a statement to inform the user about the partial dry-out condition.

It is noted that the above analysis is based on the assumption that there is a groove-to-groove liquid communication in the condenser section. According to Kamotani [9] such condition most likely prevails in one-g as well as in zero-g applications. Therefore the present program does not consider the situations where there is no liquid communication between the grooves.

3. PROGRAM DESCRIPTION

3.1 General

HTGAP's flow chart is given in Appendix A, and the program listing in Appendix B. The program is written in Fortran IV, and is designed to operate on the IBM 360 computer system. The field length of the program requires 60 K actual works, and the complications of the program requires typically .5 CPU minutes and .5 IO minutes. The CPU time varies depending mainly on the desired accuracy in the numerical iteration. The variables and constants used in HTGAP are listed at the beginning of the program. HTGAP uses metric units.

HTGAP consists of a main program and a subprogram. The main program reads the input data, conducts numerical iterations, and outputs the final results. If required, the subprogram (PUDDLE) is called, which determines the region covered by the puddle.

3.2 Input Description

The HTGAP user must correctly specify the properties of the working fluid and the pipe material, the pipe and groove geometry, the selection of the type of heat input and removal mode, and the operational mode of the program. The set-up of the input data deck is shown in Table 1. In case of multiple runs these input cards specified in Table 1 (also in the program) must be repeated for each additional run. The rest of the parameters remain fixed.

The physical properties of the working fluid and the pipe material should be evaluated at the vapor temperature (T_v) for type 1 boundary condition, and at $T_{w,c}$ for types 2 and 3 (T_v is not known a priori in these cases). In the latter cases a better accuracy is obtained by running the program twice, evaluating the physical properties at the calculated vapor temperature from the first run.

Care~~s~~ must be taken in specifying the heating and cooling zones. Four numbers are used to specify the circumferential extent of the heating (or cooling) zone. They are angles (in degrees) measured counterclockwise from the pipe bottom. Some examples are shown in Fig. 6. If only two numbers are needed (examples 2 and 3), the rest of the numbers should be set equal to or larger an aribtrary number ~~larger~~ than 500.

3.3 Output Description

The program output from the illustrative example (explained in the following section) is shown in Appendix C. On the first output page the program outputs the input data consisting of the names of the working fluid and the pipe material, the pipe and groove geometry and the heating and cooling mode. Those parameters are the same for all the cases in case of multiple runs. The following two pages describe the heat pipe operating conditions, the physical properties and the computational results for one run. The computational results include the heat pipe surface temperature distribution, the heat load of each groove and the pipe performance characteristics (average evaporator and condenser temperature drops, film coefficients, partial dry-out conditions, etc).

3.4 Sample Case

To illustrate HTGAP, the following case is studied. An axially grooved aluminum heat pipe filled with ammonia is operating at 250 K in one-g.

heat pipe geometry

evaporator length	Le = .3048 m
adiabatic length	La = .4572 m
condenser length	Lc = .1524 m
outer diameter	2Rout = .159E-1 m
inner diameter	2Rin = .1088 E-1 m
vapor core radius	R_v = .45E-2 m

groove geometry

number of grooves	N = 27
groove depth	D = .108E-2 m
average land width	$\bar{S}$ = .37E-3 m

heating and cooling mode

type 1 boundary condition. The heating region is the upper half of the pipe, and the cooling region is the lower half. No parasitic heat loss or gain is considered.

total heat transport	Q = 80 W
vapor temperature	T_v = 250 K

properties of working fluid and pipe material

fluid (ammonia) density	= 670 kg/m
fluid thermal conductivity	= .592 W/mK
aluminum thermal conductivity	= 180 W.mK

heat pipe operating conditions

one-g condition	
elevation	ELV = .6E-2 m
excess mass charge	XMASS = 1.2 g.

heat pipe performance limits

maximum heat transport (in zero-g)	Q_{limit} = 215 W
static height	X_{ST} = .14E-1 m

The sample input is given in Table 2. The program output for the above case is presented in Appendix C. The results show that the evaporator and condenser film coefficients are .67 and 1.03 W/cm^2K, & 17000 W/Km .57 ~ 9x respectively, and no partial dry-out is expected. 55 iterations are needed to obtain the temperature distribution within .01 K accuracy.

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2. Kamotani, Y., "Analysis of Axially Grooved Heat Pipe Condensers", AIAA Progress in Astronautics and Aeronautics, Vol. 56, 1977.

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4. Schneider, G.E. and Yovanovich, M.M., "Thermal Analysis of Trapezoidal Grooved Heat Pipe Walls", report to the Communications Research Center, Department of Communications, Ottawa, Ontario, 1964.

5. Kamotani, Y., "Thermal Analysis of Axially Grooved Heat Pipes", Proc. of 2nd International Heat Pipe Conference, 1976.

6. Kamotani, Y., "Evaporator Film Coefficients of Grooved Heat Pipes", Proc. of 3rd International Heat Pipe Conference, 1978.

7. Schlitt, K.R., Kirkpatrick, J.P. and Brennan, P.J., "Parametric Performance of Extruded Axial Grooved Heat Pipes from 100 to 300 K", AIAA Progress in Astronautics and Aeronautics, Vol. 39, 1976.

8. B & K Engineering, "User's Manual for Groove Analysis Program (GAP)", report BK012-1007, 1976.

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NOMENCLATURE

C's	finite difference coefficients
D	groove depth
ELV	elecation
g	gravitational acceleration
h	over-all film coefficient
heq	equivalent heat transfer coefficient
h_{par}	heat transfer coefficient for parasitic heat loss or gain
H	puddle depth
H_1	puddle depth at condenser end
k	thermal conductivity
La	length of adiabatic section
Lc	length of condenser section
Le	length of evaporator section
Lp	puddle length
L_{eff}	effective transport length (=La + 1/2 (Le + Lc))
L'_{eff}	defined in Eq. 9
N	number of grooves
Q	total heat transport
q	heat flux per unit area
Q_{limit}	maximum heat transport
q_{limit}	single groove heat transport limit
R_i	pipe inner radius
R_{out}	pipe outer radius

R_v	vapor core radius
$\bar{S}$	average land width
T	temperature
T_{si}	inner surface temperature
T_v	vapor temperature
$\bar{T}_w$	average outside surface temperature
T_{amb}	ambient temperature
W_{min}	groove minimum width
X_{ST}	static height
XMASS	excess mass charge
(r,ψ,z)	cylindrical coordinate system defined in Fig. 1
α	tilt angle
δ	spacing between two adjacent nodes
Δ	nodal width
γ's	angles to specify heating and cooling zones
θ	puddle angle
ρ	density
σ	surface tension

<u>Subscripts</u>

c	condenser
e	evaporator
ℓ	liquid
w	wall

TABLE 1 INPUT CARDS DESCRIPTION

Card No.	Format	Name	Description	Unit	Remarks
1	3F10.4	XLE	evaporator length	m	
		XLAD	adiabatic length	m	
		XLC	condenser length	m	
2	I5	NGRV	no. of grooves	---	
	5E10.4	GDEPTH	groove depth	m	
		WIDTH	average land width	m	
		ROUT	pipe outer radius	m	
		RIN	pipe inner radius	m	
		RV	vapor core radius	m	
3	5A2	IFLUID	name of working fluid	---	
	10A2	JPIPE	name of pipe material	---	
4	3F10.5	Q	total heat transport	W	if KTYPE = 1
		TV	vapor temperature	K	
		QMAX	max. heat transport	W	
	3F10.5	Q	total heat transport	W	if KTYPE = 2
		TCOND	condenser surface temp.	K	
		QMAX	max. heat transport	W	
	3F10.5	TEVP	evaporator surface temp.	K	if KTYPE = 3
		TCOND	condenser surface temp.	K	
		QMAX	max. heat transport	W	
5	3E15.4	CONDL	liquid thermal conductivity	W/mK	
		RHO	liquid density	Kg/m^3	
		CONDW	pipe thermal conductivity	W/mK	
6	3E15.4	XSM	excess mass charge	Kg	Skip this card if MGRVT = 1
		EL	elevation	m	
		XST	static height	m	
7	4F10.3	PSIE(1)	angles to specify heating zone	DEG.	
		PSIE(2)			
		PSIE(3)			
		PSIE(4)			

Table 1 Input Cards Description (cont'd)

Card No.	Format	Name	Description	Unit	Remarks
8	F10.3	PSIC(1) PSIC(2) PSIC(3) PSIC(4)	angles to specify cooling zone	DEG.	
9	F10.3 E10.4	TEMPS HPAR	ambient temp. heat transfer coeff. for parasitic heat loss or gain	K W/m^2K	

(Repeat No. 4 to 6 cards for additional cases)

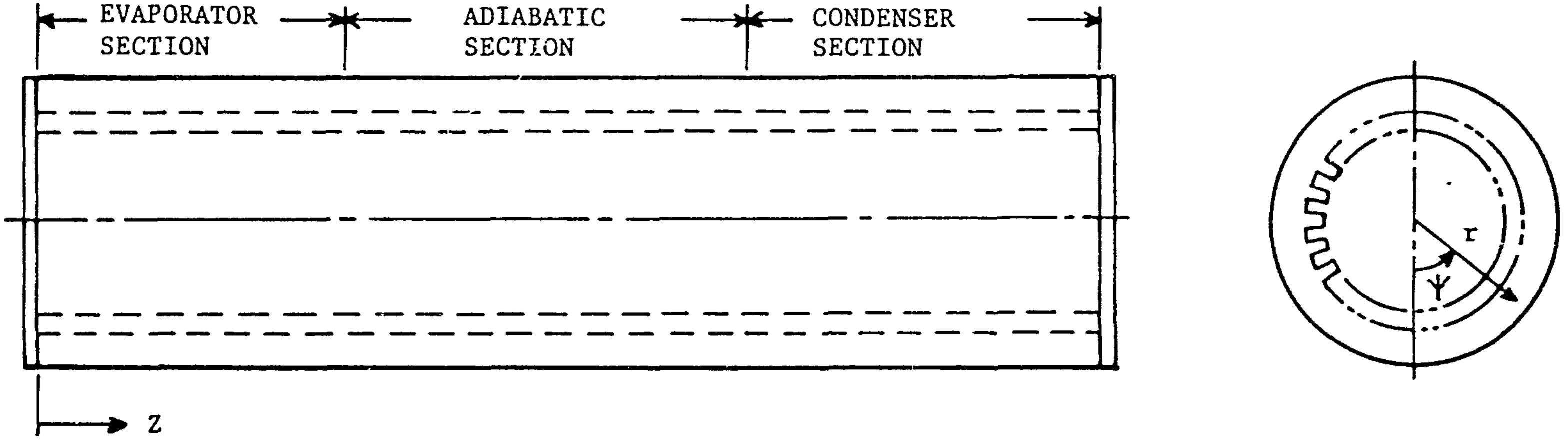
Table 2 Sample Input

COLUMN NO.

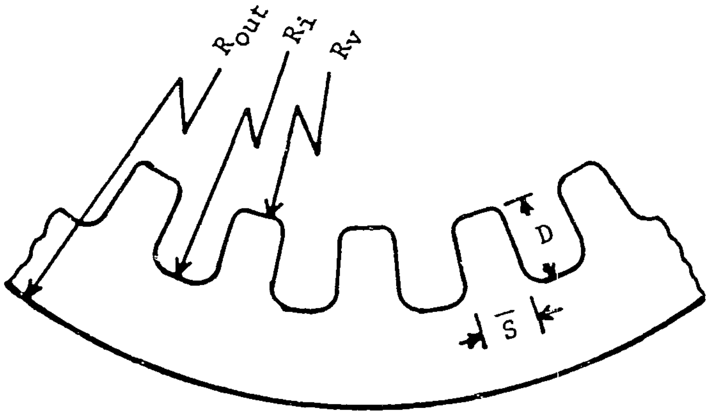
```
000000000111111111122222222223333333333444444444455555555556666666666
123456789012345678901234567890123456789012345678901234567890123456789
```

INPUT DATA

```
     .3048     .4572     .1524
   27   .108E-2    .37E-3   .795E-2   .544E-2   .450E-2
AMMONIA   ALUMINUM
      80.0     250.0     215.0
        .592E 0         .67E 3         .18E 3
         1.2E-3          .6E-2         1.4E-2
      90.0    270.0      500.0          500.0
       0.0     90.0       270.0         360.0
       0.0    .0E 0
```

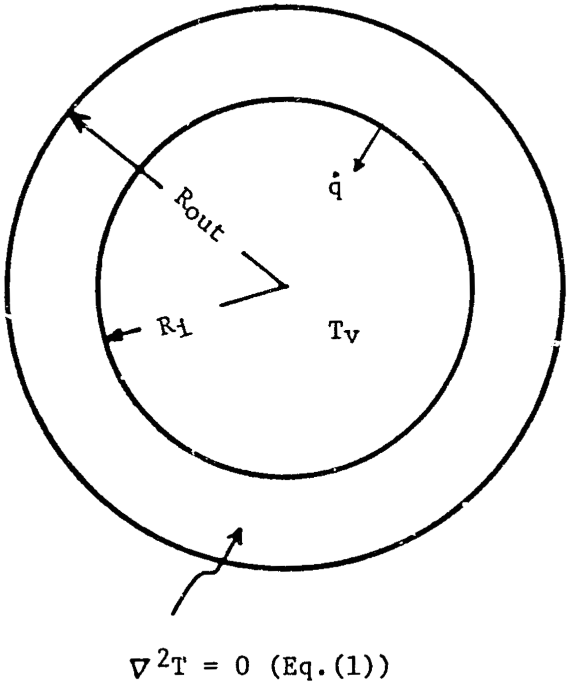


Heat Pipe Cross-section



Groove Detail

Figure 1. Heat Pipe Cross-Section



$$\dot{q} = h_{eq,e}\,(T_{si}(\gamma,Z) - T_v) \mathrm{x} AREA$$

OR

$$\dot{q} = h_{eq,c}\,(T_v - T_{si}(\gamma,Z)) \mathrm{x} AREA$$

Figure 2. Hypothetical Inner Wall Surface

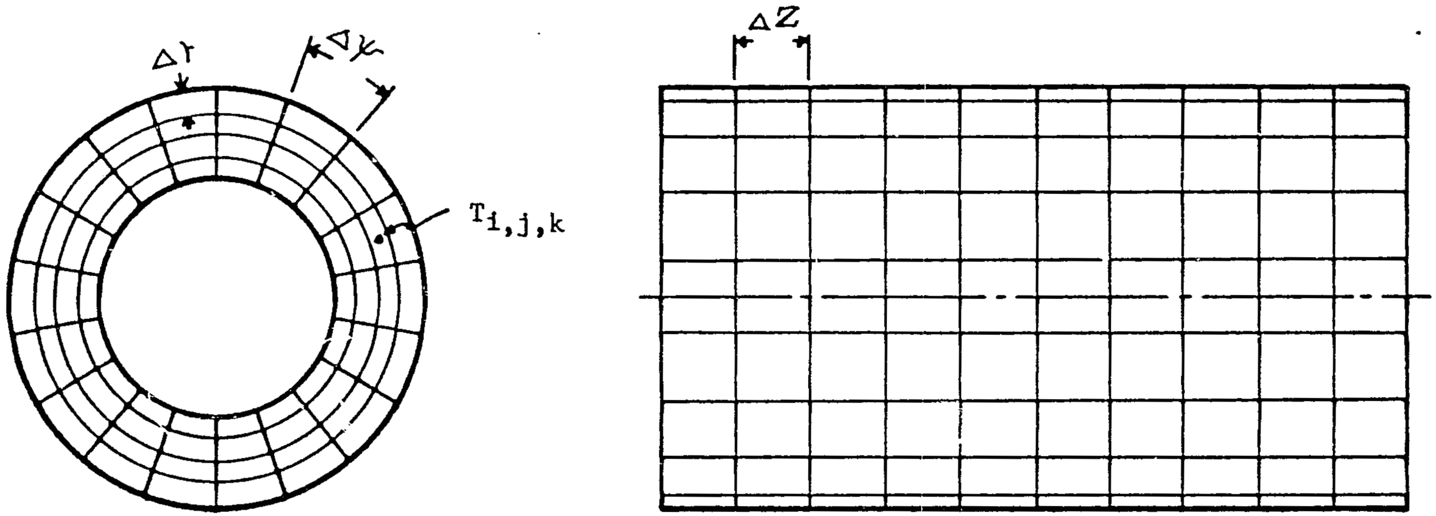


Figure 3. Heat Pipe Model

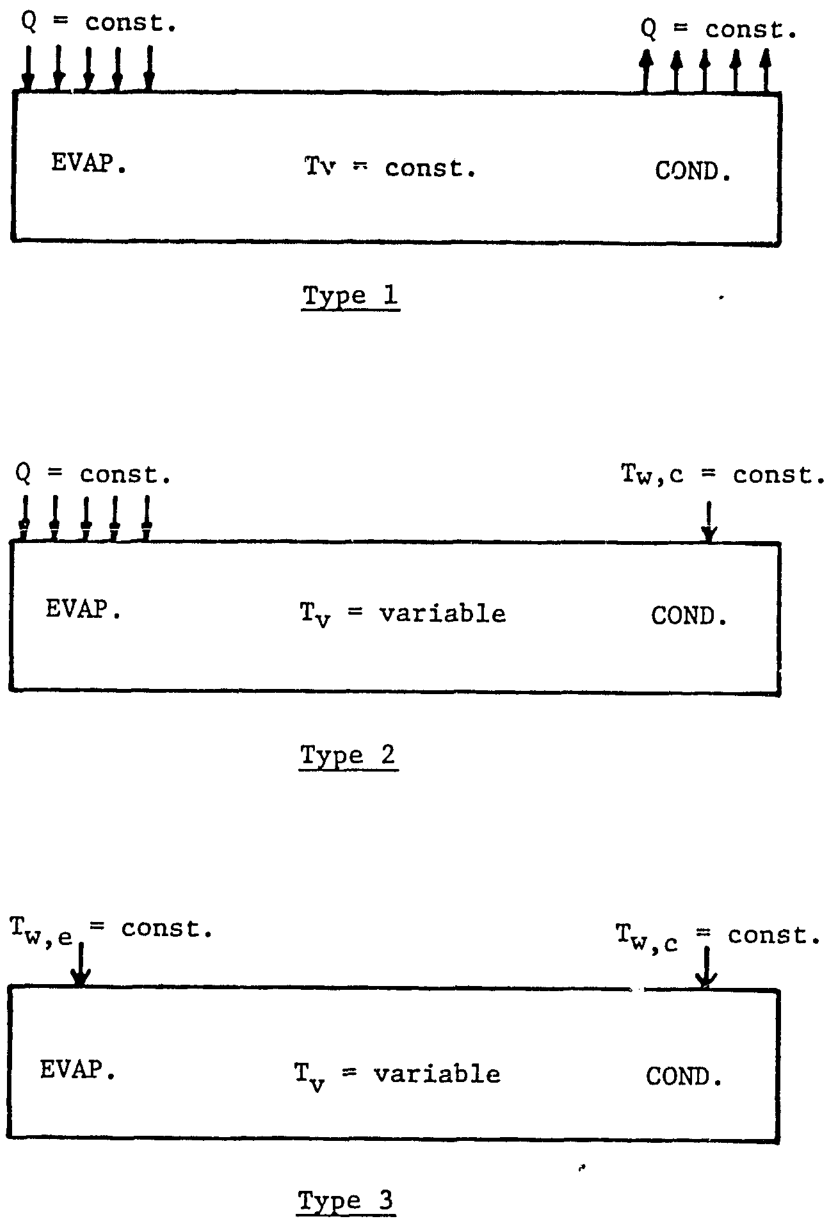


Figure 4. Exterior Boundary Conditions

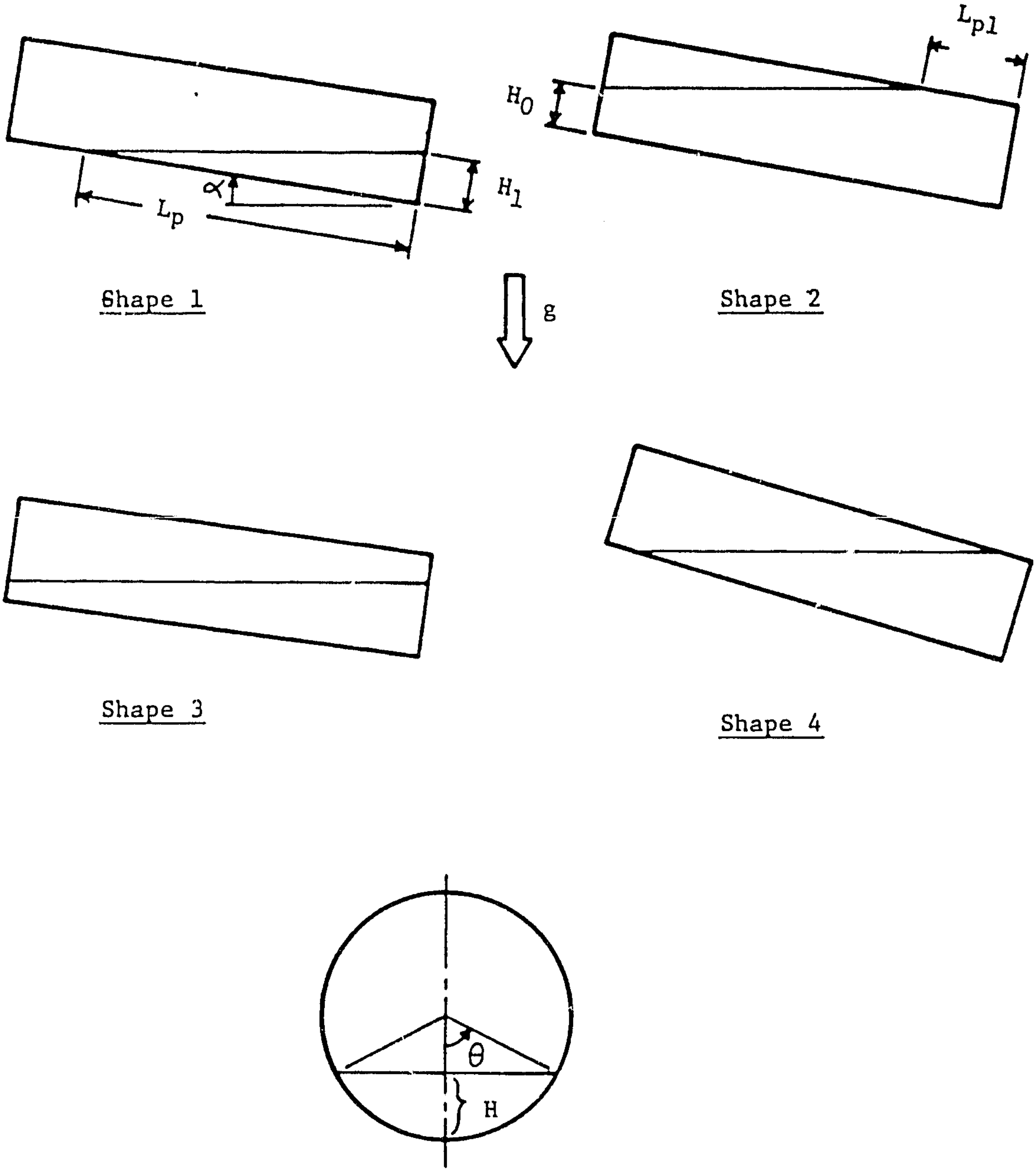
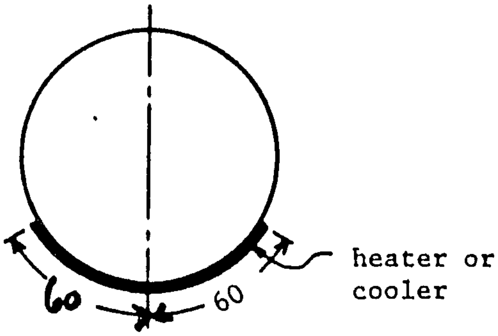


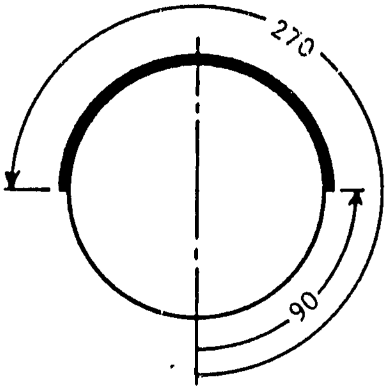
Figure 5. Puddle Shape Classification

Example 1



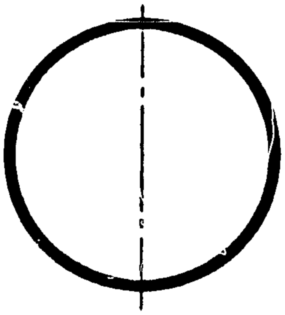
γ_1 = 0 (deg.) , γ_2 = 60
γ_3 = 300 γ_4 = 360

Example 2



γ_1 = 90 , γ_2 = 270
γ_3 = 500, γ_4 = 500

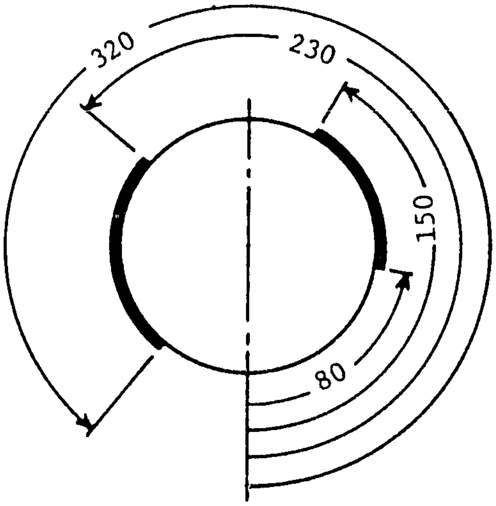
Example 3



(uniform heating or cooling)

γ_1 = 0 , γ_2 = 360
γ_3 = 500, γ_4 = 500

Example 4



(multiple heating or cooling)

γ_1 = 80 , γ_2 = 150
γ_3 = 230 , γ_4 = 320

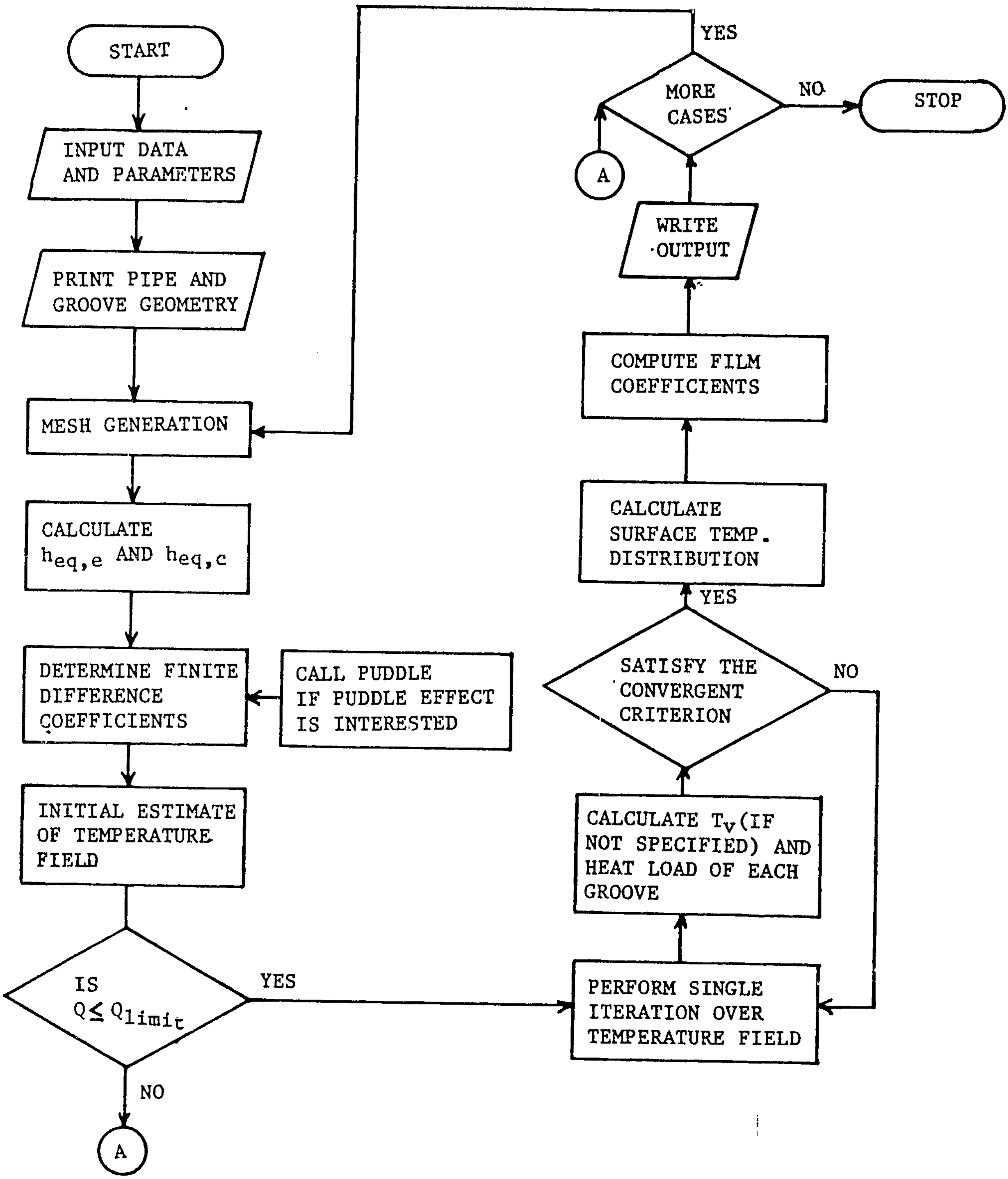
Figure 6. Heating and Cooling Zone Specification

APPENDIX A

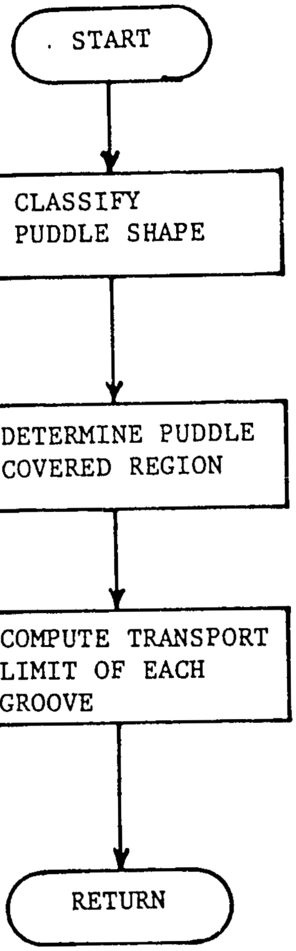
PROGRAM FLOWCHART

ORIGINAL PAGE IS
OF POOR QUALITY

MAIN PROGRAM



SUBROUTINE PUDDLE



APPENDIX B

PROGRAM LISTING

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         COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=82,SIZE=0000K,
                            SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,XREF
ISN 0002             DIMENSION R(7),PSI(35),DEGPSI(35),Z(32),DR(7),DPSI(35),DZ(32)
ISN 0003             DIMENSION T(5,29,27),TT(5,29,27),TIN(29,27),TOUT(29,27)
ISN 0004             DIMENSION PSIE(4),PSIC(4),NGE(4),NGC(4)
ISN 0005             DIMENSION C(4000,8),FS(4000),CIDMA(7),DIDMA(7)
ISN 0006             DIMENSION CONDL(5),CONDW(5),RHO(5),Q(5),TV(5),TCOND(5),TEVAP(5),
                    1          XSM(5),EL(5),XST(5)
ISN 0007             DIMENSION QMAX(5),QMAXGR(35),QSINGL(35)
ISN 0008             DIMENSION IFLUID(5),JPIPE(10)
ISN 0009             COMMON C,Z,XLE,XLAD,XLC,XL,RV,NGRV,XSTHT,L,M,MM,N,NN,NNN,
                    1       RHOL,XSMAS,ELV,QMXO,QMAXGR
               C
               C *******************************************************************
               C
               C                          NOMENCLATURE
               C
               C *******************************************************************
               C
               C     C(MP,N) = FINITE DIFFERENT COEFFICIENTS (W/K)
               C     CONL,CONDL = FLUID THERMAL CONDUCTIVITY (W/(M*K))
               C     CONW,CONDW = PIPE WALL THERMAL CONDUCTIVITY (W/(M*K))
               C     DPSI(J) = INCREMENT IN PSI ABOUT J (RAD.)
               C     DR(I) = INCREMENT IN R ABOUT I (M)
               C     DZ(K) = INCREMENT IN Z ABOUT K (M)
               C     DTSPEC = SPECIFIED ACCEPTABLE CHANGE IN TEMP. BETWEEN SUCCESSIVE
               C              ITERATIONS (K)
               C     EL,ELV = EVAPORATOR END ELEVATION (M)
               C     FILMEV = EVAPORATOR FILM COEFFICIENT (W/(M**2*K))
               C     FILMCO = CONDENSER FILM COEFFICIENT (W/(M**2*K))
               C     FS = HEAT GENERATION TERM (W)
               C     GDEPTH = GROOVE DEPTH (M)
               C     HCON = EQUIVALENT CONDENSER FILM COEFF. (W/(M**2*K))
               C     HEVP = EQUIVALENT EVAPORATOR FILM COEFF. (W/(M**2*K))
               C     HPAR = HEAT TRANSFER COEFF. FOR PARASITIC HEAT LOSS OR GAIN
               C            (W/(M**2*K))
               C     IFLUID = NAME OF WORKING FLUID
               C     IPUDL = CODE FOR PUDDLE EFFECT
               C        IPUDL = 1, PUDDLE EFFECT IS NOT INCLUDED
               C                2, PUDDLE EFFECT IS INCLUDED
               C     INIT = NO. OF ITERATIONS PER LOOP OF ITERATION
               C     JPIPE = PIPE WALL MATERIAL
               C     KTYPE = CODE TO SPECIFY BOUNDARY CONDITIONS (SEE THE MANUAL FOR
               C             THIS CODE)
               C     MGRAVT = CODE FOR GRAVITY EFFECT
               C       MGRAVT = 1, ZERO-G CONDITION
               C                2, ONE-G CONDITION
               C     MP,MPAR = STORAGE PARAMETER
               C     NCASE = NO. OF CASES TO BE RUN
               C     NGRV = NO. OF GROOVES
               C     NDIVR = NO. OF DIVISIONS IN R-DIRECTION
               C     NDIVSI = NO. OF DIVISIONS IN PSI-DIRECTION
               C     NDIVZ = NO. OF DIVISIONS IN Z-DIRECTION
               C     NDIVZE = NO. OF AXIAL DIVISIONS IN EVAPORATOR
               C     NDIVZA = NO. OF AXIAL DIVISIONS IN ADIABATIC SECTION
               C     NDIVZC = NO. OF AXIAL DIVISIONS IN CONDENSER
               C     NGC(1),(2),(3),(4) = PSIC CONVERTED TO GROOVE NUMBERS
               C     NGE(1),(2),(3),(4) = PSIE CONVERTED TO GROOVE NUMBERS
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```
C       NITN = TOTAL NUMBER OF ITERATIONS
C       PSI(J) = ANGLE OF NODES AT J (RAD.)
C       PSIC(1),(2),(3),(4) = ANGLES TO SPECIFY COOLING ZONE (DEG.)
C       PSIE(1),(2),(3),(4) = ANGLES TO SPECIFY HEATING ZONE (DEG.)
C       Q,QTOTL = TOTAL HEAT INPUT (W)
C       QMAX = MAX. HEAT TRANSPORT OF PIPE FOR OPTIMUM CHARGE (W)
C       QMXO = MAX. HEAT TRANSPORT OF SINGLE GROOVE (W)
C       QMAXGR = MAX. HEAT TRANSPORT OF SINGLE GROOVE,ADJUSTED FOR
C                TILT AND PUDDLE EFFECT
C       QMAXHP = MAX. HEAT TRANSPORT OF PIPE,ADJUSTED FOR TILT AND
C                PUDDLE EFFECT
C       QTRNSP = NET HEAT TRANSPORT OF PIPE (W)
C       QSINGL = NET HEAT TRANSPORT OF EACH GROOVE (W)
C       ROUT = PIPE OUTER RADIUS (M)
C       RIN = PIPE INNER RADIUS (GROOVE ROOT RADIUS) (M)
C       RV = VAPOR CORE RADIUS (GROOVE TIP RADIUS) (M)
C       RHOL,RHO = FLUID DENSITY (KG/M**3)
C       R(I) = RADIUS OF NODES AT I
C       TEMPS = AMBIENT TEMPERATURE (K)
C       TCOND,TWC = CONDENSER WALL SURFACE TEMP. (K)
C       TEVAP,TWE = EVAPORATOR WALL SURFACE TEMP. (K)
C       TV,TVAP = VAPOR TEMPERATURE (K)
```

```
                 C     TWCAV = AVERAGE CONDENSER WALL SURFACE TEMP. (K)
                 C     TWEAV = AVERAGE EVAPORATOR WALL SURFACE TEMP. (K)
                 C     TIN = PIPE INNER SURFACE TEMP. (K)
                 C     TOUT = PIPE OUTER SURFACE TEMP. (K)
                 C     TEMPE = ESTIMATED EVAPORATOR TEMP. (K)
                 C     TEMPC = ESTIMATED CONDENSER TEMP. (K)
                 C     TNGRC = TOTAL NUMBER OF GROOVES IN COOLING ZONE
                 C     TNGRE = TOTAL NUMBER OF GROOVES IN HEATING ZONE
                 C     W = RELAXATION PARAMETER
                 C     WIDTH = AVERAGE GROOVE LAND WIDTH (M)
                 C     XLE = LENGTH OF EVAPORATOR SECTION (M)
                 C     XLAD = LENGTH OF ADIABATIC SECTION (M)
                 C     XLC = LENGTH OF CONDENSER SECTION (M)
                 C     XL = TOTAL PIPE LENGTH (M)
                 C     XSTHT,XST = STATIC HEIGHT (M)
                 C     XSMAS,XSM = EXCESS MASS CHARGE (KG)
                 C     XPDL = PUDDLE LENGTH (M)
                 C     XTRNS = TRANSPORT LENGTH (M)
                 C     XSVOL = EXCESS VOLUME (M**3)
                 C     Z(K) = POSITION IN Z-DIRECTION OF NODES AT K (M)
                 C
                 C  ****************************************************************
                 C
                 C                FUNCTION DEFINITIONS
                 C
                 C  ****************************************************************
                 C
ISN 0010               DRP(I) = (DR(I+1)+DR(I))/2.
ISN 0011               DRN(I) = (DR(I)+DR(I-1))/2.
ISN 0012               DZP(K) = (DZ(K+1)+DZ(K))/2.
ISN 0013               DZN(K) = (DZ(K)+DZ(K-1))/2.
ISN 0014               C1(I,J,K) = CONW*(R(I)-DRN(I)/2.)*DPSI(J)*DZ(K)/DRN(I)
ISN 0015               C2(I,J,K) = CONW*(R(I)+DRP(I)/2.)*DPSI(J)*DZ(K)/DRP(I)
ISN 0016               C3(I,J,K) = CONW*DZ(K)*ALOG((R(I)+DRP(I)/2.)/(R(I)-DRN(I)/2.))/
                      1DPSI(J)
ISN 0017               C4(I,J,K) = CONW*DZ(K)*ALOG((R(I)+DRP(I)/2.)/(R(I)-DRN(I)/2.))/
                      1DPSI(J)
ISN 0018               C5(I,J,K) = CONW*DPSI(J)*(((R(I)+DRP(I)/2.)**2-(R(I)-DRN(I)/2.)
                      1**2)/2.)/DZN(K)
ISN 0019               C6(I,J,K) = CONW*DPSI(J)*(((R(I)+DRP(I)/2.)**2-(R(I)-DRN(I)/2.)
                      1**2)/2.)/DZP(K)
ISN 0020               MPAR(I,J,K) = (K-1)*L*M + (I-1)*M + J
                 C
                 C  ****************************************************************
                 C
                 C                   INPUT SECTION
                 C
                 C  ****************************************************************
                 C
                 C  INPUT OPERATING PARAMETERS
                 C
ISN 0021               IPUDL = 2
ISN 0022               KTYPE = 1
ISN 0023               MGRAVT = 2
                 C
                 C  INPUT PIPE GEOMETRY
                 C
ISN 0024               READ(5,10) XLE,XLAD,XLC
```

```
ISN 0025          XL = XLE + XLAD + XLC
            C
            C  INPUT GROOVE GEOMETRY
            C
ISN 0026          READ(5,11) NGRV,GDEPTH,WIDTH,ROUT,RIN,RV
            C
            C  INPUT FLUID AND PIPE MATERIAL NAMES
            C
ISN 0027          READ(5,12) (IFLUID(I),I=1,5),(JPIPE(J),J=1,10)
            C
            C  INPUT OPERATING CONDITIONS AND FLUID AND PIPE MATERIAL PROPERTIES
            C  FOR EACH RUN
            C
ISN 0028          NCASE = 1
ISN 0029          DO 20 IRUN=1,NCASE
ISN 0030          GO TO (1,2,3), KTYPE
ISN 0031        1 READ(5,13) Q(IRUN),TV(IRUN),QMAX(IRUN)
ISN 0032          GO TO 4
ISN 0033        2 READ(5,13) Q(IRUN),TCOND(IRUN),QMAX(IRUN)
ISN 0034          GO TO 4
ISN 0035        3 READ(5,13) TEVAP(IRUN),TCOND(IRUN),QMAX(IRUN)
ISN 0036        4 CONTINUE
```

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```
ISN 0037          READ(5,16) CONDL(IRUN),RHO(IRUN),CONDW(IRUN)
          C    IN ZERO-G CONDITION SKIP THE NEXT CARD
ISN 0038          IF(NGRAVT .EQ. 1) GO TO 20
ISN 0040          READ(5,17) XSM(IRUN),FL(IRUN),XST(IRUN)
ISN 0041       20 CONTINUE
          C
ISN 0042          READ(5,14) (PSIE(I),I=1,4)
ISN 0043          READ(5,14) (PSIC(J),J=1,4)
ISN 0044          READ(5,15) TEMPS,HPAR
          C
ISN 0045          DO 199 IJ=1,4
ISN 0046          NGE(IJ) = PSIE(IJ)*NGRV/360.
ISN 0047          NGC(IJ) = PSIC(IJ)*NGRV/360.
ISN 0048      199 CONTINUE
          C
ISN 0049       10 FORMAT(3F10.4)
ISN 0050       11 FORMAT(I5,5F10.4)
ISN 0051       12 FORMAT (5A2,10A2)
ISN 0052       13 FORMAT(3F10.5)
ISN 0053       16 FORMAT(3F15.4)
ISN 0054       17 FORMAT(3F15.4)
ISN 0055       14 FORMAT(4F10.3)
ISN 0056       15 FORMAT(F10.3,F10.4)
          C
          C    INPUT PARAMETERS
          C
ISN 0057          NDIVR = 3      10
ISN 0058          NDIVSI = NGRV
ISN 0059          NDIVZE = 10    20
ISN 0060          NDIVZA = 5     10
ISN 0061          NDIVZC = 10    20
ISN 0062          NDIVZ = NDIVZE + NDIVZA + NDIVZC
ISN 0063          L = NDIVR
ISN 0064          LL = L+1
ISN 0065          LLL = L+2
ISN 0066          M = NDIVSI
ISN 0067          MM = M+1
ISN 0068          MMM = M+2
ISN 0069          N = NDIVZ
ISN 0070          NN = N+1
ISN 0071          NNN = N+2
ISN 0072          INIT = 5
ISN 0073          W = 1.0
ISN 0074          DTSPEC = .01    .001
ISN 0075          PAI = 3.14159
          C
          C    *****************************************************************
          C
          C                     OUTPUT PIPE AND GROOVE DIMENSIONS
          C
          C    *****************************************************************
          C
ISN 0076          WRITE(6,921)
ISN 0077      921 FORMAT('1',28X,'**************************************************'/)
ISN 0078          WRITE(6,901)
ISN 0079      901 FORMAT(30X,'THERMAL ANALYSIS OF AXIALLY GROOVED HEAT PIPE'/)
ISN 0080          WRITE(6,922)
ISN 0081      922 FORMAT(29X,'**************************************************')
```

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```
ISN 0082         WRITE(6,960) (IFLUID(I),I=1,5),(JPIPE(J),J=1,10)
ISN 0083     960 FORMAT(///,15X,'NAMES OF WORKING FLUID AND PIPE MATERIAL',//,
                1          20X,'WORKING FLUID',T74,5A2/
                1          20X,'PIPE MATERIAL',T74,10A2)
ISN 0084         DOUT = ROUT*2.
ISN 0085         DIN = RIN*2.
ISN 0086         WRITE (6,902) XLE,XLAD,XLC,XL,DOUT,DIN,RV
ISN 0087     902 FORMAT(///,15X,'HEAT PIPE DIMENSIONS',//,
                1          20X,'EVAPORATOR LENGTH(M)',T70,F15.5/
                1          20X,'ADIABATIC  LENGTH(M)',T70,F15.5/
                1          20X,'CONDENSER  LENGTH(M)',T70,F15.5/
                1          20X,'TOTAL PIPE LENGTH(M)',T70,F15.5/
                1          20X,'PIPE OUTER DIAMETER(M)',T70,F15.5/
                1          20X,'PIPE INNER DIAMETER(M)',T70,F15.5/
                1          20X,'VAPOR CORE RADIUS(M)',T70,F15.5)
ISN 0088         WRITE(6,903) NGRV,GDEPTH,WIDTH
ISN 0089     903 FORMAT(//,15X,'GROOVE DIMENSIONS',//,
                1          20X,'NUMBER OF GROOVES',T75,I5/
                1          20X,'GROOVE DEPTH(M)',T70,F15.5/
                1          20X,'AVERAGE LAND WIDTH(M)',T70,F15.5)
           C
           C      OUTPUT HEATING AND COOLING MODES
```

```
      C
            WRITE(6,976)
        976 FORMAT(//,15X,'HEATING AND COOLING MODES')
            IF(NGE(1) .EQ. 0 .AND. NGE(2) .EQ. M) GO TO 977
            WRITE(6,979) PSIE(1),PSIE(2)
        979 FORMAT(/,20X,'EVAPORATOR REGION',T50,'NON-UNIFORM HEATING',/,
           1         T50,'HEATING REGION COVERS FROM PSI=',F5.1,' DEG  TO PSI='
           1         ,F5.1,' DEG')
            IF(NGE(3) .LT. M) WRITE(6,980) PSIE(3),PSIE(4)
        980 FORMAT(67X,'AND FROM PSI=',F5.1,' DEG  TO PSI=',F5.1,' DEG')
            GO TO 981
        977 WRITE(6,978)
        978 FORMAT(/,20X,'EVAPORATOR REGION', T70,'UNIFORM HEATING')
        981 CONTINUE
            IF(NGC(1) .EQ. 0 .AND. NGC(2) .EQ. M) GO TO 982
            WRITE(6,984) PSIC(1),PSIC(2)
        984 FORMAT(/,20X,'CONDENSER REGION',T50,'NON-UNIFORM COOLING',/,
           1         T50,'COOLING REGION COVERS FROM PSI=',F5.1,' DEG  TO PSI='
           1         ,F5.1,' DEG')
            IF(NGC(3) .LT. M) WRITE(6,985) PSIC(3),PSIC(4)
        985 FORMAT(67X,'AND FROM PSI=',F5.1,' DEG  TO PSI=',F5.1,' DEG')
            GO TO 986
        982 WRITE(6,983)
        983 FORMAT(/,20X,'CONDENSER REGION',T70,'UNIFORM COOLING')
        986 CONTINUE
      C
      C   ******************************************************************
      C
      C                          MESH GENERATION
      C
      C   ******************************************************************
      C
            DO 101 I=2,LL
            DR(I) = (ROUT - RIN)/L
            R(I) = RIN+(I-1.5)*DR(I)
        101 CONTINUE
            DR(1) = 0.0
            R(1) = RIN
            DR(LLL) = 0.0
            R(LLL) = ROUT
      C
            DO 102 J=1,MMM
            DPSI(J) = 2.0*PAI/M
            PSI(J) = (J-1.5)*DPSI(J)
        102 CONTINUE
            PSI(1) = 0.0
            PSI(MMM) = 2.0*PAI
      C
            DZ(1) = 0.0
            Z(1) = 0.0
            NDVE1 = NDIVZE + 1
            DO 103 K=2,NDVE1
            DZ(K) = XLE/NDIVZE
            Z(K) = (K-1.5)*DZ(K)
        103 CONTINUE
            NDVE2 = NDIVZE + 2
            NDVEA1 = NDIVZE + NDIVZA + 1
            DO 104 K=NDVE2,NDVEA1
```

```
ISN 0138          DZ(K) = XLAD/NDIVZA
ISN 0139          Z(K) = XLE + (K - NDIVZE - 1.5)*DZ(K)
ISN 0140      104 CONTINUE
ISN 0141          NDVEA2 = NDIVZE + NDIVZA + 2
ISN 0142          DO 105 K=NDVEA2,NN
ISN 0143          DZ(K) = XLC/NDIVZC
ISN 0144          Z(K) = XLE + XLAD + (K - NDIVZE - NDIVZA - 1.5)*DZ(K)
I N 0145      105 CONTINUE
ISN 0146          DZ(NNN) = 0.0
ISN 0147          Z(NNN) = XL
            C
            C *******************************************************************
            C
            C          RUN THE PROGRAM FOR THE NUMBER OF CASES SPECIFIED
            C
            C *******************************************************************
            C
ISN 0148          DO 50 IRUN=1,NCASE
            C
ISN 0149          CONL = CONDL(IRUN)
ISN 0150          RHOL = RHO(IRUN)
ISN 0151          CONW = CONDW(IRUN)
```

```
                    C
                    C     COMPUTE SINGLE GROOVE TRANSPORT LIMIT
      ISN 0152            IF(MGRAVT .EQ. 1) GO TO 120
                    C
                    C     FOR ONE-G CONDITION (PUDDLE EFFECT IS CONSIDERED LATER)
      ISN 0154            FLV = FL(IRUN)
      ISN 0155            XSTHT = XST(IRUN)
      ISN 0156            XSMAS = XSM(IRUN)
      ISN 0157            QMXO = QMAX(IRUN)/NGRV
      ISN 0158            DO 121 J=2,MM
      ISN 0159            QMAXGR(J) = QMXO*(1. - FLV/XSTHT)
      ISN 0160            IF(QMAXGR(J) .LE. 0.0) QMAXGR(J)=0.0
      ISN 0162        121 CONTINUE
      ISN 0163            GO TO 122
                    C
      ISN 0164        120 CONTINUE
                    C
                    C     FOR ZERO-G CONDITION
      ISN 0165            QMXO = QMAX(IRUN)/NGRV
      ISN 0166            DO 123 J=2,MM
      ISN 0167            QMAXGR(J) = QMXO
      ISN 0168        123 CONTINUE
                    C
      ISN 0169        122 CONTINUE
                    C
                    C  ****************************************************************
                    C
                    C         CALCULATIONS OF EVAPORATOR AND CONDENSER EQUIVALENT HEAT
                    C         TRANSFER COEFFICIENTS
                    C
                    C  ****************************************************************
                    C
      ISN 0170            HEVP = (NGRV*CONL/(2.*PAI*RIN))/(.070)+(CONL/CONW)*(GDEPTH/WIDTH))
      ISN 0171            HCON = (NGRV*CONL/(2.*PAI*RIN))/(.020+(CONL/CONW)*(GDEPTH/WIDTH))
                    C
                    C  ****************************************************************
                    C
                    C                STORAGE OF COEFFICIENTS
                    C
                    C  ****************************************************************
                    C
      ISN 0172            DO 200 K=2,NN
      ISN 0173            DO 200 J=2,MM
      ISN 0174            DO 200 I=2,LL
      ISN 0175            MP = MPAR(I,J,K)
                    C
      ISN 0176            C(MP,1) = C1(I,J,K)
      ISN 0177            C(MP,2) = C2(I,J,K)
      ISN 0178            C(MP,3) = C3(I,J,K)
      ISN 0179            C(MP,4) = C4(I,J,K)
      ISN 0180            C(MP,5) = C5(I,J,K)
      ISN 0181            C(MP,6) = C6(I,J,K)
      ISN 0182            C(MP,8) = 0.0
      ISN 0183            FS(MP) = 0.0
      ISN 0184            TOUT(J,K) = 0.0
                    C
                    C  SPECIFY BOUNDARY CONDITIONS
                    C
```

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```
                C     *NODES CONTACTING Z=0
                C
  ISN 0185             IF(K .EQ. 2) C(MP,5)=0.0
                C
                C     *NODES CONTACTING Z=XL
                C
  ISN 0187             IF(K .EQ. NN) C(MP,6)=0.0
                C
                C     *NODES CONTACTING R=ROUT
                C
  ISN 0189             IF(I .NE. LL) GO TO 200
                C
                C        PARASITIC HEAT LOSS OR GAIN
                C
  ISN 0191             C(MP,2) = C2(I,J,K)*(HPAR*DR(LL)/CONW)/(2.0 + HPAR*DR( )/CONW)
                C
                C        CLASSIFY BOUNDARY CONDITIONS INTO THREE TYPES
  ISN 0192             GO TO (201,202,203), KTYPE
  ISN 0193        201 CONTINUE
                C
                C      TYPE 1 BOUNDARY CONDITION
                C
```

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```
ISN 0194          QTOTL = Q(IRUN)
ISN 0195          TVAP = TV(IRUN)
            C
            C     EVAPORATOR (TOTAL HEAT INPUT SPECIFIED)
            C
ISN 0196          IF(NGE(3) .GT. M) GO TO 204
ISN 0198          TNGRE = (NGE(2) - NGE(1)) + (NGE(4) - NGE(3))
ISN 0199          GO TO 205
ISN 0200      204 TNGRE = NGE(2) - NGE(1)
ISN 0201      205 CONTINUE
ISN 0202          IF(J .LT. (NGE(1)+2)) GO TO 210
ISN 0204          IF(J .GE. (NGE(2)+2) .AND. J .LT. (NGE(3)+2)) GO TO 210
ISN 0206          IF(J .GE. (NGE(4)+2)) GO TO 210
ISN 0208          IF(Z(K) .GT. XLE) GO TO 210
ISN 0210          FS(MP) = DZ(K)*QTOTL/(TNGRE*XLE)
ISN 0211      210 CONTINUE
            C
            C     CONDENSER (TOTAL HEAT OUTPUT SPECIFIED)
            C
ISN 0212          IF(NGC(3) .GT. M) GO TO 211
ISN 0214          TNGRC = (NGC(2) - NGC(1)) + (NGC(4) - NGC(3))
ISN 0215          GO TO 212
ISN 0216      211 TNGRC = NGC(2) - NGC(1)
ISN 0217      212 CONTINUE
ISN 0218          IF(J .LT. (NGC(1)+2)) GO TO 220
ISN 0220          IF(J .GE. (NGC(2)+2) .AND. J .LT. (NGC(3)+2)) GO TO 220
ISN 0222          IF(J .GE. (NGC(4)+2)) GO TO 220
ISN 0224          IF(Z(K) .LT. (XLE+XLAD)) GO TO 220
ISN 0226          FS(MP) = -DZ(K)*QTOTL/(TNGRC*XLC)
ISN 0227      220 CONTINUE
ISN 0228          GO TO 200
            C
ISN 0229      202 CONTINUE
            C
            C   TYPE 2 BOUNDARY CONDITION
            C
ISN 0230          QTOTL = Q(IRUN)
ISN 0231          TWC = TCOND(IRUN)
            C
            C     EVAPORATOR (TOTAL HEAT INPUT SPECIFIED)
            C
ISN 0232          IF(NGE(3) .GT. M) GO TO 221
ISN 0234          TNGRE = (NGE(2) - NGE(1)) + (NGE(4) - NGE(3))
ISN 0235          GO TO 222
ISN 0236      221 TNGRE = NGE(2) - NGE(1)
ISN 0237      222 CONTINUE
ISN 0238          IF(J .LT. (NGE(1)+2)) GO TO 223
ISN 0240          IF(J .GE. (NGE(2)+2) .AND. J .LT. (NGE(3)+2)) GO TO 223
ISN 0242          IF(J .GE. (NGE(4)+2)) GO TO 223
ISN 0244          IF(Z(K) .GT. XLE) GO TO 223
ISN 0246          FS(MP) = DZ(K)*QTOTL/(TNGRE*XLE)
ISN 0247      223 CONTINUE
            C
            C     CONDENSER (OUTER SURFACE TEMPERATURE SPECIFIED)
            C
ISN 0248          IF(J .LT. (NGC(1)+2)) GO TO 224
ISN 0250          IF(J .GE. (NGC(2)+2) .AND. J .LT. (NGC(3)+2)) GO TO 224
ISN 0252          IF(J .GE. (NGC(4)+2)) GO TO 224
```

```
ISN 0254            IF(Z(K) .LT. (XLE+XLAD)) GO TO 224
ISN 0256            TOUT(J,K) = TWC
ISN 0257            C(MP,8) = C2(I,J,K)
ISN 0258        224 CONTINUE
ISN 0259            GO TO 200
              C
ISN 0260        203 CONTINUE
              C
              C    TYPE 3 BOUNDARY CONDITION
              C
ISN 0261            TWE = TEVAP(IRUN)
ISN 0262            TWC = TCOND(IRUN)
              C
              C     EVAPORATOR (OUTER SURFACE TEMPERATURE SPECIFIED)
              C
ISN 0263            IF(J .LT. (NGE(1)+2)) GO TO 225
ISN 0265            IF(J .GE. (NGE(2)+2) .AND. J .LT. (NGE(3)+2)) GO TO 225
ISN 0267            IF(J .GE. (NGE(4)+2)) GO TO 225
ISN 0269            IF(Z(K) .GT. XLE) GO TO 225
ISN 0271            TOUT(J,K) = TWE
ISN 0272            C(MP,8) = C2(I,J,K)
ISN 0273        225 CONTINUE
```

```
                C
                C   .CONDENSER (OUTER SURFACE TEMPERATURE SPECIFIED)
                C
ISN 0274               IF(J .LT. (NGC(1)+2)) GO TO 226
ISN 0276               IF(J .GE. (NGC(2)+2) .AND. J .LT. (NGC(3)+2)) GO TO 226
ISN 0278               IF(J .GE. (NGC(4)+2)) GO TO 226
ISN 0280               IF(Z(K) .LT. (XLE+XLAD)) GO TO 226
ISN 0282               TOUT(J,K) = TWC
ISN 0283               C(MP,8) = C2(I,J,K)
ISN 0284           226 CONTINUE
                C
ISN 0285           200 CONTINUE
                C
                C  *NODES CONTACTING R=RIN
                C     THIS PART SPECIFIES ONLY PUDDLE EFFECT
                C     HEAT TRANSFER CONDITION IS SPECIFIED IN THE ITERATION SECTION
                C
ISN 0286               IF(MGRAVT .EQ. 1) GO TO 270
ISN 0288               IF(IPUDL .EQ. 1) GO TO 270
ISN 0290               IF(XSMAS .LE. 0.0) GO TO 270
ISN 0292               IF(ELV .LE. 0.0) GO TO 270
                C      (PUDDLE EFFECT FOR ZERO-ELEVATION IS NOT TREATED IN THIS PROGRAM)
ISN 0294               CALL PUDDLE
ISN 0295           270 CONTINUE
                C
                C  ******************************************************************
                C
                C                  INITIAL ESTIMATE OF TEMPERATURE FIELD
                C
                C  ******************************************************************
                C
ISN 0296               GO TO (250,251,252), KTYPE
                C
ISN 0297           250 CONTINUE
                C
                C  FOR TYPE 1 BOUNDARY CONDITION
                C
ISN 0298               I = 1
ISN 0299               DO 253 J=1,MMM
ISN 0300               DO 253 K=1,NNN
ISN 0301               T(I,J,K) = TVAP
ISN 0302           253 CONTINUE
ISN 0303               TEMPE = TVAP + QTOTL/(2.*PAI*RIN*HEVP*XLE)
ISN 0304               TEMPC = TVAP - QTOTL/(2.*PAI*RIN*HCON*XLC)
ISN 0305               DO 254 I=2,LL
ISN 0306               DO 254 J=1,MMM
ISN 0307               DO 254 K=1,NNN
ISN 0308               T(I,J,K) = TVAP
ISN 0309               IF(Z(K) .LE. XLE) T(I,J,K)=TEMPE
ISN 0311               IF(Z(K) .GT. (XLE+XLAD)) T(I,J,K)=TEMPC
ISN 0313           254 CONTINUE
ISN 0314               GO TO 260
                C
ISN 0315           251 CONTINUE
                C
                C  FOR TYPE 2 BOUNDARY CONDITION
                C
ISN 0316               I = 1
```

```
ISN 0317          TVAP = TWC + QTOTL/(2.*PAI*RIN*HCON*XLC)
ISN 0318          DO 255 J=1,MMM
ISN 0319          DO 255 K=1,NNN
ISN 0320          T(I,J,K) = TVAP
ISN 0321      255 CONTINUE
ISN 0322          TEMPE = TWC + (1.0/(HEVP*XLE) + 1.0/(HCON*XLC))*QTOTL/(2.0*PAI
                 1 *RIN)
ISN 0323          DO 256 I=2,LL
ISN 0324          DO 256 J=1,MMM
ISN 0325          DO 256 K=1,NNN
ISN 0326          T(I,J,K) = TVAP
ISN 0327          IF(Z(K) .LE. XLE) T(I,J,K)=TEMPE
ISN 0329          IF(Z(K) .GT. (XLE+XLAD)) T(I,J,K)=TWC
ISN 0331      256 CONTINUE
ISN 0332          GO TO 260
            C
ISN 0333      252 CONTINUE
            C
            C   FOR TYPE 3 BOUNDARY CONDITION
            C
ISN 0334          I = 1
ISN 0335          TVAP = (TWE + TWC*(HCON*XLC)/(HEVP*XLE))/(1.0 + (HCON*XLC)/
```

```
                       1  (HEVP*XLE))
ISN 0336               QTOTL = 2.*PAI*RV*(TWE - TWC)/(1.0/(XLE*HEVP) + 1.0/(XLC*HCON))
ISN 0337               DO 257 J=1,MMM
ISN 0338               DO 257 K=1,NNN
ISN 0339               T(I,J,K) = TVAP
ISN 0340           257 CONTINUE
ISN 0341               DO 258 I=2,LL
ISN 0342               DO 258 J=1,MMM
ISN 0343               DO 258 K=1,NNN
ISN 0344               T(I,J,K) = TVAP
ISN 0345               IF(Z(K) .LE. XLE) T(I,J,K)=TWE
ISN 0347               IF(Z(K) .GT. (XLE+XLAD)) T(I,J,K)=TWC
ISN 0349           258 CONTINUE
                 C
ISN 0350           260 CONTINUE
                 C
ISN 0351               I = LLL
ISN 0352               DO 261 J=1,MMM
ISN 0353               DO 261 K=1,NNN
ISN 0354               T(I,J,K) = TEMPS
ISN 0355           261 CONTINUE
                 C
                 C   ***********************************************************************
                 C
                 C                         CHECK FOR TRANSPORT LIMIT
                 C
                 C   ***********************************************************************
                 C
                 C     CALCULATE HEAT TRANSPORT LIMIT OF HEAT PIPE
ISN 0356               QMAXHP = 0.0
ISN 0357               DO 262 J=2,MM
ISN 0358           262 QMAXHP = QMAXHP + QMAXGR(J)
                 C     IF TOTAL HEAT INPUT IS LARGER THAN HEAT PIPE TRANSPORT LIMIT,
                 C     TERMINATE COMPUTATION.
ISN 0359               IF(QTOTL .GT. QMAXHP) GO TO 973
                 C
                 C   ***********************************************************************
                 C
                 C                          ITERATION
                 C
                 C   ***********************************************************************
                 C
                 C
ISN 0361               ITN = 1
ISN 0362           300 CONTINUE
ISN 0363               DO 350 II=1,INIT
ISN 0364               DO 310 KK=1,N
ISN 0365               K = NNN - KK
ISN 0366               DO 310 J=2,MM
ISN 0367               I = 2
ISN 0368               MP = MPAR(I,J,K)
ISN 0369               TT(I,J,K) = T(I,J,K)
ISN 0370               IF(C(MP,1) .LE. .1E-5) GO TO 302
ISN 0372               IF(T(I,J,K) .GT. TVAP) GO TO 301
ISN 0374               C(MP,1) = C1(I,J,K)*(HCON*DR(2)/CONW)/(2. + HCON*DR(2)/CONW)
ISN 0375               GO TO 302
ISN 0376           301 C(MP,1) = C1(I,J,K)*(HEVP*DR(2)/CONW)/(2. + HEVP*DR(2)/CONW)
ISN 0377           302 CONTINUE
```

```
ISN 0378        C(MP,7) = C(MP,1) + C(MP,2) + C(MP,3) + C(MP,4) + C(MP,5) +
               1 C(MP,6)
ISN 0379        D = C(MP,1)*T(I-1,J,K) + C(MP,3)*T(I,J-1,K) + C(MP,4)*T(I,J+1,K)
               1 + C(MP,5)*T(I,J,K-1) + C(MP,6)*T(I,J,K+1)
ISN 0380        CTDMA(I) = -C(MP,2)/C(MP,7)
ISN 0381        DTDMA(I) = D/C(MP,7)
          C
ISN 0382        DO 303 I=3,L
ISN 0383        MP = MPAR(I,J,K)
ISN 0384        TT(I,J,K) = T(I,J,K)
ISN 0385        D = C(MP,3)*T(I,J-1,K) + C(MP,4)*T(I,J+1,K) + C(MP,5)*T(I,J,K-1)
               1 + C(MP,6)*T(I,J,K+1)
ISN 0386        C(MP,7) = C(MP,1) + C(MP,2) + C(MP,3) + C(MP,4) + C(MP,5) +
               1 C(MP,6)
ISN 0387        DEN = C(MP,7) + C(MP,1)*CTDMA(I-1)
ISN 0388        CTDMA(I) = -C(MP,2)/DEN
ISN 0389        DTDMA(I) = (D + C(MP,1)*DTDMA(I-1))/DEN
ISN 0390    303 CONTINUE
          C
ISN 0391        I = LL
ISN 0392        MP = MPAR(I,J,K)
ISN 0393        TT(I,J,K) = T(I,J,K)
```

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ISN 0394          D = C(MP,2)*T(I+1,J,K) + C(MP,3)*T(I,J-1,K) + C(MP,4)*T(I,J+1,K) +
                 1 C(MP,5)*T(I,J,K-1) + C(MP,6)*T(I,J,K+1) + FS(MP) + C(MP,8)*
                 1 TOUT(J,K)
ISN 0395          C(MP,7) = C(MP,1) + C(MP,2) + C(MP,3) + C(MP,4) + C(MP,5) +
                 1 C(MP,6) + C(MP,8)
ISN 0396          DEN = C(MP,7) + C(MP,1)*CTDMA(I-1)
ISN 0397          DTDMA(I) = (D + C(MP,1)*DTDMA(I-1))/DEN
            C
            C     TEMPERATURE CALCULATIONS
            C
ISN 0398          I = LL
ISN 0399          T(I,J,K) = DTDMA(I)
ISN 0400          DO 304 II=2,L
ISN 0401          I = LLL - II
ISN 0402          T(I,J,K) = DTDMA(I) - CTDMA(I)*T(I+1,J,K)
ISN 0403      304 CONTINUE
            C
            C     RELAXATION
            C
ISN 0404          DO 305 I=2,LL
ISN 0405          T(I,J,K) = (1.0 - W)*TT(I,J,K) + W*T(I,J,K)
ISN 0406      305 CONTINUE
ISN 0407          DO 306 I=2,LL
ISN 0408          IF(J .EQ. 2) T(I,MMM,K)=T(I,J,K)
ISN 0410          IF(J .EQ. MM) T(I,1,K)=T(I,J,K)
ISN 0412      306 CONTINUE
            C
ISN 0413      310 CONTINUE
            C
            C     VAPOR TEMPERATURE AND TOTAL HEAT TRANSPORT CALCULATIONS
            C
ISN 0414          TTVAP = TVAP
ISN 0415          I = 2
ISN 0416          DO 315 K=2,NN
ISN 0417          DO 315 J=2,MM
ISN 0418          MP = MPAR(I,J,K)
ISN 0419          IF(C(MP,1) .LE. .1E-5) GO TO 317
ISN 0421          IF(T(I,J,K) .GT. TVAP) GO TO 316
ISN 0423          C(MP,1) = C1(I,J,K)*(HCON*DR(2)/CONW)/(2. + HCON*DR(2)/CONW)
ISN 0424          GO TO 317
ISN 0425      316 C(MP,1) = C1(I,J,K)*(HEVP*DR(2)/CONW)/(2. + HEVP*DR(2)/CONW)
ISN 0426      317 CONTINUE
ISN 0427          C(MP,7) = C(MP,1) + C(MP,2) + C(MP,3) + C(MP,4) + C(MP,5) +
                 1 C(MP,6)
ISN 0428          CPRIME = C(MP,7) - C(MP,1) + C1(I,J,K)
ISN 0429          TIN(J,K) = (1.0/C1(I,J,K))*(CPRIME*T(I,J,K) - C(MP,2)*T(I+1,J,K)
                 1 - C(MP,3)*T(I,J-1,K) - C(MP,4)*T(I,J+1,K) - C(MP,5)*T(I,J,K-1) -
                 1 C(MP,6)*T(I,J,K+1))
ISN 0430      315 CONTINUE
ISN 0431          HDT = 0.0
ISN 0432          HDA = 0.0
ISN 0433          QTRNSP = 0.0
ISN 0434          DO 318 J=2,MM
ISN 0435          QSUM = 0.0
ISN 0436          DO 330 KK=1,N
ISN 0437          K = NNN - KK
ISN 0438          MP = MPAR(I,J,K)
ISN 0439          IF(C(MP,1) .LE. 0.0) GO TO 330
```

```
ISN 0441          IF(TIN(J,K) .GT. TVAP) GO TO 319
ISN 0443          HDT = HDT + HCON*TIN(J,K)*RIN*DPSI(J)*DZ(K)
ISN 0444          HDA = HDA + HCON*RIN*DPSI(J)*DZ(K)
ISN 0445          GO TO 330
ISN 0446      319 HDT = HDT + HEVP*TIN(J,K)*RIN*DPSI(J)*DZ(K)
ISN 0447          HDA = HDA + HEVP*RIN*DPSI(J)*DZ(K)
ISN 0448          QSUM = QSUM + HEVP*(TIN(J,K) - TVAP)*RIN*DPSI(J)*DZ(K)
ISN 0449          IF(QSUM .GT. QMAXGR(J)) GO TO 331
ISN 0451      330 CONTINUE
ISN 0452          GO TO 332
ISN 0453      331 CONTINUE
            C     IF QSUM IS LARGER THAN THE TRANSPORT LIMIT OF THE GROOVE, THE
            C     GROOVE PARTIALLY DRYS OUT.
ISN 0454          K1 = K
ISN 0455          DO 335 K=2,NN
ISN 0456          IF(K .LT. K1) GO TO 334
ISN 0458          C(MP,1) = C1(I,J,K)
ISN 0459          GO TO 335
ISN 0460      334 C(MP,1) = .1E-5
            C     (FOR DRIED-OUT GROOVES C(MP,1) IS SET EQUAL TO A SMALL NUMBER
            C     FOR CONVENIENCE OF NUMERICAL ITERATION)
ISN 0461      335 CONTINUE
```

```
ISN 0462      332 CONTINUE
ISN 0463          QSINGL(J) = QSUM
ISN 0464          QTRNSP = QTRNSP + QSUM
ISN 0465      318 CONTINUE
ISN 0466          GO TO (311,312,312), KTYPE
ISN 0467      312 TVAP = HQT/HQA
ISN 0468          TVAP = (1.0 - W)*TTVAP + W*TVAP
ISN 0469          I = 1
ISN 0470          DO 321 J=1,MMM
ISN 0471          DO 321 K=1,NNN
ISN 0472          T(I,J,K) = TVAP
ISN 0473      321 CONTINUE
ISN 0474      311 CONTINUE
             C
ISN 0475      350 CONTINUE
             C
             C  *******************************************************************
             C
             C                        CONVERGENCE CHECK
             C
             C  *******************************************************************
             C
ISN 0476          DTMAX = ABS(TVAP-TTVAP)
ISN 0477          DO 360 K=2,NN
ISN 0478          DO 360 J=2,MM
ISN 0479          DO 360 I=2,LL
ISN 0480          DT = ABS(T(I,J,K)-TT(I,J,K))
ISN 0481          IF(DT .GT. DTMAX) DTMAX=DT
ISN 0483      360 CONTINUE
             C
             C     IS THIS MAXIMUM CHANGE ACCEPTABLE
             C
ISN 0484          ITN = ITN + 1
ISN 0485          IF(DTMAX .GT. DTSPEC) GO TO 300
             C
             C     NUMBER OF ITERATION REQUIRED FOR CONVERGENCE
             C
ISN 0487          NITN = (ITN - 1)*INIT
             C
             C  ******************** ********************************************
             C
             C            SURFACE TEMPERATURE CALCULATION
             C
             C  *******************************************************************
             C
ISN 0488          I = LL
ISN 0489          DO 370 K=2,NN
ISN 0490          DO 370 J=2,MM
ISN 0491          MP = MPAR(I,J,K)
ISN 0492          C(MP,7) = C(MP,1) + C(MP,2) + C(MP,3) + C(MP,4) + C(MP,5) +
                 1 C(MP,6)
ISN 0493          CPRIME = C(MP,7) - C(MP,2) + C2(I,J,K)
ISN 0494          TOUT(J,K) = (1.0/C2(I,J,K))*(CPRIME*T(I,J,K) - C(MP,1)*T(I-1,J,K)
                 1 - C(MP,3)*T(I,J-1,K) - C(MP,4)*T(I,J+1,K) - C(MP,5)*T(I,J,K-1)
                 1 - C(MP,6)*T(I,J,K+1))
ISN 0495      370 CONTINUE
             C
             C  *******************************************************************
```

```
                C
                C   AVERAGE SURFACE TEMPERATURES OF EVAPORATOR AND CONDENSER
                C
                C   ******************************************************************
                C
ISN 0496              GO TO (371,372,373), KTYPE
ISN 0497          371 CONTINUE
                C
                C   FOR TYPE 1 BOUNDARY CONDITION
                C
ISN 0498              TWES = 0.0
ISN 0499              TWCS = 0.0
ISN 0500              DO 374 K=2,NN
ISN 0501              DO 374 J=2,MM
ISN 0502              IF(Z(K) .LT. XLE) TWES=TWES+TOUT(J,K)*ROUT*DPSI(J)*DZ(K)
ISN 0504              IF(Z(K) .GT. (XLE+XLAD)) TWCS=TWCS+TOUT(J,K)*ROUT*DPSI(J)*DZ(K)
ISN 0506          374 CONTINUE
ISN 0507              TWEAV = TWES/(2.*PAI*ROUT*XLE)
ISN 0508              TWCAV = TWCS/(2.*PAI*ROUT*XLC)
ISN 0509              GO TO 375
                C
ISN 0510          372 CONTINUE
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                   C
                   C  FOR TYPE 2 BOUNDARY CONDITION
                   C
      ISN 0511           TWCAV = TWC
      ISN 0512           TWES = 0.0
      ISN 0513           DO 376 K=2,NN
      ISN 0514           DO 376 J=2,MM
      ISN 0515           IF(Z(K) .LT. XLE) TWES=TWES+TOUT(J,K)*ROUT*DPSI(J)*DZ(K)
      ISN 0517       376 CONTINUE
      ISN 0518           TWEAV = TWES/(2.*PAI*ROUT*XLE)
      ISN 0519           GO TO 375
                   C
      ISN 0520       373 CONTINUE
                   C
                   C  FOR TYPE 3 BOUNDARY CONDITION
                   C
      ISN 0521           TWEAV = TWE
      ISN 0522           TWCAV = TWC
      ISN 0523       375 CONTINUE
                   C
                   C
                   C  ******************************************************************
                   C
                   C          EVAPORATOR AND CONDENSER OVERALL FILM CIEFFICIENTS
                   C
                   C  ******************************************************************
                   C
      ISN 0524           FILMEV = QTRNSP/(2.*PAI*RV*XLE*(TWEAV - TVAP))
      ISN 0525           FILMCO = QTRNSP/(2.*PAI*RV*XLC*(TVAP - TWCAV))
                   C
                   C  ******************************************************************
                   C
                   C                     OUTPUT SECTION
                   C
                   C  ******************************************************************
                   C
      ISN 0526           WRITE(6,961) IRUN
      ISN 0527       961 FORMAT('1',14X,'CASE NUMBER =',I2)
      ISN 0528           WRITE(6,905)
      ISN 0529       905 FORMAT(//,15X,'HEAT PIPE OPERATING CONDITIONS')
      ISN 0530           IF(MGRAVI .EQ. 1) GO TO 965
      ISN 0532           WRITE(6,966)
      ISN 0533       966 FORMAT(//,20X,'ONE-G CONDITION')
      ISN 0534           GO TO 967
      ISN 0535       965 WRITE(6,968)
      ISN 0536       968 FORMAT(//,20X,'ZER-G CONDITION')
      ISN 0537       967 CONTINUE
      ISN 0538           GO TO (906,907,908), KTYPE
      ISN 0539       906 WRITE(6,909) QTOTL,TVAP
      ISN 0540       909 FORMAT(20X,'TYPE 1 BOUNDARY CONDITION'//
                        1          20X,'TOTAL HEAT INPUT(W)',T67,F15.2/
                        1          20X,'VAPOR TEMPERATURE(K)',T67,F15.2)
      ISN 0541           GO TO 950
      ISN 0542       907 WRITE(6,910) QTOTL,TWC
      ISN 0543       910 FORMAT(20X,'TYPE 2 BOUNDARY CONDITION'//
                        1          20X,'TOTAL HEAT INPUT(W)',T67,F15.2/
                        1          20X,'CONDENSER WALL TEMPERATURE(K)',T67,F15.2)
      ISN 0544           GO TO 950
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ISN 0545        908 WRITE(6,911) TWE,TWC
ISN 0546        911 FORMAT(20X,'TYPE 3 BOUNDARY CONDITION'//
                   1         20X,'EVAPORATOR WALL  TEMPERATURE(K)',T67,F15.2/
                   1         20X,'CONDENSER  WALL  TEMPERATURE(K)',T67,F15.2)
ISN 0547            WRITE (6,958) QMAX(IRUN)
ISN 0548        958 FORMAT (20X,'MAX. HEAT TRANSPORT UNDER O-G(W)',T67,F15.2)
ISN 0549        950 CONTINUE
ISN 0550            WRITE(6,912) TEMP ,HPAR
ISN 0551        912 FORMAT(20X,'AMBIENT TEMPERATURE(K)',T67,F15.2/
                   1         20X,'HEAT TRANSFER COEFF. FOR PARASITIC'/
                   1         20X,'HEAT LOSS OR GAIN(W/(M**2*K))',T70,E15.5)
ISN 0552            IF(MGRAVT .EQ. 1) GO TO 969
ISN 0554            WRITE (6,970) XSMAS,ELV,XSTHT
ISN 0555        970 FORMAT(20X,'EXCESS MASS CHARGE(KG)',T70,E15.5/
                   1         20X,'ELEVATION(M)',T70,F15.5/
                   1         20X,'STATIC HEIGHT OF PIPE(M)',T70,E15.5)
ISN 0556        969 CONTINUE
ISN 0557            WRITE(6,904) RHOL,CONL,CONW
ISN 0558        904 FORMAT(//,15X,'PROPERTIES OF WORKING FLUID AND PIPE MATERIAL',//,
                   1         20X,'FLUID DENSITY(KG/M**3)',T70,E15.5/
                   1         20X,'FLUID THERMAL CONDUCTIVITY(W/(M*K))',T70,E15.5/
                   1         20X,'WALL  THERMAL CONDUCTIVITY(W/(M*K))',T70,E15.5)
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```
ISN 0559           WRITE(6,913)
ISN 0560       913 FORMAT (////,35X,'SURFACE TEMPERATURE DISTRIBUTION (DEGREES K)'//)
ISN 0561           WRITE(6,914)
ISN 0562       914 FORMAT(2X,'AXIAL',30X,'CIRCUMFERENTIAL LOCATION')
ISN 0563           WRITE(6,930)
ISN 0564       930 FORMAT(1X,'LOCATION')
ISN 0565           WRITE(6,931)
ISN 0566       931 FORMAT(3X,'Z (M)',35X,'PSI (DEGREES)'/)
ISN 0567           DO 951 J=1,MMM
ISN 0568           DEGPSI(J) = PSI(J)*180.0/PAI
ISN 0569       951 CONTINUE
ISN 0570           WRITE(6,915) (DEGPSI(J),J=2,MM,3)
ISN 0571       915 FORMAT(10X,12F9.1)
ISN 0572           WRITE(6,932)
ISN 0573       932 FORMAT( )
ISN 0574           DO 952 K=2,NN,2
ISN 0575           WRITE (6,916) Z(K),(TOUT(J,K),J=2,MM,3)
ISN 0576       916 FORMAT(F7.3,3X,12F9.2)
ISN 0577       952 CONTINUE
ISN 0578           WRITE(6,987)
ISN 0579       987 FORMAT('1',35X,'HEAT TRANSPORT OF EACH GROOVE'/)
ISN 0580           WRITE (6,988) (J,J=1,12)
ISN 0581           WRITE(6,989) (QSINGL(J),J=2,13)
ISN 0582           WRITE (6,988) (J,J=13,24)
ISN 0583           WRITE(6,989) (QSINGL(J),J=14,25)
ISN 0584           WRITE (6,988) (J,J=25,M)
ISN 0585           WRITE(6,989) (QSINGL(J),J=26,MM)
ISN 0586       988 FORMAT(//,2X,'GROOVE NO.',6X,12I8)
ISN 0587       989 FORMAT(/,2X,'HEAT TRANSPORT (W)',12F8.3)
ISN 0588           WRITE(6,917)
ISN 0589       917 FORMAT(///,30X,'HEAT PIPE PERFORMANCE CHARACTERISTICS',//)
ISN 0590           DTEVAP = TWEAV - TVAP
ISN 0591           DTCOND = TVAP - TWCAV
ISN 0592           WRITE (6,918) QTRNSP,QMAXHP,TVAP,TWEAV,TWCAV,DTEVAP,DTCOND,
                  1            FILMEV,FILMCO
ISN 0593       918 FORMAT(20X,'TOTAL HEAT TRANSPORT(W)',T70,F15.2/
                  1         20X,'MAXIMUM HEAT TRANSPORT(W)',T70,F15.2/
                  1         20X,'VAPOR TEMPERATURE(K)',T70,F15.2//
                  1         20X,'AVERAGE EVAP. SURFACE TEMP.(K)',T70,F15.2/
                  1         20X,'AVERAGE COND. SURFACE TEMP.(K)',T70,F15.2//
                  1         20X,'AVERAGE EVAP. TEMPERATURE DROP(K)',T70,F15.2/
                  1         20X,'AVERAGE COND. TEMPERATURE DROP(K)',T70,F15.2//
                  1         20X,'EVAPORATOR FILM COEFFICIENT(W/(M**2*K)',T70,F15.4/
                  1         20X,'CONDENSER FILM COEFFICINT(W/(M**2*K)',T70,F15.4)
ISN 0594           IF(MGRAVT .EQ. 1) GO TO 945
ISN 0596           IF(IPUDL .EQ. 1) GO TO 946
ISN 0598           WRITE(6,947)
ISN 0599       947 FORMAT(/,20X,'PUDDLE EFFECT IS INCLUDED')
ISN 0600           GO TO 945
ISN 0601       946 WRITE(6,948)
ISN 0602       948 FORMAT(/,20X,'PUDDLE EFFECT IS NOT INCLUDED')
ISN 0603       945 CONTINUE
ISN 0604           DO 953 J=2,MM
ISN 0605           IF(QSINGL(J) .GT. QMAXGR(J)) GO TO 954
ISN 0607       953 CONTINUE
ISN 0608           WRITE(6,955)
ISN 0609       955 FORMAT(/,20X,'NO PARTIAL DRY-OUT IS EXPECTED')
ISN 0610           GO TO 956
```

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ISN 0611        954 WRITE(6,957)
ISN 0612        957 FORMAT(/,20X,'PARTIAL DRY-OUT IS EXPECTED')
ISN 0613        956 CONTINUE
ISN 0614            WRITE(6,971) NITN
ISN 0615        971 FORMAT(//,20X,'TOTAL NUMBER OF ITERATIONS REQUIRED =',I5)
ISN 0616            GO TO 50
              C
ISN 0617        973 CONTINUE
ISN 0618            WRITE(6,961) IRUN
ISN 0619            WRITE(6,975)
ISN 0620        975 FORMAT(//,20X,'TOTAL HEAT INPUT EXCEEDS HEAT TRANSPORT LIMIT ')
              C
              C
ISN 0621         50 CONTINUE
ISN 0622            STOP
ISN 0623            END
```

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COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=82,SIZE=0000K,
                   SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,XREF
ISN 0002               SUBROUTINE PUDDLE
                 C
                 C    THIS SUBROUTINE DETERMINES THE REGION COVERED BY A LIQUID POOL AND
                 C    IMPOSES CONDITION THAT HEAT TRANSFER RATE IS ZERO OVER THE REGION
                 C    THIS PROGRAM ALSO CALCULATES CHANGE OF MAX. HEAT TRANSPORT DUE TO
                 C    PUDDLE FOR EACH GROOVE
                 C
ISN 0003               DIMENSION C(4000,8),Z(32),QMAXGR(35),XPDL(35),XTRNS(35)
ISN 0004               COMMON C,Z,XLE,XLAD,XLC,XL,RV,NGRV,XSTHT,L,M,MM,N,NN,NNN,
                      1        RHOL,XSMAS,FLV,QMXO,QMAXGR
                 C
                 C
ISN 0005               MPAR(I,J,K) = (K-1)*L*M + (I-1)*M + J
ISN 0006               PAI = 3.14159
                 C
ISN 0007               DO 740 J=2,MM
ISN 0008               XPDL(J) = 0.0
ISN 0009           740 CONTINUE
ISN 0010               XSVOL = XSMAS/RHOL
                 C
                 C     CLASSIFY PUDDLE SHAPE
                 C
ISN 0011               XH1 = 2.0*XSVOL/(PAI*RV*XL) + .5*FLV
ISN 0012               XHO = XH1 - FLV
ISN 0013               IF(FLV .GT. (2.0*RV)) GO TO 703
ISN 0015               IF(XHO .LE. 0.0) GO TO 710
ISN 0017               IF(XH1 .GT. (2.0*RV)) GO TO 711
ISN 0019               GO TO 712
ISN 0020           703 CONTINUE
ISN 0021               IF(XH1 .LE. (2.0*RV)) GO TO 710
ISN 0023               IF(XHO .GT. 0.0) GO TO 711
ISN 0025               GO TO 713
                 C
ISN 0026           710 CONTINUE
                 C
                 C   PUDDLE SHAPE 1
                 C
ISN 0027               XH1 = 2.0*RV*SQRT(XSVOL*FLV/(PAI*XL*(RV)**3))
ISN 0028               XLP = XH1*XL/FLV
ISN 0029               I = 2
ISN 0030               DO 720 KK=1,N
ISN 0031               K = NNN - KK
ISN 0032               DO 720 J=2,MM
ISN 0033               MP = MPAR(I,J,K)
ISN 0034               ZHC = XL - Z(K)
ISN 0035               IF(ZHC .GT. XLP) GO TO 721
ISN 0037               HGP = 1.0 - XH1/RV + ZHC*FLV/(RV*XL)
ISN 0038               IF(HGP .GT. 1.0) HGP=1.0
ISN 0040               PANGL = ARCOS(HGP)
ISN 0041               JPUD = PANGL*NGRV/(2.*PAI)
ISN 0042               IF(J .GT. (JPUD+1) .AND. J .LT. (MM-JPUD+1)) GO TO 720
ISN 0044               C(MP,1) = 0.0
ISN 0045               XPDL(J) = ZHC
ISN 0046           720 CONTINUE
ISN 0047           721 CONTINUE
ISN 0048               GO TO 750
```

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```
              C
ISN 0049        711 CONTINUE
              C
              C  BUNDLE SHAPE 2
              C
ISN 0050            XLPI = XL - SQRT(4.0*XL*(PAI*XL*(RV)**2 - XSVOL)/(PAI*RV*FLV))
ISN 0051            XHO = 2.0*RV - (XL - XLPI)*FLV/XL
ISN 0052            I = 2
ISN 0053            DO 725 KK=1,N
ISN 0054            K = NNN - KK
ISN 0055            DO 725 J=2,MM
ISN 0056            MP = MPAR(I,J,K)
ISN 0057            ZHC = XL - Z(K)
ISN 0058            IF(ZHC .GT. XLPI) GO TO 726
ISN 0060            C(MP,1) = 0.0
ISN 0061        726 CONTINUE
ISN 0062            PANGL = ARCOS((ZHC - XLPI)*FLV/(RV*XL) - 1.0)
ISN 0063            JPUD = PANGL*NGRV/(2.*PAI)
ISN 0064            IF(J .GT. (JPUD+1) .AND. J .LT. (MM-JPUD+1)) GO TO 725
ISN 0066            C(MP,1) = 0.0
ISN 0067            XPDL(J) = ZHC
ISN 0068        725 CONTINUE
```

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```
ISN 0069          GO TO 750
            C
ISN 0070      712 CONTINUE
            C
            C , PUDDLE SHAPE 3
            C
ISN 0071          XH1 = 2.0*XSVOL/(PAI*RV*XL) + .5*FLV
ISN 0072          I = 2
ISN 0073          DO 730 KK=1,N
ISN 0074          K = NNN - KK
ISN 0075          DO 730 J=2,MM
ISN 0076          MP = MPAR(I,J,K)
ISN 0077          ZHC = XL - Z(K)
ISN 0078          PANGL = ARCOS(1.0 - XH1/RV + ZHC*FLV/(RV*XL))
ISN 0079          JPUD = PANGL*NGRV/(2.*PAI)
ISN 0080          IF(J .GT. (JPUD+1) .AND. J .LT. (MM-JPUD+1)) GO TO 730
ISN 0082          C(MP,1) = 0.0
ISN 0083          XPDL(J) = ZHC
ISN 0084      730 CONTINUE
ISN 0085          GO TO 750
            C
ISN 0086      713 CONTINUE
            C
            C  PUDDLE SHAPE 4
            C
ISN 0087          XLP1 = XL - SQRT(4.0*XL*(PAI*XL*(RV)**2 - XSVOL)/(PAI*RV*FLV))
ISN 0088          XLP = XLP1 + 2.0*RV*XL/FLV
ISN 0089          I = 2
ISN 0090          DO 735 KK=1,N
ISN 0091          K = NNN - KK
ISN 0092          DO 735 J=2,MM
ISN 0093          MP = MPAR(I,J,K)
ISN 0094          ZHC = XL - Z(K)
ISN 0095          IF(ZHC .GT. XLP1) GO TO 736
ISN 0097          C(MP,1) = 0.0
ISN 0098      736 CONTINUE
ISN 0099          IF(ZHC .GT. XLP) GO TO 737
ISN 0101          PANGL = ARCOS((ZHC - XLP1)*FLV/(RV*XL) - 1.0)
ISN 0102          JPUD = PANGL*NGRV/(2.*PAI)
ISN 0103          IF(J .GT. (JPUD+1) .AND. J .LT. (MM-JPUD+1)) GO TO 735
ISN 0105          C(MP,1) = 0.0
ISN 0106          XPDL(J) = ZHC
ISN 0107      735 CONTINUE
ISN 0108      737 CONTINUE
            C
ISN 0109      750 CONTINUE
            C
ISN 0110          DO 741 J=2,MM
ISN 0111          IF(XPDL(J) .GT. XLC) GO TO 742
ISN 0113          XTRNS(J) = .5*XLF + XLAD + .5*(XLC - XPDL(J))
ISN 0114          GO TO 743
ISN 0115      742 IF(XPDL(J) .GT. (XLC+XLAD)) GO TO 744
ISN 0117          XTRNS(J) = .5*XLF + (XLC + XLAD - XPDL(J))
ISN 0118          GO TO 743
ISN 0119      744 XTRNS(J) = .5*(XL - XPDL(J))
ISN 0120      743 CONTINUE
ISN 0121          XTRNSO = .5*XLF + XLAD + .5*XLC
ISN 0122          QMAXGR(J) = QMXO*(XTRNSO/XTRNS(J))*(1.0 - (FLV/XSTHT)*
```

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```
                       1 (1.0 - XPDL(J)/XL))
      ISN 0123      741 CONTINUE
                  C
      ISN 0124          RETURN
      ISN 0125          END
```

APPENDIX C

SAMPLE OUTPUT

****

THERMAL ANALYSIS OF AXIALLY GROOVED HEAT PIPE

****

NAMES OF WORKING FLUID AND PIPE MATERIAL

WORKING FLUID	AMMONIA
PIPE MATERIAL	ALUMINUM

HEAT PIPE DIMENSIONS

EVAPORATOR LENGTH(M)	0.30480E 00
ADIABATIC LENGTH(M)	0.45720E 00
CONDENSER LENGTH(M)	0.15240E 00
TOTAL PIPE LENGTH(M)	0.91440E 00
PIPE OUTER DIAMETER(M)	0.15900E-01
PIPE INNER DIAMETER(M)	0.10880E-01
VAPOR CORE RADIUS(M)	0.45000E-02

GROOVE DIMENSIONS

NUMBER OF GROOVES	27
GROOVE DEPTH(M)	0.10800E-02
AVERAGE LAND WIDTH(M)	0.37000E-03

HEATING AND COOLING MODES

EVAPORATOR REGION	NON-UNIFORM HEATING
	HEATING REGION COVERS FROM PSI= 90.0 DEG TO PSI=270.0 DEG
CONDENSER REGION	NON-UNIFORM COOLING
	COOLING REGION COVERS FROM PSI= 0.0 DEG TO PSI= 90.0 DEG
	AND FROM PSI=270.0 DEG TO PSI=360.0 DEG

CASE NUMBER = 1

HEAT PIPE OPERATING CONDITIONS

ONE-G CONDITION
TYPE 1 BOUNDARY CONDITION

TOTAL HEAT INPUT(W)	80.00
VAPOR TEMPERATURE(K)	250.00
AMBIENT TEMPERATURE(K)	0.0
HEAT TRANSFER COEFF. FOR PARASITIC HEAT LOSS OR GAIN(W/(M**2*K))	0.0
EXCESS MASS CHARGE(KG)	0.12000E-02
ELEVATION(M)	0.60000E-02
STATIC HEIGHT OF PIPE(M)	0.14000E-01

PROPERTIES OF WORKING FLUID AND PIPE MATERIAL

FLUID DENSITY(KG/M**3)	0.67000E 03
FLUID THERMAL CONDUCTIVITY(W/(M*K))	0.59200E 00
WALL THERMAL CONDUCTIVITY(W/(M*K))	0.18000E 03

SURFACE TEMPERATURE DISTRIBUTION (DEGREES K)

AXIAL LOCATION Z (M)	CIRCUMFERENTIAL LOCATION PSI (DEGREES)								
	6.7	46.7	86.7	126.7	166.7	206.7	246.7	286.7	326.7
0.015	250.77	250.95	251.44	251.80	251.93	251.87	251.60	251.07	250.81
0.076	250.78	250.96	251.45	251.81	251.94	251.88	251.62	251.08	250.82
0.137	250.78	250.96	251.45	251.81	251.94	251.88	251.62	251.08	250.82
0.198	250.78	250.96	251.45	251.81	251.94	251.88	251.62	251.08	250.82
0.259	250.78	250.95	251.45	251.81	251.94	251.88	251.61	251.08	250.82
0.351	250.02	250.02	250.02	250.03	250.03	250.03	250.03	250.02	250.02
0.533	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00
0.716	249.98	249.99	249.99	250.00	250.00	250.00	249.99	249.99	249.99
0.785	246.81	247.61	248.76	249.42	249.63	249.55	249.11	248.06	247.22
0.815	246.18	247.12	248.56	249.33	249.58	249.49	249.01	247.79	246.60
0.846	246.17	247.11	248.55	249.33	249.58	249.49	249.00	247.78	246.59
0.876	246.17	247.11	248.55	249.33	249.58	249.49	249.00	247.78	246.59
0.907	246.17	247.11	248.55	249.33	249.58	249.49	249.00	247.78	246.59

HEAT TRANSPORT OF EACH GROOVE

GROOVE NO.	1	2	3	4	5	6	7	8	9	10	11	12
HEAT TRANSPORT (W)	1.713	1.785	1.911	2.094	2.340	2.652	3.015	3.331	3.585	3.781	3.924	4.018
GROOVE NO.	13	14	15	16	17	18	19	20	21	22	23	24
HEAT TRANSPORT (W)	4.067	4.069	4.027	3.939	3.800	3.608	3.356	3.042	2.678	2.364	2.115	1.927
GROOVE NO.	25	26	27									
HEAT TRANSPORT (W)	1.796	1.718	1.690									

HEAT PIPE PERFORMANCE CHARACTERISTICS

TOTAL HEAT TRANSPORT(W)	78.34
MAXIMUM HEAT TRANSPORT(W)	132.15
VAPOR TEMPERATURE(K)	250.00
AVERAGE EVAP. SURFACE TEMP.(K)	251.36
AVERAGE COND. SURFACE TEMP.(K)	248.23
AVERAGE EVAP. TEMPERATURE DROP(K)	1.36
AVERAGE COND. TEMPERATURE DROP(K)	1.77
EVAPORATOR FILM COEFFICIENT(W/(M**2*K)	0.6701E 04
CONDENSER FILM COEFFICINT(W/(M**2*K)	0.1028E 05

PUDDLE EFFECT IS INCLUDED

NO PARTIAL DRY-OUT IS EXPECTED

TOTAL NUMBER OF ITERATIONS REQUIRED = 55