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CROCK AND SHOCK: FORTRAN CODES FOR
OPTIMIZATION OF HEAT-REJECTION SYSTEMS
FOR SPACE POWER PLANTS

AEC Research and Development Report

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

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CROCK AND SHOCK: FORTRAN CODES FOR
OPTIMIZATION OF HEAT-REJECTION SYSTEMS
FOR SPACE POWER PLANTS

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I. INTRODUCTION

The heat rejection system for space power plants is a major weight item and for high power systems may be the heaviest single component. For this reason, the radiator will have a profound influence on the system design point. Optimizing the radiator for minimum weight is a complex problem because of the large number of variables involved. Heat transfer, fluid flow, and meteoroid protection characteristics of the radiator are all closely interrelated, and any one of them can be improved only at the expense of the others. For example, a reduction in condensing pressure drop requires an increase in the number of tubes or tube diameter, thus increasing tube weight and meteoroid armor requirements; increasing pressure drop permits decreasing tube weight, but at the cost of lowering radiating temperature or increasing pump power. Similarly, increasing fin thickness raises the effectiveness of the fins and allows a reduction in number of tubes, but only at the expense of pressure drop and fin weight.

To aid the power system designer in selecting the minimum weight point for the radiator, two computer codes were written and programmed for the IBM-709. They are called CROCK and SHOCK; the first selects the minimum weight design for a system in which the waste cycle heat is radiated directly to space from the condenser; the second, for a system which radiates the sensible heat lost from a single-phase fluid.

II. CROCK

A. GENERAL

CROCK is a code that solves a series of seven equations describing heat transfer, fluid flow, meteoroid protection, and geometric properties of a radiator-condenser. The last of the seven equations sums the weight of the radiator. Printout is either in tabular form showing weight as a function of the various design parameters, or in one line showing the design parameters which give the minimum weight configuration.

B. HEAT TRANSFER EQUATIONS

Three of the seven equations solved by CROCK describe heat transfer in a finned-tube radiator with constant tube temperature. The first is a least-squares fit of a 4th order polynomial to the curve of Figure 1. The relationship between fin effectiveness and radiation modulus can be expressed as follows:

$$M_R = 12.56 - 48.40\eta + 74.56\eta^2 - 53.58\eta^3 + 14.86\eta^4 \quad \dots (1)$$

The second heat transfer equation in the code is a statement of the Stefan-Boltzmann radiation law for a finned-tube radiator.¹

$$Q_R = \eta\sigma\epsilon AT^4 \quad \dots (2)$$

Equation 2 can be rewritten, for a cylindrical radiator, radiating from one side, as

$$L = \frac{C_1 Q_R}{\eta(T_o^4 + T_l^4)D_{AV}} \quad \dots (3)$$

C_1 is one of 15 dimensional constants that will be described later.

The third heat transfer equation is a statement of the definition of the radiation modulus, M_R :

$$M_R = \frac{l^2 \sigma \epsilon T_o^3}{k_s t_s} \quad \text{for radiation from one side,} \quad \dots (4a)$$

Figure 1. Fin Effectiveness vs Radiation Modulus

and

$$M_R = \frac{2\ell^2 \sigma \epsilon T_o^3}{k_s t_s} \quad \text{with radiation from both sides.} \quad \dots (4b)$$

For the cylindrical tube-and-fin radiator, Equation 4 becomes

$$t_s = \frac{C_2 D_{AV}^2 T_o^3}{N^2 M_R k_s} \quad \dots (5)$$

C. FLUID FLOW

The pressure drop in a condenser tube was derived in Reference 1, by direct integration of the Lockhart-Martinelli correlation.² It is given as,

$$\Delta P_c = \frac{0.402 W^{1.68} \mu_g^{0.32} L}{N^{1.68} D_i^{4.68} \rho_g g_c} \left(\frac{\nu_l}{\nu_g} \right)^{0.0825} - \frac{1.62 W^2}{\rho_g g_c D_i^4 N^2} \quad \dots (6)$$

The constants and fluid properties in Equation 6 may be separated to give

$$\Delta P_c = C_3 \left(D_i \right)^{C_4} L \left(\frac{W}{N} \right)^{C_5} \phi_1 - C_6 \left(D_i \right)^{-4} \left(\frac{W}{N} \right)^2 \phi_2 \quad \dots (7)$$

where

$$\phi_1 = \frac{0.402 \mu_g^{0.32}}{\rho_g g_c} \left(\frac{\nu_l}{\nu_g} \right)^{0.0825}$$

and

$$\phi_2 = \frac{1.62}{\rho_g g_c}$$

Comparison of Equations 6 and 7 shows C_4 and C_5 to be -4.68 and 1.68 respectively. However, the constants were left in the form, C_4 and C_5 , to allow a different dependence on diameter or flow rate to be used if that should be desired.

D. METEOROID PROTECTION

The criteria for meteoroid protection are based on the analysis of Bjork³ as elaborated in Reference 1. The equation of Reference 1 is

$$t = K \left[\frac{A_v \tau}{1 - P(o)} \right]^{0.3} \quad \dots (8)$$

If armor consists of two layers, namely a tube thickness and a fin (shell) thickness, then Equation 8 becomes

$$\frac{t_w}{K_w} + \frac{t_s}{K_s} = \left[\frac{A_v \tau}{1 - P(o)} \right]^{0.3} \quad \dots (8a)$$

In the code, the equation is rewritten as

$$t_w = \left(\frac{ND_i L}{C_8} \right)^{\frac{1}{C_{10}}} - \frac{t_s}{C_9} \quad \dots (9)$$

E. RADIATOR GEOMETRY

The tube and fin detail is shown in Figure 2a for radiation from one side, and in Figure 2b for radiation from both sides. In the former case, it is assumed that the back side of the radiator provides sufficient armor to protect the thin side of the tube from meteoroid puncture.¹

The relationship between tube OD and ID may be written,

$$D_o = D_i + C_{16} (t_w + C_{11}) \quad \dots (10)$$

where $C_{16} = 0.002$ and $C_{11} = 0$, when the armor is uniform around the entire tube (radiation from both sides); and $C_{16} = 0.001$ and $C_{11} =$ the "thin side" wall thickness when protection is required from only one side (radiation from one side).

a) RADIATION FROM ONE SIDE

b) RADIATION FROM BOTH SIDES

Figure 2. Detail of Tube and Fin Arrangement

Provision is also made for using a material for meteoroid armor that may not be suitable for use as a condenser tube. In this case, the primary armor material is the tube as shown in Figure 2, but a liner, or insert, has been inserted into the tube that has the proper fluid compatibility properties.

The weight of the radiator is simply the sum of the weight of the tubes, fin and insert:

$$Wt = \rho_T NL(C_{12}D_o^2 - C_{13}D_i^2) + \rho_s(C_{14}Lt_s D_{AV}) + C_{15}NLD_i \rho_i \dots (11)$$

The average radiator diameter, D_{AV} , can be used for shapes other than cylindrical by means of the following substitution,

$$D_{AV} = \frac{A_s}{\pi L}$$

F. CODE CALCULATIONAL METHOD

Equations 1, 3, 5, 7, 9, 10 and 11 are the seven equations used by the code to minimize radiator weight. Aside from dimensional constants, which are part of the input, and material properties, stored in the subroutines, there are 15 unknowns in the seven equations. These are: Q_R , T_o , D_{AV} , ΔP_C , η , N , W , T_1 , M_R , L , t_s , D_i , t_w , D_o , and Wt .

Two further equations are involved in the properties of the working fluid, namely the relation between vapor pressure and temperature, and between radiator power and flow rate (related by the latent heat of vaporization). This leaves six independent variables. There are three variables, Q , T_o , and D_{AV} , for which no optimum (i. e., minimum weight) value exists.*

Values of these three variables must be specified as input to the code. If ranges of Q_R , T_o , and D_{AV} are of interest, then the code will compute weights for the ranges given.

*Obviously the lower the heat load, and the higher the temperature, the lighter the radiator will be. The reason that radiator weight decreases monotonically with increasing D_{AV} is that no manifold weights are considered, thus favoring a large number of very short tubes. This weight advantage is of course illusory.

Next, ranges of ΔP_c , η , and N are specified. These may be written in as input, or else ranges built into the code may be used. Once values of ΔP_c , η , and N are selected, the machine will consecutively solve Equations 1, 3, 5, 7, 9, 10, and 11 for M_R , L , t_s , D_i , t_w , D_o , and Wt respectively.

There are two calculational methods available. In the first, or normal calculation, the machine starts with initial input values of ΔP_c , η , and N , and goes through the seven equations to calculate the radiator weight. Then N is increased, weight is calculated, and the procedure is repeated until the given range of N is exhausted. Then η is changed and the procedure is repeated for the range of N 's. This continues until the entire range of values of ΔP_c , η , and N has been exhausted. All the calculations are printed out, and the optimum must be found by searching through the output for the lowest weight case.

In the second method, called the optimum operation, weights are calculated for increasing values of N , and the calculations continue until a minimum weight (for the particular values of ΔP_c and η) is reached. This weight is stored as WtN . Then η is changed and the procedure is repeated until a new minimum is reached. The WtN 's are compared until a minimum WtN is reached. This is stored as $Wt\eta$. Then the range of ΔP_c is surveyed, and the $Wt\eta$'s are compared. The minimum value of $Wt\eta$ is the true minimum weight radiator. The only printout in the optimum operation is the minimum weight case, including all significant design parameters.

G. CODE INPUT

CROCK normally requires 45 pieces of input data on eleven cards. Sample data sheets are shown on Page 12. The sixteen input constants can be derived for many radiator geometries from the seven equations in which they appear. Values are given in Table I for two commonly encountered geometries.

The meteoroid protection constants, K 's, are actually material properties, but have been left as input to permit use of different criteria for meteoroid protection than those of References 1 and 3. The values of K are listed in Table II for several different materials.

TABLE I
INPUT CONSTANTS

Cylinder or Cone (Figure 2a)	Flat Plate, Radiating from Both Sides (Figure 2b)
C(1) $1.27 \times 10^{12}/\epsilon$	$6.35 \times 10^{11}/\epsilon$
C(2) $5.05 \times 10^{-5}\epsilon$	$1.01 \times 10^{-4}\epsilon$
C(3) 740	Same as for cylinder
C(4) -4.68	Same as for cylinder
C(5) 1.68	Same as for cylinder
C(6) 139	Same as for cylinder
C(7) t_w^*	Same as for cylinder
C(8) $12 \left[\frac{1 - P(o)}{\tau} \right] (K_w)^{-C_{10}}$	$6 \left[\frac{1 - P(o)}{\tau} \right] (K_w)^{-C_{10}}$
C(9) K_s/K_w	$2K_s/K_w$
C(10) 3.33	Same as for cylinder
C(11) t_w^* (same as C_7)	0
C(12) $6.2 \times 10^{-3}\dagger$	Same as for cylinder
C(13) 5.45×10^{-3}	Same as for cylinder
C(14) 2.63×10^{-4}	Same as for cylinder
C(15) $2.182 \times 10^{-5} t_i$	Same as for cylinder
C(16) 0.001	0.002

*Minimum allowable for strength and corrosion

†For geometry in Figure 2a, otherwise 5.45×10^{-3} neglecting weight of fillets.

TABLE II
VALUE OF K FOR VARIOUS MATERIALS

Material	Meteoroid Constant K
Beryllium	45.7
Aluminum	43.6
Copper	26.6
Steel	24.2

The fifth input card contains the identification of materials of the radiator. Each working fluid and material of construction is identified by a number as follows:

<u>Working Fluids</u>	<u>Number</u>	<u>Allowable Temperature Range</u>
Mercury	1	500 to 1000°F
Rubidium	2	800 to 2200°F
Sodium	3	1000 to 2200°F
Potassium	4	1000 to 2200°F
<u>Tube Material</u>		
Steel	1	
Beryllium	2	
<u>Shell Material</u>		
Aluminum	1	
Copper	2	
Beryllium	3	
<u>Insert Material</u>		
No insert	1	
Haynes 25 alloy	2	

The sixth card identifies three options available to the code user. To read in the vapor flow rate, NOP 1 is set equal to 1 as shown on the sample data sheet. To calculate $\dot{W}$ from the radiative power, NOP 1 is set equal to 2.

NOP 2 is the choice of the "normal" calculation or one of the optimization routines. If NOP 2 = 1, all cases are calculated and printed out. If NOP 2 = 2, the code selects and prints the optimum conditions as described in Section F above, using "built-in" ranges of N from 10 to 200 tubes, η from 0.96 to 0.40, and ΔP from 5 to 50% of the inlet pressure. If NOP 2 = 3, the optimization routine is again used, but with ranges of N, η , and ΔP read in as input.

NOP 3 is the choice of whether or not to consider meteoroid armor. If NOP 3 = 1, then the radiator is calculated assuming meteoroid protection as specified in the input constants. If NOP 3 = 2, then tube wall thickness is set equal to C_7 , rather than calculated on the basis of meteoroid protection.

The last five cards contain the ranges of operating condition to be surveyed, and are self-explanatory as shown on the sample data sheets.

H. CODE OUTPUT

Printout from the machine includes all the fifteen unknowns in the seven code equations. If the normal operation is used, output will include all cases computed. If one of the optimum routines is chosen, printout will include for each value of Q , T_o , and D_{AV} , the values of the remaining 12 design parameters which yield the minimum weight radiator.

I. COMPUTING TIME REQUIRED

The optimization routine requires about 1 minute on the IBM-709 for each combination of Q_R , T_o , and D_{AV} or

$$\theta_{OPT} = Q_R^* T_o^* D_{AV}^*$$

The time required for the "normal" operation may be estimated as follows:

$$\theta_{NOR} = 0.0025 Q_R^* T_o^* D_{AV}^* N^* \Delta P_c^* \eta^* .$$

J. CODE LISTING

A listing of the complete CROCK code is given below.

FORTRAN FLOATING 8 DIGIT DECIMAL DATA

DECK NO. CROCK PROGRAMMER SAMPLE DATA DATE PAGE 1 of 3 JOB NO.

NUMBER		D	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1		+	0 1	IC = 1, (cards 2 through 11)
13		-		or 2, (cards 5 through 11)
25		-		or 3, (cards 7 through 11)
37		-		or 4 (cards 10 and 11)
49		-	73	80
61		-		1
1		-		C(1)
13		-		C(2)
25		-		C(3)
37		-		C(4)
49		-	73	80 C(5)
61		-		2 C(6)
1		-		C(7)
13		-		C(8)
25		-		C(9)
37		-		C(10)
49		-	73	80 C(11)
61		-		3 C(12)
1		-		C(13)
13		-		C(14)
25		-		C(15)
37		-		C(16)
49		-	73	80
61		-		4

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FORTRAN FLOATING 8 DIGIT DECIMAL DATA

DECK NO. CROCK PROGRAMMER SAMPLE DATA DATE _____ PAGE 2 of 3 JOB NO. _____

NUMBER	D	IDENTIFICATION	DESCRIPTION	DO NOT KEY PUNCH
1	+ 0 1		NWFS - Number of initial working fluid	
13	+ 0 1		NWFD - Increment of working fluid number	
25	+ 0 1		NWFE - Number of final working fluid	
37	+ 0 1		NTM - Number of tube material	
49	+ 0 1	73	NSM - Number of shell material	80
61	+ 0 1		NIM - Number of insert material	5
1	+ 0 1		NOP 1 = 1, read in W, = 2, calculate W	
13	+ 0 1		NOP 2 = 1, normal operation, = 2 optimum, = 3 optimum	
25	+ 0 1		NOP 3 = 1, meteoroid protection included, = 2, no meteoroid prot	
37	-			
49	-	73		80
61	-			6
1	-		QS - Radiative power, kilowatts, initial value	
13	-		DQ - Radiative power, kilowatts, increment	
25	-		QE - Radiative power, kilowatts, final value	
37	-		TOS Inlet saturation temperature, °R, initial value	
49	-	73	DTO Inlet saturation temperature, °R, increment	80
61	-		TOE Inlet saturation temperature, °R, final value	7
1	-		DAVS Average radiator diameter, feet, initial value	
13	-		DDAV Average radiator diameter, feet, increment	
25	-		DAVE Average radiator diameter, feet, final value	
37	-			
49	-	73		80
61	-			8

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FORTRAN FLOATING 8 DIGIT DECIMAL DATA

DECK NO. CROCK PROGRAMMER SAMPLE DATA DATE _____ PAGE 3 of 3 JOB NO. _____

NUMBER	D	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1	-		W, Inlet vapor flow rate (Omit card if NOP = 2)
13	-		
25	-		
37	-		
49	-	73	80
61	-		9
1	-		DPS
13	-		DDP
25	-		DPE
37	-		ETAS (> ETAE)
49	-	73	80
61	-		1 0
1	-		ENS
13	-		DEN
25	-		ENE
37	-		
49	-	73	80
61	-		1 1
1	-		
13	-		
25	-		
37	-		
49	-	73	80
61	-		

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```

* XEQ 00000010
C CR0GK,C0NDENSER-RADIATOR OPTIMIZATION CODE 00000020
D 00000030
  DIMENSION C(30),TWF(2),TTM(2),TSM(2),TIM(2),TOP2(3),S(12),S1(12),S00000040
  X2(12),S3(12) 00000050
C 00000060
  EQUIVALENCE (DP,S(1)),(ETA,S(2)),(EL,S(3)),(TI,S(4)),(DAV,S(5)),(00000070
  XEN,S(6)),(D00,S(7)),(DI,S(8)),(DF,S(9)),(TS,S(10)),(TW,S(11)),(WT,00000080
  XS(12)),(WTN,S1(12)),(WTEFA,S2(12)),(WTMIN,S3(12)) 00000090
G 00000100
  NC=16 00000110
  10 READ INPUT TAPE 5,1000,IC 00000120
  1000 FORMAT (6I12) 00000130
  GO TO (20,30,40,50,54),IC 00000140
  20 READ INPUT TAPE 5,1001,(C(I),I=1,NC) 00000150
  1001 FORMAT (6E12.8) 00000160
  30 READ INPUT TAPE 5,1000,NWFS,NWFD,NWFE,NTM,NSM,NIM,N0P1,N0P2,N0P3 00000170
  GO TO (32,34,34),N0P2 00000180
  32 TOP2(1)=6HNORMAL 00000190
  TOP2(2)=6H CALCU 00000200
  TOP2(3)=6HLATION 00000210
  GO TO 40 00000220
  34 TOP2(1)=6H OPTIM 00000230
  TOP2(2)=6HUM ROU 00000240
  TOP2(3)=4HTINE 00000250
  40 READ INPUT TAPE 5,1001,QS,DQ,QE,T0S,DT0,T0E,DAVS,DDAV,DAVE 00000260
  CALL TUBE (TIM,RT,NTM) 00000270
  CALL SHELL (TSM,EKS,RS,NSM) 00000280
  CALL INSERT (TIM,RI,NIM) 00000290
  GO TO (50,52),N0P1 00000300
  50 READ INPUT TAPE 5,1001,W 00000310
  52 GO TO (54,60,54),N0P2 00000320
  54 READ INPUT TAPE 5,1001,DPS,DDP,DPE,ETAS,DETA,ETAE,ENS,DEN,ENE 00000330
  60 NWFE=NWFS-NWFD 00000340
  70 NWFE=NWFE+NWFD 00000350
  IWF=1 00000360
  Q=QS-DQ 00000370
  80 Q=Q+DQ 00000380
  T0=T0S-DT0 00000390
  90 T0=T0+DT0 00000400
  TAB=1.0/T0 00000410
  CALL FLUID(TWF,P0,PHI1,PHI2,TAB,NWF,IWF,DH,T0) 00000420
  IF(PHI1)1002,1003,1003 00000430

  1003 IF(PHI2)1002,1004,1004 00000440
  1004 GO TO (110,100),N0P1 00000450
  100 W=0.9477*Q/DH 00000460
  110 WRITE OUTPUT TAPE 6,2000,T0P2,TWF,TTM,TSM,TIM,Q,W,T0,P0,(I,C(I),I=00000470
  X1,NC) 00000480
  2000 FORMAT (1H1,36X,28HHEIGHT DETERMINATION PROBLEM/42X,3A6//36X,17HW00000490
  XRKING FLUID IS ,2A6/36X,17HTUBE MATERIAL IS ,2A6/36X,18HSHELL MATE00000500
  XRIAL IS ,2A6/36X,19HINSERT MATERIAL IS ,2A6//46X,4HQ = 1PE11.3/4600000510
  XX,4HW = 1PE11.3/41X,9HT ZERO = 1PE11.3/41X,9HP ZERO = 1PE11.3/(4300000520
  XX,1HC,13,3H = 1PE11.3)) 00000530
  GO TO (135,130,135),N0P2 00000540
  130 DPS=0.05*P0 00000550
  DDP=DPS 00000560
  DPE=0.5*P0 00000570
  ETAS=0.96 00000580
  DETA=-0.02 00000590
  ETAE=0.40 00000600
  EN6=10.0 00000610
  DEN=5.0 00000620
  ENF=200.0 00000630
  135 DAV=DAVS-DDAV 00000640
  140 DAV=DAV+DDAV 00000650
  S1(12)=1.0E+10 00000660
  S2(12)=S1(12) 00000670
  S3(12)=S2(12) 00000680
  DP=DPS-DDP 00000690
  150 DP=DP+DDP 00000700
  P1=LOGEF(P0-DP) 00000710
  CALL CALTI(T1,P1,NWF) 00000720
  ETA=ETAS-DETA 00000730
  160 ETA=ETA+DETA 00000740
  EMR=ETAMR(ETA) 00000750
  T03=T0**3 00000760
  EL=C(1)*Q/(ETA*DAV*(T03-T0+T1)**4)) 00000770
  GO TO (170,180,180),N0P2 00000780
  170 WRITE OUTPUT TAPE 6,2001,DP,ETA,EL,T1,DAV 00000790
  2001 FORMAT (1H1,39X,10HDELTA P = 1PE11.3/44X,6HETA = 1PE11.3/46X,4HL =00000800
  X 1PE11.3/45X,5HT1 = 1PE11.3/43X,7HD AV = 1PE11.3//9X,1HN,12X,2HD00000810
  X12X,2HDI,10X,7HDELTA F,7X,7HT SHELL,7X,6HT WALL,8X,6HWEIGHT//) 00000820
  180 EN=ENS-DEN 00000830
  190 EN=EN+DEN 00000840
  T6=C(2)*T03*(DAV/EN)**2/(EKS*EMR) 00000850
  A=C(3)*EL*(W/EN)**C(5)*PHI1 00000860
  B=C(6)*(W/EN)**2*PHI2 00000870

```

ITER=1	00000880
DI=FINDDI(A,B,C(4),DP,ITER)	00000890
IF(ITER-1)1007,1007,1006	00000900
1007 GO TO (200,210),N0P3	00000910
200 TW=(EN*DI*EL/C(8))*{(1.0/C(10))-TS/C(9)}	00000920
IF (TW-C(7)) 210,210,220	00000930
210 TW=C(7)	00000940
220 D00=D1+C(16)*ITW+C(111)	00000950
DF=A*DI**C(4)	00000960
WT=RT*EN*GL*(C(12)*D00**2-C(13)*DI**2)+RS*C(14)*EL*TS*DAY+C(15)*EN	00000970
X*EL*DI*RI	00000980
GO TO (230,240,240),N0P2	00000990
230 WRITE OUTPUT TAPE 6,2002,EN,D00,DI,DF,TS,TW,WT	00001000
2002 FORMAT (7(3X,1PE11.3))	00001010
GO TO 260	00001020
240 IF (WTN-WT) 270,270,250	00001030
250 DO 255 I=1,12	00001040
255 S1(I)=S(I)	00001050
260 IF (ENE-EN) 290,290,190	00001060
270 IF (WTETA-WTN) 300,300,280	00001070
280 DO 285 I=1,12	00001080
285 S2(I)=S1(I)	00001090
WTN=1.0E+10	00001100
290 IF (ETA-ETAE) 320,320,160	00001110
300 IF (WTMIN-WTETA) 330,330,310	00001120
310 DO 315 I=1,12	00001130
315 S3(I)=S2(I)	00001140
WTN=1.0E+10	00001150
WTETA=1.0E+10	00001160
320 IF (DPE-DP) 325,325,150	00001170
325 GO TO (340,330,330),N0P2	00001180
330 WRITE OUTPUT TAPE 6,2001,(S3(I),I=1,5)	00001190
WRITE OUTPUT TAPE 6,2002,(S3(I),I=6,12)	00001200
340 IF (DAVE-DAV) 350,350,140	00001210
350 IF (T0E-T0) 360,360,90	00001220
360 IF (QE-Q) 370,370,80	00001230
370 IF (NWE-NWF) 10,10,70	00001240
1002 WRITE OUTPUT TAPE 6,1005	00001250
1005 FORMAT(48H1 PH11 OR PH12 IN THE WORKING FLUID IS MINUS)	00001260
1006 WRITE OUTPUT TAPE 6,2000,T0P2,TWF,TM,TSM,TIM,Q,W,T0,P0,(I,C(I),I=	00001270
11,NC)	00001280
CALL EXIT	00001290
STOP	00001300
END	00001310
SUBROUTINE FLUID(TWF,P0,PH11,PH12,TAB,NWF,IWF,DH,T0)	
C	00001320
DIMENSION TWF(2)	00001330
C	00001340
GO TO (10,20,30,40,100),NWF	00001350
C	00001360
WORKING FLUID 1 IS MERCURY	00001370
10 GO TO (11,12),IWF	00001380
11 IWF=2	00001390
TWF(1)=6HMERCUR	00001400
TWF(2)=1HY	00001410
12 PH11=EXP{((-9.737459E+10*TAB+2.748660E+08)*TAB-2.465877E+05)*TAB+0.0001430	00001420
16.377706E+01}	00001430
PH12=EXP{((-9.457726E+09*TAB-2.320702E+07)*TAB+3.044673E+04)*TAB-1.00001450	00001440
1.688936E+01}	00001450
P0=EXP{((-3.746494E+08*TAB-1.521585E+06)*TAB-1.099345E+04)*TAB+1.300001470	00001460
131343E+01}	00001470
DH=130.38-0.0041428*T0	00001480
GO TO 100	00001490
C	00001500
WORKING FLUID 2 IS RUBIDIUM	00001510
20 GO TO (21,22),IWF	00001520
21 IWF=2	00001530
TWF(1)=6HRUBIDI	00001540
TWF(2)=2HUM	00001550
22 PH11=EXP{((-2.531754E+10*TAB+4.210310E+07)*TAB-9.347454E+03)*TAB-0.0001570	00001560
19.504662}	00001570
PH12=EXP{((-3.30962E+10*TAB+5.352754E+07)*TAB-1.301492E+04)*TAB-4.00001590	00001580
1.281826}	00001590
P0=EXP{((-4.153953E+06*TAB-7.202195E+03)*TAB-1.649197E+04)*TAB+1.200001610	00001600
121354E+01}	00001610
DH=((-4.376812E-09*T0-2.470695E-05)*T0-9.727435E-03)*T0+4.162659E+000001630	00001620
12	00001630
GO TO 100	00001640
C	00001650
WORKING FLUID 3 IS SODIUM	00001660
30 GO TO (31,32),IWF	00001670
31 IWF=2	00001680
TWF(1)=6HSODIUM	00001690
TWF(2)=1H	00001700
32 PH11=EXP{((-2.337645E+10*TAB+4.107770E+07)*TAB-5.355764E+03)*TAB-0.0001720	00001710
18.804301}	00001720
PH12=EXP{((-1.994319E+10*TAB+3.298157E+07)*TAB+2.571595E+03)*TAB-0.0001740	00001730
15.610036}	00001740
	00001750

P0=EXPF((12.136471E+08*TAB-1.266813E+06)*TAB-2.095514E+04)*TAB+1.300001760	00001770
104225E+01)	00001780
DH=((1-2.082634E-08*T0+1.677671E-04)*T0-6.656092E-01)*T0+2.455463E+00001790	00001800
103	00001810
G0 T0 100	00001820
C	00001830
C WORKING FLUID 4 IS POTASSIUM	00001840
40 G0 T0 (41,42),INF	00001850
41 INF=2	00001860
TWF(1)=6HPOTASS	00001870
TWF(2)=3HIUM	00001880
42 PHL1=EXPF((-2.245597E+10*TAB+3.711830E+07)*TAB-5.590792E+03)*TAB-00001890	00001900
19.287697)	00001910
PHL2=EXPF((-4.193607E+10*TAB+6.211710E+07)*TAB-1.415495E+04)*TAB-00001920	00001930
13.338982)	00001940
P0=EXPF((19.751538E+08*TAB-2.475961E+06)*TAB-1.611750E+04)*TAB+1.100001910	00001950
191610E+01)	00001960
DH=((18.254096E-09*T0-4.817396E-05)*T0-1.316712E-02)*T0+9.887944E+00001970	00001980
12	00001990
G0 T0 100	00002000
C	00002010
C	00002020
100 RETURN	00002030
END	00002040
SUBROUTINE TUBE (TTM,RT,NTM)	00002050
C	00002060
DIMENSION TTM(2)	00002070
C	00002080
G0 T0 (10,20,100),NTM	00002090
C	00002100
C TUBE MATERIAL IS STEEL	00002110
10 TTM(1)=5HSTEEL	00002120
TTM(2)=1H	00002130
	00002140
	00002150
	00002160
	00002170
	00002180
	00002190
	00002200
	00002210
	00002220
	00002230
	00002240
	00002250
	00002260
	00002270
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	00002470
	00002480
	00002490
	00002500
	00002510
	00002520
	00002530
	00002540
	00002550
	00002560
	00002570
	00002580
	00002590
	00002600
	00002610
	00002620
	00002630

	TIM(2)=3H 25	00002640
	RI=567.0	00002650
	GO TO 100	00002660
100	RETURN	00002670
	END	00002680
	FUNCTION #INDDI(A1,B,C4,D,ITER)	00002690
C		00002700
	ITER=1	00002710
	N0ITER=0	00002720
	DIG=0.5	00002730
	C=C4+4.0	00002740
	A=A1/D	00002750
	B=B/D	00002760
10	N0ITER=N0ITER+1	00002770
	IF(N0ITER-1000)1,1,2	00002780
2	WRITE OUTPUT TAPE 6,3	00002790
3	FORMAT(73H1 ITERATION TEST OF 1000 WAS EXCEEDED. CHECK TEMPERA	00002800
	TURE OF MATERIALS)	00002810
	ITER=2	00002820
	GO TO 4	00002830
1	DI=DIG-(DIG**4-A*DIG**C+B)/(4.0*DIG**3-A*C*DIG**(C-1.0))	00002840
	IF (ABS((DI-DIG)/DI)-0. 01) 30,20,20	00002850
20	DIG=DI	00002860
	GO TO 10	00002870
30	FINDDI=DI	00002880
4	RETURN	00002890
	END	00002900
	FUNCTION BTAMR (X)	00002910
C		00002920
	BTAMR=((114.86222*X-53.58389)*X+74.55952)*X-48.39639)*X+12.56077	00002930
	RETURN	00002940
	END	00002950
	SUBROUTINE CALT1(T1,P1,NWF)	00002960
C		00002970
	GO TO (10,20,30,40,100),NWF	00002980
C		00002990
C	WORKING FLUID 1 IS MERCURY	00003000
10	T1=1.0/(((1.720672E-08*P1-1.167414E-07)*P1-7.709339E-05)*P1+1.090	00003010
	1610E-03)	00003020
	GO TO 100	00003030
C		00003040
C	WORKING FLUID 2 IS RUBIDIUM	00003050
20	T1=1.0/(((1.441485E-11*P1+1.033086E-10)*P1-6.062093E-05)*P1+7.404	00003060
	1381E-04)	00003070
	GO TO 100	00003080
C		00003090
C	WORKING FLUID 3 IS SODIUM	00003100
30	T1=1.0/(((2.806842E-10*P1-7.972614E-09)*P1-4.491846E-06)*P1+6.026	00003110
	1644E-05)	00003120
	GO TO 100	00003130
C		00003140
C	WORKING FLUID 4 IS POTASSIUM	00003150
40	T1=1.0/(((1.262278E-08*P1-5.761615E-08)*P1-5.516082E-05)*P1+6.864	00003160
	1969E-04)	00003170
	GO TO 100	00003180
C		00003190
100	RETURN	00003200
	END	00003210
*	DATA	00003220

III. SHOCK

A. GENERAL

SHOCK is a code analogous to CROCK that calculates and optimizes the design parameters of a space radiator that rejects the sensible heat lost from a single-phase fluid. Code input and output are very similar to those in CROCK. Since, however, there is no direct relationship between pressure drop and radiating temperature selection of the optimum pressure drop and temperature drop depends on some rather tenuous assumptions.

B. HEAT TRANSFER EQUATIONS

The principle difference between the condenser-radiator and the sensible heat radiator is that in the latter, the tube temperature is variable over the tube length.

The sensible heat lost by a fluid in a tube-and-fin radiator is shown in Reference 1 to be,

$$WC_P(T_o - T_1) = \eta \sigma \epsilon A T_E^4, \quad \dots (12)$$

where

$$T_E = \left[\frac{3T_o^3 T_1^3}{T_o^2 + T_o T_1 + T_1^2} \right]^{1/4} \quad \dots (13)$$

Equations 12 and 13 are based on a heat balance around a differential element of fin and tube. Integration of the heat balance assumes a constant, weighted average value of η and neglects axial conduction through the fin.

Axial conduction in the fin may be neglected since for any reasonable fin arrangement the gradient perpendicular to the tube will be at least an order of magnitude greater than the axial gradient.

To check whether M_R and η could be evaluated at the temperature, T_E , a radiator design was analyzed in two different ways; the first was evaluation of η and M_R at the temperature, T_E ; the second was to break down the radiator into elemental strips, each of which is evaluated according to the method for handling constant base-temperature (condensing) radiators. The results agreed

to within 1%. Therefore, the same form of the fin effectiveness and Stefan-Boltzmann relations are used for the sensible heat radiator as were used for a condenser-radiator, with the tube temperature taken to be constant and equal to T_E .

The relationship between fin effectiveness and radiation modulus is given by Equation 1. The Stefan-Boltzmann law may be rewritten for the sensible heat radiator, since the radiator power is the sensible heat lost by the fluid, as

$$L = \frac{W C_P \Delta T}{0.538 \times 10^{-8} D_{AV} \eta T_E^4 C_6 C_8} \quad \dots (14)$$

The radiation modulus, defined in Equation 4, becomes

$$t_s = \frac{5.07 \times 10^{-5} C_6 C_8 D_{AV}^2 T_E^3}{M_R k_s N^2} \quad \dots (15)$$

C. FLUID FLOW

The pressure drop in a fluid in turbulent flow is given by the Fanning Equation:

$$\Delta P = \frac{2fLu^2 \rho_f}{g_c D_i} \quad \dots (16)$$

where f , the Fanning friction factor, is given by

$$f = 0.316(Re)^{-0.25} \quad \dots (17)$$

Combining Equations 16 and 17, for N parallel tubes and solving for D_i , the tube inside diameter,

$$D_i = 0.0738 \mu_f^{0.053} \left(\frac{W}{N} \right)^{0.368} \left(\frac{L}{\rho_f \Delta P} \right)^{0.211} \quad \dots (18)$$

The pumping power is

$$Q_P = \frac{0.543 \times 10^{-4} W \Delta P}{\rho_f C_l} . \quad \dots (19)$$

In the condenser-radiator, there was a straight-forward trade-off of pressure drop; higher pressure drops lead to smaller and lighter tubes, but to lower radiating temperatures, since the equilibrium condensing temperature is determined by the static pressure. In a sensible-heat radiator, on the other hand, there is no direct relationship between pressure and radiator temperature. Similarly, the liquid temperature drop may be made smaller and smaller, simply by increasing flow rate; here again, there is no straight-forward trade-off.

To permit approximate optimization, it is assumed that the penalty paid for pumping power is an increase in radiator power. That is,

$$Q_R = (Q_E + Q_P) \left(\frac{1 - \eta_c}{\eta_c} \right) \quad \dots (20a)$$

instead of the more common form,

$$Q_R = Q_E \left(\frac{1 - \eta_c}{\eta_c} \right) . \quad \dots (20b)$$

Obviously, the cost of additional pump work will be greater than just the weight required to radiate the incremental waste heat. The heat source, power conversion system, and pump will all have to be enlarged to provide the extra power. Using this assumed trade-off, the minimum-weight system results when the pump power is about 10% of the electrical power. When components other than the radiator are considered, this fraction will probably be less than 5% of the electrical output of the system.

With the above qualification in mind, the flow rate is solved for by combining Equations 19 and 20a to give

$$W = \frac{5.4C_1(3413)\rho_f Q_E}{5.4C_1\left(\frac{C_2}{1-C_2}\right)\rho_f C_P \Delta T - \Delta P} \quad \dots (21a)$$

If it is desired to specify the radiated power instead of the net electrical power, by setting C_1 , the pump efficiency, equal to a very large number, say 10^6 ; and by substituting C_2 , the conversion efficiency, equal to 0.5 in Equation 21a, the flow rate equation becomes:

$$W = \frac{3413Q_R}{C_P \Delta T} \quad \dots (21b)$$

D. METEOROID PROTECTION

The criteria for meteoroid protection are exactly the same as for the condenser-radiator. The code equation is:

$$t_w = K_{1w} \left\{ \left[\frac{C_8 C_3 N D_i L}{12(1-C_4)} \right]^{0.3} - \frac{t_s}{K_{1s}} - \frac{C_7}{K_{1i}} \right\} \quad \dots (22)$$

E. RADIATOR GEOMETRY

The tube and fin configuration is the same as for the condenser-radiator. The relationship between tube OD and ID is:

$$D_o = 0.001 \left[C_5(2.0 - C_8) + t_w C_8 + 2C_7 \right] + D_i \quad \dots (23)$$

The weight of the radiator, including the liquid hold-up (which was negligible in the condenser) is given by

$$Wt = 0.001L \left\{ N \left[6.19\rho_t D_o^2 + 5.45(\rho_f - \rho_t) D_i^2 + 21.8t_L(\rho_i - \rho_t)(D_i + t_i) \right] + 0.262 D_{AV} \rho_s t_s \right\} \quad \dots (24)$$

F. CODE CALCULATIONAL METHOD

Equations 1, 13, 14, 15, 18, 19, 21a, 22, 23, and 24 are the ten equations used by the code. These ten equations contain 17 unknowns, aside from material properties and input: Q , T_o , ΔT , ΔP , η , N , T_E , W , Q_P , M_R , L , t_s , D_i , t_w , D_o , D_{AV} , and Wt .

Thus we have seven independent variables. As was the case with CROCK, no optimum value exists for Q , T_o , and D_{AV} . These variables, are specified as code input. Next ranges of ΔT , ΔP , η , and N are chosen. As before, these may be read in as input, or built-in ranges may be used. The machine then consecutively solves Equations 12, 21a, 19, 1, 14, 15, 18, 21, 23, and 24 for T_E , W , Q_P , M_R , L , t_s , D_i , t_w , D_o , and Wt respectively.

The calculational methods are exactly analogous to those of CROCK. There is the option of using either the "normal" operation or the optimum operation. The procedure and printout are the same as in CROCK.

G. CODE INPUT

SHOCK normally requires 38 pieces of input data on nine cards. Sample data sheets are shown on Page 25. The eight input constants are explained on the sample data sheets. The fourth card contains the identification of materials of the radiator. Each working fluid and material of construction is identified by a number as follows:

<u>Working Fluid</u>	<u>Number</u>
NaK-78	1
Lithium	2
Sodium	3
Mixed terphenyls (Santowax)	4
<u>Tube Material</u>	
Beryllium	1
Niobium	2
Aluminum	3
Steel	4

<u>Shell Material</u>	<u>Number</u>
Beryllium	1
Niobium	2
Aluminum	3
Copper	4
<u>Insert Material</u>	
Haynes 25 alloy	1

The fifth card identifies two options available to the code user, NOP 2 and NOP 3. These options have exactly the same meaning as in CROCK, and are explained in Section G under the CROCK description.

The last four cards contain the ranges of operating conditions to be surveyed, and are explained on the sample data sheets.

H. CODE OUTPUT

The output is of the same format as CROCK.

I. COMPUTING TIME REQUIRED

The optimization routine requires about 1 minute on the IBM-709 for each combination of Q , T_o , and D_{AV} , or $\theta_{OPT} = Q^* T_o^* D_{AV}^*$.

The time required for the normal operation may be estimated as follows:

$$\theta_{NOR} = 0.0025 Q^* T_o^* D_{AV}^* \Delta P^* \eta^* N^* \Delta T^*$$

J. CODE LISTING

A listing of the complete SHOCK code is given below.

FORTRAN FLOATING 8 DIGIT DECIMAL DATA

DECK NO. SHOCK PROGRAMMER SAMPLE DATA DATE _____ PAGE 1 of 3 JOB NO. _____

NUMBER	D	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1	+	0 1	IC = 1 (Read in cards 2 through 9)
13	-		or 2 (Read in cards 4 through 9)
25	-		or 3 (Read in cards 6 through 9)
37	-		or 4 (Read in cards 8 and 9)
49	-	73	80
61	-		1
1	-		C(1), Pump efficiency
13	-		C(2), Conversion efficiency (see note on Card No 6)
25	-		C(3), Time of exposure, years
37	-		C(4), Non-puncture probability
49	-	73	80 C(5), Minimum allowable tube wall thickness, mils
61	-		2 C(6), Surface emissivity
1	-		C(7), Thickness of tube liner, mils
13	-		C(8), 1 or 2, for radiation from one side or from two sides
25	-		
37	-		
49	-	73	80
61	-		3
1	-		NWFS, Number of initial working fluid
13	-		NWFD, Increment of working fluid number
25	-		NWFE, Number of final working fluid
37	-		NTM, Number of tube material
49	-	73	80 NSM, Number of shell material
61	-		4 NIM, Number of insert material

FORTRAN FLOATING 8 DIGIT DECIMAL DATA

DECK NO. SHOCK PROGRAMMER SAMPLE DATA DATE _____ PAGE 2 of 3 JOB NO. _____

	NUMBER	D	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1		+ 0 1		NOP 2 = 1, for normal operation
13		-		or 2, for optimum operation, built in Nos, skip cards 8 and 9
25		-		or 3, for optimum operation, read in cards 8 and 9
37		+ 0 1		NOP 3 = 1, meteoroid protection included
49		-	73	or 2, no meteoroid protection, $t_w = C(5)$
61		-	5	
1		-		QS, Initial power, kw } Electric power, to read in
13		-		DQ, Power increment, kw } radiative power, C(2) must be
25		-		QE, Final power, kw } equal to 0 5
37		-		TOS, Radiator inlet temperature, °R, initial value
49		-	73 80	DTO, Radiator inlet temperature, °R, increment
61		-	6	TOE, Radiator inlet temperature, °R, final value
1		-		DAVS, Radiator average diameter, ft, initial value
13		-		DDAV, Radiator average diameter, ft, increment
25		-		DAVE, Radiator average diameter, ft, final value
37		-		
49		-	73 80	
61		-	7	
1		-		DPS, Fluid pressure drop, psi, initial value
13		-		DDP, Fluid pressure drop, psi, increment
25		-		DPE, Fluid pressure drop, psi, final value
37		-		ETAS, Fin effectiveness, initial value, (≤ 0.98)
49		-	73 80	DETA, Fin effectiveness, increment (negative number)
61		-	8	ETAE, Fin effectiveness, final value (≥ 0.40)

FORTRAN FLOATING 8 DIGIT DECIMAL DATA

DECK NO. SHOCK PROGRAMMER SAMPLE DATA DATE _____ PAGE 3 of 3 JOB NO. _____

NUMBER	D	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1	-		ENS, Number of tubes, initial value
13	-		DEN, Number of tubes, increment
25	-		ENE, Number of tubes, final value
37	-		DTS, Fluid temperature drop, °F, initial value
49	-		DDT, Fluid temperature drop, °F, increment
61	-		DTE, Fluid temperature drop, °F, final value
1	-		
13	-		
25	-		
37	-		
49	-		
61	-		
1	-		
13	-		
25	-		
37	-		
49	-		
61	-		
1	-		
13	-		
25	-		
37	-		
49	-		
61	-		
1	-		
13	-		
25	-		
37	-		
49	-		
61	-		

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27

	7347-01	R A STONE	782-0810920
* XEQ			00000010
C		*****	00000020
C		*****	00000030
C TITLE			00000040
C		*****	00000050
C SHOCK, SENSIBLE HEAT RADIATOR OPTIMIZATION CODE			00000060
C		*****	00000070
C DATA INPUT			00000080
C			00000090
C 1ST CARD FORMAT(6I12)			00000100
C JC=1 C S PLUS 2,3,4			00000110
C =2 NWFS,NWFD,NWFE,NTM,NSM,NIM,NOP2,NOP3, PLUS 3,4			00000120
C =3 QS,DQ,QE,TOS,DTG,TOE,DAVS,DDAV,DAVE, PLUS 4			00000130
C =4 OPS,DDP,DPE,ETAS,ETA,ETA,ENS,DEN,ENE,DTS,DDTS,DTE			00000140
C			00000150
C 2ND CARD FORMAT(6E12,8)			00000160
C C(1)=ETA(P)=PUMP EFFICIENCY,DIMENSIONLESS			00000170
C C(2)=ETA(C)=CONVERSION EFFICIENCY,DIMENSIONLESS			00000180
C C(3)=TAU=TIME OF EXPOSURE,YEARS			00000190
C C(4)=P(0)=PROBABILITY THAT NO PUNCTURES WILL OCCUR,DIMENSIONLESS			00000200
C C(5)=BETA=MINIMUM TUBE WALL THICKNESS,MILS			00000210
C C(6)=EPSILON=SURFACE EMISSIVITY,DIMENSIONLESS			00000220
C			00000230
C 3RD CARD FORMAT(6E12,8)			00000240
C C(7)=T(L)=THICKNESS OF LINER,MILS			00000250
C C(8)=1 OR 2,RADIATION FROM ONE SIDE OR TWO SIDES			00000260
C			00000270
C 4TH CARD FORMAT(6I12)			00000280
C NWFS=INITIAL WORKING FLUID			00000290
C NWFD=DELTA WORKING FLUID			00000300
C NWFE=FINAL WORKING FLUID			00000310
C NTM=TUBE MATERIAL			00000320
C NSM=SHELL MATERIAL			00000330
C NIM=INSERT MATERIAL			00000340
C			00000350
C 5TH CARD FORMAT(6I12)			00000360
C NOP2=1 NORMAL OPERATION			00000370
C =2 OPTIMUM OPERATION-BUILT IN NOS. SKIP CARDS 8 AND 9			00000380
C =3 OPTIMUM OPERATION-READ IN NOS. CARDS 8 AND 9			00000390
C NOP3=1 T(W) IS CALCULATED			00000400
C =2 T(W)=BETA			00000410
C			00000420
C 6TH CARD FORMAT(6E12,8)			00000430
C			
C QS=INITIAL NET ELECTRIC POWER OUTPUT, KW			00000440
C DQ=DELTA Q			00000450
C QE=FINAL NET ELECTRIC POWER OUTPUT, KW			00000460
C TOS=INITIAL RADIATOR INLET TEMPERATURE, DEGREES R			00000470
C DTG=DELTA TG			00000480
C TOE=FINAL RAD. INLET TEMPERATURE, DEGREES R			00000490
C			00000500
C 7TH CARD FORMAT(6E12,8)			00000510
C DAVS=INITIAL RADIATOR AVERAGE DIAMETER,FT			00000520
C DDAV=DELTA DAV			00000530
C DAVE=FINAL RADIATOR AVERAGE DIAMETER,FT			00000540
C			00000550
C 8TH CARD FORMAT(6E12,8)			00000560
C OPS=INITIAL FLUID PRESSURE DROP,PSI			00000570
C DDP=DELTA DELTA P			00000580
C OPB=FINAL FLUID PRESSURE DROP,PSI			00000590
C ETAS=INITIAL FIN EFFECTIVENESS,DIMENSIONLESS L.T. OR = TG .98			00000600
C ETA=DELTA ETA (MINUS NUMBER)			00000610
C ETAE=FINAL FIN EFFECTIVENESS,DIMENSIONLESS G.T. OR = TG .40			00000620
C			00000630
C 9TH CARD FORMAT(6E12,8)			00000640
C ENS=INITIAL NUMBER OF TUBES,DIMENSIONLESS			00000650
C DEN=DELTA N			00000660
C ENE=FINAL NUMBER OF TUBES,DIMENSIONLESS			00000670
C DTS=INITIAL FLUID TEMPERATURE DROP,DEGREES R			00000680
C DDTS=DELTA DELTA T			00000690
C DTE=FINAL FLUID TEMPERATURE DROP,DEGREES R			00000700
C			00000710
C		*****	00000720
C			00000730
C PRINTOUT			00000740
C			00000750
C L=LENGTH OF RADIATOR,FT			00000760
C W=TOTAL FLUID FLOW, LBS/HR			00000770
C DO=DIAMETER OF OUTER TUBE,IN			00000780
C DI=DIAMETER OF INNER TUBE,IN			00000790
C QP=PUMPING POWER REQUIRED,KW			00000800
C T SHELL= SHELL THICKNESS,MILS			00000810
C T WALL= TUBE THICKNESS,MILS			00000820
C WEIGHT= WEIGHT,LBS			00000830
C		*****	00000840
C			00000850
C			00000860
C MAIN PROGRAM			00000870

C		00000880
C		00000890
	DIMENSION C(8),TWF(2),TTM(2),TSM(2),TIM(2),T0P2(3),S(13),S1(13),S2(13),S3(13)	00000900
		00000910
C		00000920
	EQUIVALENCE(DP,S(1)),(ETA,S(2)),(EL,S(3)),(TI,S(4)),(W,S(5)),(DAV,00000930	
	1S(6)),(EN,S(7)),(D00,S(8)),(DI,S(9)),(QP,S(10)),(TS,S(11)),(TW,S(10000940	
	22)),(WT,S(13)),(WTN,S(13)),(WTETA,S2(13)),(WTMIN,S3(13))	00000950
C		00000960
C	INPUT DATA	00000970
C		00000980
	10 READ INPUT TAPE 5,1000,IC	00000990
	1000 FORMAT(6I12)	00001000
	60 T0 (20,30,40,50),IC	00001010
C		00001020
C	IC=1	00001030
C		00001040
	20 READ INPUT TAPE 5,1001,(C(I),I=1,8)	00001050
	1001 FORMAT(6E12.8)	00001060
C		00001070
C	IC=2	00001080
C		00001090
	30 READ INPUT TAPE 5,1000,NWFS,NWFD,NWFE,NTM,NSM,NIM,N0P2,N0P3	00001100
	60 T0(32,34,34),N0P2	00001110
	32 T0P2(1)=6HNORMAL	00001120
	T0P2(2)=6H CALCU	00001130
	T0P2(3)=6HLATION	00001140
	60 T0 40	00001150
	34 T0P2(1)=6H OPTIM	00001160
	T0P2(2)=6HUM ROU	00001170
	T0P2(3)=4HTINE	00001180
C		00001190
C	IC=3	00001200
C		00001210
	40 READ INPUT TAPE 5,1001,QS,DQ,QE, T0S,DT0,T0E,DAVS,DDAV,DAVE	00001220
C		00001230
C	DETERMINE TUBE,SHELL,INSERT MATERIALS	00001240
C		00001250
	CALL TUBE(TTM,RT,WK,NTM)	00001260
	ISH=1	00001270
	CALL SHELL (TSM,RS,SK,AK,NSM,ISH,TEFF)	00001280
	ISH=2	00001290
	CALL INSERT(TIM,RI,EKL,NIM)	00001300
C		00001310
	60 T0 (50,60,50),N0P2	00001320
C		00001330
C	IC=4	00001340
C		00001350
	50 READ INPUT TAPE 5,1001,DPS,DDP,DPE,ETAS,DETA,ETA,E,ENS,DEN,ENE,DTS,	00001360
	1DDTS,DTE	00001370
C		00001380
	60 NWE=NWFS-NWFD	00001390
	70 NWF=NWF+NWFD	00001400
	IWF=1	00001410
	CALL FLUID(TWF,RF,AMUF,CP,TEFF,NWF,IWF)	00001420
C		00001430
C	FUNCTION OF Q	00001440
C		00001450
	Q=QS-DQ	00001460
	80 Q=Q+DQ	00001470
C		00001480
C	FUNCTION OF T	00001490
C		00001500
	TD= T0S-DT0	00001510
	90 TD=TD+DT0	00001520
	T03=T0+*3	00001530
C		00001540
	WRITE OUTPUT TAPE 6,2000,T0P2,TWF,TTM,TSM,TIM,Q,T0,(I,C(I), I=1,8)	00001550
	2000 FORMAT (1H1,36X,28HWEIGHT DETERMINATION PROBLEM/42X,3A6//36X,17HW00001560	
	IRKING FLUID IS ,2A6/36X,17HTUBE MATERIAL IS ,2A6/36X,18HSHELL MATE00001570	
	2RIAL IS ,2A6/36X,19HINSERT MATERIAL IS ,2A6//46X,4HQ = 1PE11.3/4100001580	
	3X,9HT ZERO = 1PE11.3//43X,1HC,I3,3H = 1PE11.3))	00001590
C		00001600
	60 T0 (135,130,135),N0P2	00001610
	130 DPS=5.0	00001620
	DDP=5.0	00001630
	DPE=50.0	00001640
	ETAS=.96	00001650
	DETA=-0.02	00001660
	ETA=-.40	00001670
	ENS=10.0	00001680
	DEN=5.0	00001690
	DT0=50.0	00001700
	DDTS=50.0	00001710
	DTE=300.0	00001720
	ENE=300.0	00001730
C		00001740
C	FUNCTION OF D	00001750

C		00001760
135	DAV=DAVS-DDAV	00001770
140	DAV=DAV+DDAV	00001780
C		00001790
C	FUNCTION OF DELTA T	00001800
G		00001810
	T1=DTS-DDTS	00001820
100	T1=T1+DDTS	00001830
	TEFF=((3.0*T1)/(1.0/(T0-T1)**3)-(1.0/T03)))**25	00001840
	CALL FLUID (TMF,RF,AMUF,CP,TEFF, NWF,IWF)	00001850
	TE4=TEFF**4	00001860
	CALL SHELL (TSM,RS,SK,AK,NSM,ISH,TEFF)	00001870
	S1(13)=1.0E+10	00001880
	S2(13)=S1(13)	00001890
	S3(13)=S2(13)	00001900
C		00001910
C	FUNCTION OF DELTA P	00001920
C		00001930
	DP=DP5-DDP	00001940
150	DP=DP+DDP	00001950
	W=15.4*C(1)*3413.0*RF*Q/(15.4*C(1)*(C(2)/(1.0-C(2)))*RF*T1*CP-DP)	00001960
	QP=.543E-4*W*DP/(C(1)*RF)	00001970
C		00001980
C	FUNCTION OF ETA	00001990
C		00002000
	IF(ETA=-.3999)500,501,501	00002010
501	IF(ETA=-.98)502,502,500	00002020
502	IF(ETA=504,500,500	00002030
504	ETA=ETAS-DBTA	00002040
160	ETA=ETA+DETA	00002050
	EMR=12.561-48.396*ETA+74.560*ETA**2-53.584*ETA**3+14.862*ETA**4	00002060
	EL=(W*CP*T1)/(1.538E-8*DAV*ETA*TE4*C(6)*C(8))	00002070
	G0 T0 (170,180,180),NOP2	00002080
C		00002090
170	WRITE OUTPUT TAPE 6,2001,DP,ETA, EL,T1,W,DAV	00002100
2001	FORMAT (1H1,39X,10HDELTA P = 1PE11.3/44X,6HETA = 1PE11.3/46X,4HL =00002110	
	1 1PE11.3/45X,5HT) = 1PE11.3/46X,4HW = 1PE11.3/43X,7HD AV = 1PE11.300002120	
	2//9X,1HN,12X,2HD0,12X,2HDI,10X,7H QP ,7X,7HT SHELL,7X,6HT WALL00002130	
	3,8X,6HWEIGHT//)	00002140
C		00002150
C	FUNCTION OF N	00002160
C		00002170
180	EN=ENS-DEN	00002180
190	EN=EN+DEN	00002190
	TS=5.07E-5*(C(6)*C(8)/(EMR*AK))*(DAV/EN)**2*TEFF**3	00002200
	D(=.0738*AMUF**0.0526*(W/EN)**368*(EL/(DP*RF))**.211	00002210
	G0 T0(200,210),NOP3	00002220
200	ALPHA=(C(3)*C(8)/(12.0*(1.0-C(4))))** .3	00002230
	TW=WK*(ALPHA*(EN*DI*EL)**.3-TS/(C(8)*SK)-C(7)/EKL)	00002240
	IF(TW-C(5))210,210,220	00002250
210	TW=C(5)	00002260
220	D00=.001*(C(5)*(2.0-C(8))+TW*C(8)+2.0*C(7))+DI	00002270
	TL=C(7)*.001	00002280
	WT=.001*EL*(EN*(6.19*RT*D00**2+5.45*(RF-RT)*DI**2+21.8*TL*(RI-RT)*00002290	
	1(DI+TL))+.262*DAV*TS*RS)	00002300
	G0 T0 (230,240,240),NOP2	00002310
230	WRITE OUTPUT TAPE 6,2002,EN,D00, DI,QP,TS,TW,WT	00002320
2002	FORMAT(713X,1PE11.31)	00002330
	G0 T0 260	00002340
240	IF(WTN-WT)270,270,250	00002350
250	D0 255 I=1,13	00002360
256	S1(I)=S(I)	00002370
C		00002380
C	N CHANGES	00002390
C		00002400
260	IF(ENE-EN) 290,290,190	00002410
270	IF(WTETA-WTN)300,300,280	00002420
280	D0 285 I=1,13	00002430
285	S2(I)=S1(I)	00002440
	WTN=1.0E+10	00002450
C		00002460
C	ETA CHANGES	00002470
C		00002480
290	IF(ETA-ETAE) 320,320,160	00002490
300	IF(WTMIN-WTETA)330,330,310	00002500
310	D0 315 I=1,13	00002510
315	S3(I)=S2(I)	00002520
	WTN=1.0E+10	00002530
	WTETA=1.0E+10	00002540
C		00002550
C	DELTA P CHANGES	00002560
C		00002570
320	IF(DPE-DP) 325,325,150	00002580
325	G0 T0 (340,330,330),NOP2	00002590
330	WRITE OUTPUT TAPE 6,2001,(S3(I),I=1,6)	00002600
	WRITE OUTPUT TAPE 6,2002,(S3(I),I=7,13)	00002610
C		00002620
C	DELTA T CHANGES	00002630

C		00002640
	340 DO 600 KTL=1,12	00002650
	600 S3(KTI)=0.0	00002660
	IF(OT6-T1)341,341,100	00002670
C		00002680
C	D CHANGES	00002690
C		00002700
	341 IF(DAVE-DAV)350,350,140	00002710
C		00002720
C	T CHANGES	00002730
C		00002740
	350 IF(T06-T0)360,360,90	00002750
C		00002760
C	Q CHANGES	00002770
C		00002780
	360 IF(QE-Q)370,370,80	00002790
	370 IF(NWFE-NWF)10,10,70	00002800
	500 WRITE OUTPUT TAPE 6,503,ETAS,ETA,DETA	00002810
	503 FORMAT(7I1) CHECK INPUT DATA FOR ETA LIMITS ARE WRONG OR DELTA	00002820
	ETA IS NOT MINUS/10X,14HINITIAL ETA = 1PE11.3/10X,12HDELTA ETA = 1P	00002830
	2E11.3/10X,12HFINAL ETA = 1PE11.3)	00002840
	GO TO 10	00002850
	END	00002860
		00002870
		00002880
		00002890
	SUBROUTINE TUBE(TTM,RT,WK,NTM)	00002900
	DIMENSION TTM(2)	00002910
	GO TO (10,20,30,40,100),NTM	00002920
C		00002930
C	TUBE MATERIAL IS BERYLLIUM	00002940
C		00002950
	10 TTM(1)=6HBERYLL	00002960
	TTM(2)=3HIUM	00002970
	RT=115.8	00002980
	WK=45.7	00002990
	GO TO 100	00003000
C		00003010
C	TUBE MATERIAL IS NIOBIUM	00003020
C		00003030
	20 TTM(1)=6HNI0BIU	00003040
	TTM(2)=1HM	00003050
	RT=524.0	00003060
	WK=24.1	00003070
	GO TO 100	00003080
C		00003090
C	TUBE MATERIAL IS ALUMINUM	00003100
C	FOR MODIFIED LOW-TEMPERATURE SNAP 2 APPLICATIONS	00003110
	30 TTM(1)=6HALUMIN	00003120
	TTM(2)=2HUM	00003130
	RT=169.5	00003140
	WK=43.6	00003150
	GO TO 100	00003160
C		00003170
C	TUBE MATERIAL IS STEEL	00003180
C	FOR MODIFIED LOW-TEMPERATURE SNAP 2 APPLICATIONS	00003190
	40 TTM(1)=5HSTBEL	00003200
	TTM(2)=1H	00003210
	RT=484.0	00003220
	WK=24.2	00003230
	GO TO 100	00003240
C		00003250
	100 RETURN	00003260
	END	00003270
		00003280
	SUBROUTINE SHELL(TSM,RS,SK,AK,NSM,ISH,TEFF)	00003290
	DIMENSION TSM(2)	00003300
	GO TO (10,20,30,40,100),NSM	00003310
C		00003320
C	SHELL MATERIAL IS BERYLLIUM	00003330
C		00003340
	10 GO TO (11,12),ISH	00003350
	11 TSM(1)=6HBERYLL	00003360
	TSM(2)=3HIUM	00003370
	RS=115.8	00003380
	SK=45.7	00003390
	GO TO 100	00003400
	12 AK=76.0	00003410
	GO TO 100	00003420
C		00003430
C	SHELL MATERIAL IS NIOBIUM	00003440
C		00003450
	20 GO TO (21,22),ISH	00003460
	21 TSM(1)=6HNI0BIU	00003470
	TSM(2)=1HM	00003480
	RS=524.0	00003490
	SK=24.1	00003500
	GO TO 100	00003510

22	AK=0.006215*TEFF+26.14	00003520
	G0 T0 100	00003530
C		00003540
C	SHELL MATERIAL IS ALUMINUM	00003550
C	FOR MODIFIED LOW-TEMPERATURE SNAP 2 APPLICATIONS	00003560
30	G0 T0 (31,32),ISH	00003570
31	TSM(1)=6HALUMIN	00003580
	TSM(2)=2HUM	00003590
	R6=169.5	00003600
	SK=43.6	00003610
	G0 T0 100	00003620
32	AK=118.0	00003630
	G0 T0 100	00003640
C		00003650
C	SHELL MATERIAL IS COPPER	00003660
C	FOR MODIFIED LOW-TEMPERATURE SNAP 2 APPLICATIONS	00003670
40	G0 T0 (41,42),ISH	00003680
41	TSM(1)=6HCOPPER	00003690
	TSM(2)=1H	00003700
	R6=558.0	00003710
	SK=26.6	00003720
	G0 T0 100	00003730
42	AK=196.0	00003740
	G0 T0 100	00003750
C		00003760
100	RETURN	00003770
	END	00003780
	SUBROUTINE INSERT(TIM,RI,EKL,NIM)	00003790
	DIMENSION TIM(2)	00003800
	G0 T0 (10,100),NIM	00003810
C		00003820
C	INSERT MATERIAL IS HAYNES 25	00003830
C		00003840
10	TIM(1)=6HHAYNES	00003850
	TIM(2)=3H 25	00003860
	RI=567.0	00003870
	EKL=24.0	00003880
	G0 T0 100	00003890
C		00003900
100	RETURN	00003910
	END	00003920
		00003930
		00003940
		00003950
	SUBROUTINE FLUID(TWF,RF,AMUF,CP,TEFF,NWF,IWF)	00003960
	DIMENSION TWF(2)	00003970
	G0 T0 (10,40,70,91,100),NWF	00003980
C		00003990
C	WORKING FLUID IS NAK	00004000
C		00004010
10	G0 T0 (20,30),IWF	00004020
20	IWF=2	00004030
	TWF(1)=3HNAK	00004040
	TWF(2)=1H	00004050
	G0 T0 100	00004060
30	RF=58.9-8.43E-3*TEFF	00004070
	AMUF=10.0**((580.0/TEFF-4.32)	00004080
	CPNA=((2.417622E-12*TEFF+2.258457E-8)*TEFF-9.454042E-5)*TEFF+.3826	00004090
	1809	00004100
	CPK=(((-2.375877E-13*TEFF+2.384695E-8)*TEFF-6.513298E-5)*TEFF+.2271	00004110
	1290	00004120
	CP=.228*CPNA+.772*CPK	00004130
	G0 T0 100	00004140
C		00004150
C	WORKING FLUID IS LITHIUM	00004160
C		00004170
40	G0 T0 (50,60),IWF	00004180
50	IWF=2	00004190
	TWF(1)=6HLITHIU	00004200
	TWF(2)=1HM	00004210
	G0 T0 100	00004220
60	RF=((8.185452E-11*TEFF-2.626330E-7)*TEFF-2.706528E-3)*TEFF+34.0908	00004230
	12	00004240
	AMUF=((4.415739E-15*TEFF+4.464695E-11)*TEFF-3.208042E-7)*TEFF+5.910000	00004250
	18890E-4	00004260
	CP=(((-1.872635E-11*TEFF+1.263106E-7)*TEFF-2.851784E-4)*TEFF+1.2036	00004270
	174	00004280
	G0 T0 100	00004290
C		00004300
C	WORKING FLUID IS SODIUM	00004310
C		00004320
70	G0 T0 (80,90),IWF	00004330
80	IWF=2	00004340
	TWF(1)=6HSODIUM	00004350
	TWF(2)=1H	00004360
	G0 T0 100	00004370
90	RF=((3.283276E-10*TEFF-8.898787E-7)*TEFF-7.6828E-3)*TEFF+63.33105	00004380
	AMUF=(((-1.071558E-13*TEFF+6.568115E-10)*TEFF-1.370394E-6)*TEFF+1.000004	00004390

179586E-3	00004400
CP=(12.417622E-12*TEFF+2.258457E-8)*TEFF-9.454042E-5)*TEFF+3.8268000004410	00004410
19E-1	00004420
G0 T0 100	00004430
C	00004440
C WORKING FLUID IS SANTOWAX OM	00004450
C FOR MODIFIED LOW-TEMPERATURE SNAP 2 APPLICATIONS	00004460
91 G0 T0 (92,93),IWF	00004470
92 IWF=2	00004480
TWF(1)=6HSANTOW	00004490
TWF(2)=5HAX OM	00004500
G0 T0 100	00004510
93 RF=-2.79E-2*TEFF+84.1	00004520
AMUF=8.50E+9*TEFF*(-4.5)	00004530
CP=1.282E-4*TEFF+0.394	00004540
G0 T0 100	00004550
C	00004560
C	00004570
100 RETURN	00004580
END	00004590
* DATA	00004600

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NOMENCLATURE

- A = radiating area, ft^2
 A_v = area vulnerable to meteoroid puncture, ft^2
 A_s = shell area, ft^2 (equal to $A/2$ for radiation from both sides)
 C_P = heat capacity, $\text{Btu/lb-}^\circ\text{F}$
 D_{AV} = radiator average diameter, ft
 D_i = tube inside diameter, in.
 D_o = tube outside diameter, in.
 f = Fanning friction factor, dimensionless
 g_c = dimensional conversion factor, $32.2 \text{ lbm-ft/lbf-sec}^2$
 K = meteoroid protection constant, defined in Equation 8, $(\text{mils/ft}^2\text{-yr})^{1/3}$
 k = thermal conductivity, $\text{Btu/hr-ft-}^\circ\text{F}$
 L = radiator length and tube length, ft
 ℓ = fin half-width
 M_R = radiation modulus, dimensionless
 N = number of tubes
 ΔP = pressure drop, psi , ΔP_c is condenser pressure drop, psi
 $P(o)$ = probability of no meteoroid puncture
 Q = power, kw , Q_P is pump power; Q_R is radiator power, Q_E is electric power
 Re = Reynolds number
 T = temperature, $^\circ\text{R}$
 t = thickness, mils
 W = flow rate in radiator, lb/sec in CROCK, lb/hr in SHOCK
 Wt = radiator weight, lb
 ϵ = emissivity, dimensionless
 θ_{OPT} = computing time for optimization program, minutes

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θ_{NOR} = computing time for normal calculation program, minutes

μ = viscosity, lbm/ft-hr

ν = kinematic viscosity, ft²/hr

ρ = density, lb/ft³

σ = Stefan-Boltzmann constant, 0.1713 Btu/hr-ft²-(°R)⁴

τ = time of exposure to micrometeoroids, yr

ϕ_1, ϕ_2 = fluid properties defined in Equation 7

η = fin effectiveness, dimensionless

η_c = overall conversion efficiency, dimensionless

SUBSCRIPTS

o = entrance condition

l = exit condition

c = condensing

E = effective

f = fluid

g = gas

i = insert

l = liquid

s = shell or fin

t = tube

w = wall

SUPERSCRIPT

* = number of values of an input variable to be surveyed in the code calculation

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