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TRANSFER FUNCTIONS FOR RADIATOR DYNAMICS IN THE SNAP-8 SYSTEM

by Robert W. Leko and Kent S. Jefferies

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ABSTRACT

An analytical study was conducted to determine approximate radiator transfer functions for use in SNAP-8 ground test facilities. Theoretical equations for transient heat transfer and flow processes in the radiator were programmed on a digital computer. With this computer simulation, the frequency response of the radiator-outlet temperature was determined. Approximate transfer functions were determined from the frequency-response information. The transfer function determined for outlet temperature to inlet temperature was a single lag of third order cascaded with a dead-time function. The time constant and dead time were inversely proportional to flow rate. The simplified transfer function chosen to describe the response of outlet temperature to inlet flow rate was a first-order lag. The first-order lag time constant was in inverse proportion to the flow rate.

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SUMMARY

In the design of practical controls for space-radiator simulation, simple mathematical representation of radiator dynamics is needed. An analytical study, therefore, was conducted to determine approximate radiator transfer functions for use in SNAP-8 ground test facilities. Theoretical equations for transient heat-transfer and flow processes in the radiator were programmed on a digital computer. With this computer simulation, the frequency response of the radiator-outlet temperature was determined for small perturbations in inlet temperature and flow rate around steady-state values. Approximate transfer functions were determined from the frequency-response information.

The transfer function determined for outlet temperature to inlet temperature was a single lag of third order cascaded with a dead-time function. This form agreed very well with the computer-generated frequency response for a range of flow rates from design value to 10 percent of design value, provided the time constant and dead time were varied inversely with the flow rate.

The frequency response generated by the computer program for the radiator outlet temperature to flow rate was like that of a first-order lag with a resonance effect superimposed in the midfrequency range. The simplified transfer function chosen to describe the response of outlet temperature to inlet flow rate was a first-order lag. The first-order lag form of transfer function adequately covered flow rates from design to 10 percent of design value, provided the time constant was adjusted in inverse proportion to the flow rate.

INTRODUCTION

SNAP-8 is a nuclear electrical generating system currently under development for space power applications (ref. 1). The power-conversion system of SNAP-8 uses the Rankine cycle and transfers the waste heat of this cycle to a heat-rejection loop. The working fluid of the heat rejection loop is sodium-potassium eutectic (NaK). The heat-rejection loop uses a radiator to reject the waste heat to space. For ground tests of systems it is usually necessary to use convectively cooled heat exchangers which have heat transfer characteristics substantially different from those of a flight-type radiator operating in space, where heat rejection is strictly radiative. Thus, in order to conduct meaningful studies of system dynamics in a test cell, some method of forcing the convectively cooled heat exchanger to behave like a flight radiator is required. Therefore, a radiator simulator is employed in ground testing of SNAP-8.

The design and performance of a radiator simulator for a SNAP-8 test facility at the Lewis Research Center is discussed in reference 2. In this reference, it was brought out that, for improved design of radiator simulators, more definition of the radiator dynamics is required in the form of simple mathematical models that are compatible with the limited control equipment available in test facilities. Therefore, an analytical study was conducted to determine simple transfer functions that approximate the dynamics of the SNAP-8 radiator.

The analysis consisted of deriving the appropriate heat balance and flow equations from which a dynamic digital-computer simulation of the radiator was programmed. A cylindrical radiator 9.26 meters in length and 3.72 meters in diameter was assumed for this analysis although no final radiator has been selected at present for SNAP-8. The computer simulation was used to generate frequency response plots of radiator outlet temperature to inlet temperature at various flow rates. Also, frequency response was obtained for outlet temperature to flow rate at various steady-state values of flow rate. From the frequency-response maps, the desired transfer functions were determined. The report includes the derivation of the equations and the computer program in addition to presenting the frequency response and resulting transfer functions.

SYMBOLS

Mathematical symbol	FORTRAN symbol	Description
A_{cs}		cross-sectional area, m^2
A_F		area of fin for heat transfer by radiation, m^2
A_t		area of tube armor for heat transfer by radiation, m^2
c_A		specific heat of tube and armor, J/((kg)(K))
c_F		specific heat of fin, J/((kg)(K))
c_f		specific heat of fluid, J/((kg)(K))

Mathematical symbol	FORTRAN symbol	Description
E		internal energy, J/kg
H		enthalpy of fluid, J/kg
L		time lag, or dead time, sec
M		exponent for transfer function for temperature disturbances, dimensionless
m_A		mass of tubes and armor, kg
m_F		mass of fin, kg
m_f		mass of fluid, kg
N		lump or node number, dimensionless
Q_1		heat transferred to fin, J/sec
Q_2		rate of energy transfer from fluid to tube by forced convections, $6.28\ ur\ (t - T)/A_{cs}$, $J/((m^3)(sec))$
R		convective heat transfer resistance, ((sec)(K))/J
r		tube radius, m
T	TDRA	temperature of fluid, K
T_N		temperature of fluid at N^{th} node, K
T_F		temperature of fin, K
T_d	= 619	design temperature of fluid, K
t	TRA	tube temperature, K
t_N		tube temperature of N^{th} lump, K
U		overall heat transfer coefficient, $J/((m^2)(sec)(K))$
v		fluid velocity, m/sec
W		mass of fluid in lump, kg
w		fluid flow rate, kg/sec
w_d	= 4.54	design point fluid flow rate, kg/sec
ΔX		lump length, m
$1/Rcw$		$6.28\ rUW/\rho cwA_{cs}$, dimensionless

Mathe- matical symbol	FORTRAN symbol	Description
ϵ		emissivity
σ		Stefan-Boltzmann constant, $J/((m^2)(sec)(K^4))$
ρ		density, kg/m^3
θ		time, sec
δ		$\Delta X/v = W/w$, time for fluid to move through one lump, sec
τ		time constant, sec
τ_D		design point time constant, sec
τ_o		time constant of third-order transfer function, sec
τ_1, τ_2, τ_3		general time constants, sec
τ_4		time constant of first-order lag transfer function, sec
	*	multiplication sign
$\Delta\theta$	DTIME	calculation time interval, sec
$D/D\theta$		substantial derivative
	TIME	time, sec
	C7	inlet fluid temperature, K
	FLOWD	flow rate per tube, kg/sec
	A159 = 170.	conductivity of armor, $J/((m)(sec)(K))$
	TRAD	average radiator surface temperature, K
	FINEF	fin effectiveness
	DFIN14	derivative of the fourth root of fin effectiveness with respect to radiator surface temperature, K^{-1}
	AMPL	amplitude, K or kg/sec as appropriate
	OMEGA	frequency, rad/sec
	STEP	step change variable, K or kg/sec as appropriate
	AMPLR	amplitude ratio, dimensionless
	RETOT = 0.02184	thermal resistance of tube wall, $((sec)(K))/J$

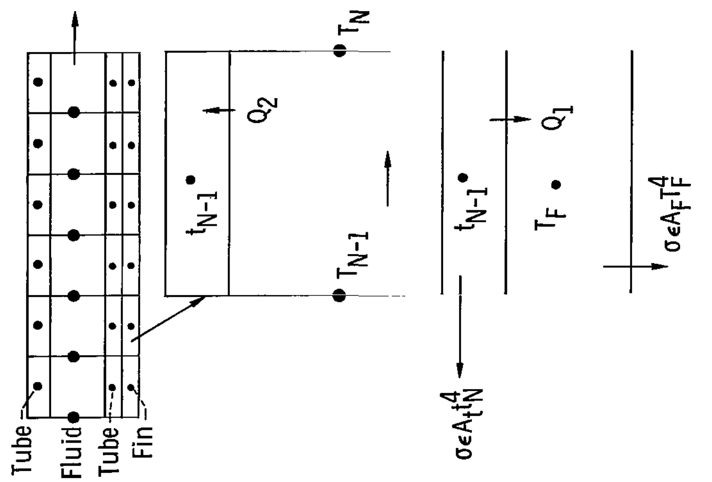
Mathematical symbol	FORTRAN symbol	Description
	CON(1) = 233.3	reciprocal of mass of fluid per node per tube, 1/kg
	CON(2) = 0.05212	thermal conductivity multiplied by area and divided by specific heat of fluid, kg/sec
	C1 = 5.103×10^{-8}	emissivity of radiator surface multiplied by the Stefan-Boltzmann constant, $J/((m^2)(sec)(K^4))$
	HCAPTA = 35.26	heat capacity of tube and armor, J/K
	HCAPF = 1.977	heat capacity of fin, J/K
	AARM = 0.001918	radiation area of armor surface for one lump of one tube, m^2
	AFIN = 0.015	radiation area of one lump of two fins, two fins per tube, m^2
	FINWI = 0.03414	fin width, m
	FINTH = 0.00762	fin thickness at root, m

COMPUTER SIMULATION

Derivation of Equations

The physical description of the heat-rejection loop radiator model assumed in this analysis is shown in figure 1. It is a cylindrical shape 9.26 meters in length and 3.72 meters in diameter. The radiator model assumed is comprised of 153 tube-and-fin segments which make up the radiating surface. The heat passes from the NaK fluid to the tube wall by forced convection and is then conducted from the tubes to the fins where it is radiated to space.

In the analysis it was assumed that any one tube and fin combination behaves exactly like all the others so that we may focus our attention on just one for simplicity. Next, axial heat conduction in the tube wall has not been taken into account. The analysis is one dimensional. Variation in material transport properties as a function of temperature has not been taken into account. There are no solar, planetary, or other external heat source inputs to the radiator assumed in this analysis because no SNAP-8 mission has been defined.



(a)

In writing the computer program it was convenient to divide the radiator into axial lumps as shown in sketch (a).

The energy balance for a unit volume of the fluid can be stated as follows:

Rate of accumulation of internal energy	+	Net rate of internal energy convected with stream	=	Net rate of energy transferred by forced convection

In equation form this energy balance appears as

$$\frac{\partial(\rho E)}{\partial \theta} + \frac{\partial(\rho v H)}{\partial X} = Q_2 \tag{1}$$

$$\frac{\rho c_f dT}{d\theta} + \rho v c_f \frac{dT}{dX} = \frac{6.28\ Ur(t - T)}{A_{cs}}$$

or

$$\frac{DT}{d\theta} = \frac{-6.28\ Ur(T - t)}{\rho c_f A_{cs}} \qquad \text{(substantial derivative)}$$

or

$$\frac{DT}{T - t} = \frac{-6.28\ Ur}{\rho c_f A_{cs}} \tag{2}$$

Assuming that the tube temperature is constant for each lump and during the time period from $\theta - \delta$ to θ, the previous equation was integrated to give the following equation:

$$T_N(\theta) - t_{N-1}(\theta - \delta) = \left[T_{N-1}(\theta - \delta) - t_{N-1}(\theta - \delta)\right] e^{-6.28\ UrW/w\rho c_f A_{cs}} \tag{3}$$

Equation (3) was rearranged to give the following equation for calculating fluid temperature:

$$T_N(\theta) = T_{(N-1)}(\theta - \delta) + \left(1 - e^{-1/Rc_f w}\right)\left[t_{(N-1)}(\theta - \delta) - T_{(N-1)}(\theta - \delta)\right] \tag{4}$$

The operational form of this equation as it appears in the computer program is

```
TDRA(K) = TDRA(K - 1) + FACT1 * (TRA(K - 1) - TDRA(K - 1))
```
(5)

An energy balance was made over the tube and armor in the manner shown below.

Heat transferred from fluid to tube	-	Change in internal energy of tube	=	Heat energy radiated by tube to space	+	Heat transferred to fin

This energy balance can be written in equation form as

$$(T_N - t_N)\left(1 - e^{-1/Rc_f w}\right)c_f w - m_a c_a \frac{dt_N}{d\theta} = \sigma\epsilon A_t t_N^4 + Q_1 \tag{6}$$

An energy balance was made over the fins in the following manner:

Heat transferred to fin	=	Change in internal energy of fin	+	Heat radiated by fin to space

In equation form the above energy balance as applied to the fins appears as

$$Q_1 = m_F c_F \frac{dT_{F_N}}{d\theta} + \sigma\epsilon A_F T_{F_N}^4 \tag{7}$$

Using the definition of fin effectiveness as the ratio of heat radiated at the average fin temperature T_F to the heat that could be radiated if the fin were at the fin root temperature t.

$$\Omega = \frac{\sigma\epsilon A_F T_{F_N}^4}{\sigma\epsilon A_F t_N^4}$$

or

$$T_{F_N} = \Omega^{1/4} t_N$$

and

$$\frac{dT_{F_N}}{d\theta} = \Omega^{1/4}\frac{dt_N}{d\theta} + t_N \frac{d\Omega^{1/4}}{dt_N}\frac{dt_N}{d\theta}$$

Equation (7) can then be rewritten in terms of fin root temperature (tube temperature) as follows:

$$Q_1 = m_F c_F\left(\Omega^{1/4} + t_N \frac{d\Omega^{1/4}}{dt_N}\right)\frac{dt_N}{d\theta} + \sigma\epsilon A_F \Omega t_N^4 \tag{8}$$

Combining equations (6) and (8)

$$(T_N - t_N)\left(1 - e^{-1/Rc_f w}\right)c_f w - m_a c_a \frac{dt_N}{d\theta} = \sigma\epsilon A_t t_N^4$$

$$+ m_F c_F\left(\Omega^{1/4} + t_N \frac{d\Omega^{1/4}}{dt_N}\right)\frac{dt_N}{d\theta} + \sigma\epsilon A_F \Omega t_N^4 \tag{9}$$

Rearranging equation (9)

$$\frac{dt_N}{d\theta} = \frac{(T_N - t_N)\left(1 - e^{-1/Rc_f w}\right)c_f w - \sigma\epsilon\left(A_t t_N^4 + A_F \Omega t_N^4\right)}{m_a c_a + m_F c_F\left(\Omega^{1/4} + t_N \frac{d\Omega^{1/4}}{dt_N}\right)} \tag{10}$$

Integrating equation (10) over the time interval $(\theta - \Delta\theta) \rightarrow \theta$.

$$t_N(\theta) = t_N(\theta - \Delta\theta) + \left[\frac{(T_N - t_N)\left(1 - e^{-1/Rc_f w}\right)c_f w - \sigma\epsilon(A_t + \Omega A_F)t_N^4}{m_A c_A + m_F c_F\left(\Omega^{1/4} + t_N \frac{d\Omega^{1/4}}{dt_N}\right)}\right]\Delta\theta \tag{11}$$

The operational form of equation (11) as it appears in the program is

```
TRA(J) = TRA(J) + ((TDRA(J) - TRA(J)) * FACTOR/RETOT - HEAT(J))/(HCAPTA
                     + HCAPF * (FIN14 + TRA(J) * DFIN14)) * DTIME        (12)
```

Equation (12) solves for the temperature of the tube at each lump.

Computer Techniques

The computer program consisted of two parts: (1) a subroutine subprogram, and (2) a main program.

The operational equations (eqs. (5) and (12)) which appeared previously are contained in the subroutine. A complete listing of the subroutine subprogram is included in the appendix.

The main program provides for the initialization of constants and for other information required by the subroutine subprogram. The main program makes a series of calls to the subroutine. During this series of calls the subroutine then solves for the steady-state temperature profile in the radiator and fluid for a given set of conditions. Using the steady-state condition returned to the main program from the subroutine, the main program makes a second series of calls to the subroutine to obtain the dynamic effects. This is accomplished by means of a sinusoidal analysis. In the case of inlet temperature disturbance, the perturbing function is a sine wave in inlet fluid temperature. The inlet temperature perturbation equation in the main program is

$$TDRA(1) = 619.0 + AMPL * SIN(OMEGA * TIME) + STEP \tag{13}$$

The value of amplitude was 5.56 K for flow rates of 10, 20, 50, and 100 percent of design flow rate. The sinusoidal analysis is achieved by setting amplitude and omega to some appropriate values and STEP to zero. A step change can be simulated by setting amplitude and omega to zero and assigning an appropriate value to STEP.

The analysis in the case of flow rate disturbance proceeds in an exactly analogous manner to that previously described for inlet temperature disturbance. Using the steady-state condition returned to the main program from the subroutine, the dynamic effects induced by a change of inlet flow rate is programmed as the equation given below:

$$FLOWD = (4.54 + AMPL * SIN(OMEGA * TIME) + STEP/153.0 \tag{14}$$

The value of amplitude is 0.00693, 0.01375, 0.0346, and 0.0693 kilogram per second for flow rates of 10, 20, 50, and 100 percent of design flow rate. The values were chosen to correspond with the same percentage change of amplitude as in the inlet temperature perturbation studies. A complete listing of the main program is included in the appendix.

FREQUENCY RESPONSE AND TRANSFER FUNCTIONS

The dynamic response of the SNAP-8 radiator exit temperature to a change in inlet fluid temperature can be found in terms of its frequency response characteristics. The Bode plot shows amplitude ratio and phase angle plotted against frequency. The amplitude ratio against frequency portion of the plot is made on log-log paper. This enables adding amplitude ratios directly to build up more complex structured transfer functions. The phase angle against frequency part of the plot is done on semilog paper. Phase angles may also be added directly to build up more complex structured transfer functions.

A parametric study was made of the radiator response of exit temperature to a sinusoidal change in inlet temperature. The parameter was fluid (NaK) flow rate. Data for plots were generated for 10, 20, 50, and 100 percent of the design point flow rate value. The design point flow rate is 4.54 kilograms per second. The design point fluid inlet temperature is 619.0 K. The frequency response data was generated for a constant inlet temperature.

The Bode plot (fig. 2) shows the dynamic response of the SNAP-8 radiator exit temperature to changes in inlet temperature. Throughout this report, the same symbol is used consistently to indicate a particular value of the flow rate parameter. A circle, for example, indicates design point flow of 4.59 kilograms per second. The amplitude ratios are normalized; that is, the amplitude ratio at each frequency is divided by the steady-state value of amplitude ratio.

One criterion of this study was to obtain the simplest form of transfer function adequately representing the radiator dynamics. This criterion arose because it was desired to have the simplest analog computer in a ground test simulator for controlling the radiator dynamics. A transfer function of the form shown below fits the Bode plots of figure 2 to give the proper amplitude ratio over the frequency range studied

$$\frac{G_{\Delta T_{out}}}{\Delta T_{in}} = \frac{1}{(1 + \tau_1 S)(1 + \tau_2 S)(1 + \tau_3 S)}$$

Consistent with the criterion for simplicity, a transfer function of the form shown below was selected instead.

$$\frac{G_{\Delta T_{out}}}{\Delta T_{in}} = \frac{1}{(1 + \tau_o S)^3}$$

This result agrees favorably with the conclusions given in reference 2.

The phase angle portion of the Bode plot shown in figure 2 dictated the need for a time lag, or dead time, element. The time lag transfer function is given below.

$$G = e^{-LS}$$

The total transfer function as indicated by the Bode diagram therefore becomes

$$\frac{G_{\Delta T_{out}}}{\Delta T_{in}} = \frac{e^{-LS}}{(1 + \tau_o S)^3}$$

The solid lines shown in figure 2 represent the locus of points given by the simplified transfer function. The important result was found that the time constant τ_o is given by the relation shown below:

$$\tau_o = \tau_D * (w_d/w)$$

where $\tau_D = 6.25$ seconds is the value of τ_o at the design flow rate. An equally important result was found that the lag function constant L was given by the relation

$$L = L_D * (w_d/w)$$

where

$$L_D = 50.0 \text{ sec}$$

These findings make the results more general; they can be extended to specific flow rates not treated herein. Very good agreement is shown in figure 2 between the Bode plots of the simplified transfer function and the computer program for inlet temperature disturbance over the frequency range studied.

The dynamic response of the SNAP-8 radiator exit temperature to a change in inlet flow rate is indicated by the Bode plots shown in figure 3. The assorted symbols show the computer program generated points. These points display a small resonance effect in the midfrequency range; however, to account for this effect would overly complicate the transfer functions. Asymptotes fitted to the data points indicated that the simplified transfer function should be a first-order lag. The phase angle approaching 90^o at higher frequencies also points to a first-order lag form of transfer function. Therefore, the simplified transfer function for outlet fluid temperature to fluid flow rate was chosen to be

$$\frac{G_{\Delta T_{out}}}{(\Delta \text{flow})_{in}} = \frac{1}{(1 + \tau_4 S)^1}$$

Flow rates of 10, 20, 50, and 100 percent of design point flow rate are shown in figure 3(a) to (d), respectively. Again, the important relation for the time constant shown below is valid

$$\tau_4 = \tau_D * (w_d/w)$$

where

$$\tau_D = 45.0 \text{ sec}$$

is the value of τ_4 at the design flow rate. The solid lines in figure 3 show the locus of points given by the simplified transfer function model.

The value of time constant shown was chosen to give a good average fit over the frequency range studied. The agreement between the simplified transfer function and computer generated results can be improved for lower frequencies by varying the time constants for specific cases where this may be required.

Since the simplified transfer functions are given in normalized form, they must be combined with a steady-state gain factor in their application. The steady-state amplitude ratios of fluid outlet temperature to inlet fluid temperature and to inlet flow rate are plotted against flow rate in figure 4.

SUMMARY OF RESULTS

From the analysis of the dynamic characteristics of a typical waste-heat radiator for SNAP-8, the following results were obtained:

1. For the assumed radiator, the transfer function relating changes in outlet temperature to changes in inlet temperature is close to a third-order lag multiplied by a dead-time element. The time constant of the third-order lag varies inversely with flow rate. The design flow rate time constant is 6.25 seconds. The dead time also varies with flow rate, being equal to the design point value (50 sec) multiplied by the ratio of the design point flow rate to the given flow rate. This type of transfer function agreed very well with the frequency response generated by the computer simulation of the radiator for flow rates from 10 to 100 percent of design flow.

2. The simplified transfer function for the radiator relating changes in outlet temperature to changes in flow rate is a first-order lag. The time constant of the first-order lag varies with flow rate, being equal to the design point time constant (45.0 sec) multiplied by the ratio of design point flow rate to the given flow rate. A resonance effect in the frequency response generated by the computer simulation precluded the simplified transfer function from matching this frequency response closely in the midfrequency ranges.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 13, 1968,
701-04-00-02-22.

APPENDIX - COMPUTER PROGRAM LISTING

```
$IBFTC MAIN P  LIST
C      THIS IS A FORTRAN IV SOURCE DECK PROGRAM FOR
C      COMPUTING THE FREQUENCY RESPONSE OF THE SNAP-8
C      RADIATOR FOR PERTURBATIONS IN INLET TEMPERATURE
C      OR INLET FLOW RATE.  THE ASSUMED RADIATOR DESIGN
C      IS A CYLINDER 9.260 METERS IN LENGTH AND 3.72
C      METERS IN DIAMETER.  THE PROGRAM IS GENERAL
C      EXCEPT FOR THE INITIALIZATION OF CONSTANTS.
C      METRIC UNITS ARE USED.
       COMMON TIME,DTIME,C7,FLOWD,TDRA(41),TRA(41),FINEF,DFIN14,THEAT
   700 FORMAT (1H 12F10.5)
   701 FORMAT (94H1      TIME       TDRA(41)      TRA(41)       FINEF       DF
      1IN14       TRAD       TIMIL       THEAT   )
   702 FORMAT (1H ,8F12.5)
       TIME=0.0
       CTIME=0.0
       DTIME=0.1
       C7=619.
       FLOWD=.454/153.0
       WRITE (6,701)
    10 CALL RADTOR
       CTIME=CTIME+DTIME
       IF(CTIME-4.95) 500,30,30
    30 CTIME=CTIME-5.0
       T=0.0
       DO 35 I=2,40
    35 T=T+TRA(I)
       TRAD=((TRA(1)+TRA(41))/2.0+T)/40.0
       WRITE (6,702) TIME,TDRA(41),TRA(41),FINEF,DFIN14,TRAD,TIMIL,THEAT
   500 TIME=TIME+DTIME
       IF(TIME-1200.0) 10,10,3
     3 TMAX=TDRA(41)
       TMIN=TMAX
       TIME=.00001
       DTIME=0.11
       READ (5,700) AMPL,OMEGA,STEP
       WRITE (6,700) AMPL,OMEGA,STEP
    12 IF(TIME.LE.50.) AMPLU=AMPL*TIME/50.
       TDRA(1)= 619. +AMPLU*SIN(OMEGA*TIME)+STEP           (Eq. (13))
C      OR FLOWD=(4.54+AMPLU*SIN(OMEGA*TIME)+STEP)/153.0 (Eq. (14))
       CALL RADTOR
       CTIME=CTIME+DTIME
       IF(CTIME-.95) 504,34,34
    34 CTIME=CTIME-1.0
       WRITE (6,700) TIME,THEAT,FLOWD,(TDRA(I),I=1,41,5)
   504 TIME=TIME+DTIME
       TMAX=AMAX1(TMAX,TDRA(41))
       TMIN=AMIN1(TMIN,TDRA(41))
       IF(TIME-2500.0) 12,12,5
     5 AMPLR=(TMAX-TMIN)/(2.0*AMPL)
       WRITE (6,700) AMPLR
       STOP
       END
```

```
$IBFTC RADIAT  LIST
         SUBROUTINE RADTOR
      COMMON TIME,DTIME,C7,FLOWD,TDRA(41),TRA(41),FINEF,DFIN14,THEAT
      DIMENSION HEAT(41),FINF(22),CON(2)
      DATA (FINF(I),I=1,22)/1.0,.854,.783,.727,.681,.642,.608,.578,.554,
     1.532,.512,.495,.480,.466,.453,.441,.430,.420,.410,.401,.393,.385/
      DATA      A159,RETOT,CON(1),CON(2),AARM,AFIN,C1,FINWI,FINTH,
     1 HCAPTA,HCAPF/    170.,.02184,233.3,.05212,.001918,.015,5.103E-8,
     2 .03414,.000762,35.26,1.977/
      THEAT=0.0
      IF(TIME)502,502,503
  502 FACTOR=(1.-EXP(-CON(2)/FLOWD))/(CON(2)/FLOWD)
C
C     INITIAL CONDITIONS
      DO 510 I=1,41
      TRA(I)=C7
  510 TDRA(I)=C7
      RETURN
C
C     MAIN BODY OF SUBROUTINE
  503 DO 520 J=1,41
      SI=C1*TRA(J)**3*FINWI**2/(A159*FINTH)
      I=SI*10.
      IF(I.LT.0)  I=0
      SI=SI-FLOAT(I)/10.
      B=(FINF(I+1)-FINF(I+2))*10.0
      FINEF=FINF(I+1)-B*SI
      FIN14=SQRT(SQRT(FINEF))
      DFIN14=-B*3.0*SI/(FIN14**3*4.0*TRA(J))
C
C     INTEGRATION
      HEAT(J)=C1*(AARM+AFIN*FINEF)*TRA(J)**4
      TRA(J)=TRA(J)+((TDRA(J)-TRA(J))*FACTOR/RETOT-HEAT(J))/(HCAPTA+HCAP (Eq. (12))
     1F*(FIN14+TRA(J)*DFIN14))*DTIME
  520 THEAT=THEAT+HEAT(J)
      DXR=DXR+CON(1)*FLOWD*DTIME
      IF(DXR-1.)505,550,550
  550 DXR=DXR-1.
      FACT1=1.-EXP(-CON(2)/FLOWD)
      FACTOR=FACT1/(CON(2)/FLOWD)
      DO 560 I=1,40
      K=42-I
  560 TDRA(K)=TDRA(K-1)+FACT1*(TRA(K-1)-TDRA(K-1)) (Eq. (5))
      IF(DXR-1.)505,550,550
  505 RETURN
      END
```

REFERENCES

1. Anon.: AIAA Specialists Conference on Rankine Space Power Systems. Vol. 1. AEC Rep. CONF-651026, vol. 1, 1965.
2. Schoenberg, Andrew A.; Bilski, Raymond S.; and Thollot, Pierre A.: Theory and Testing of a Space Radiator Simulator for a SNAP-8 Ground Test Facility. NASA TM X-1375, 1967.

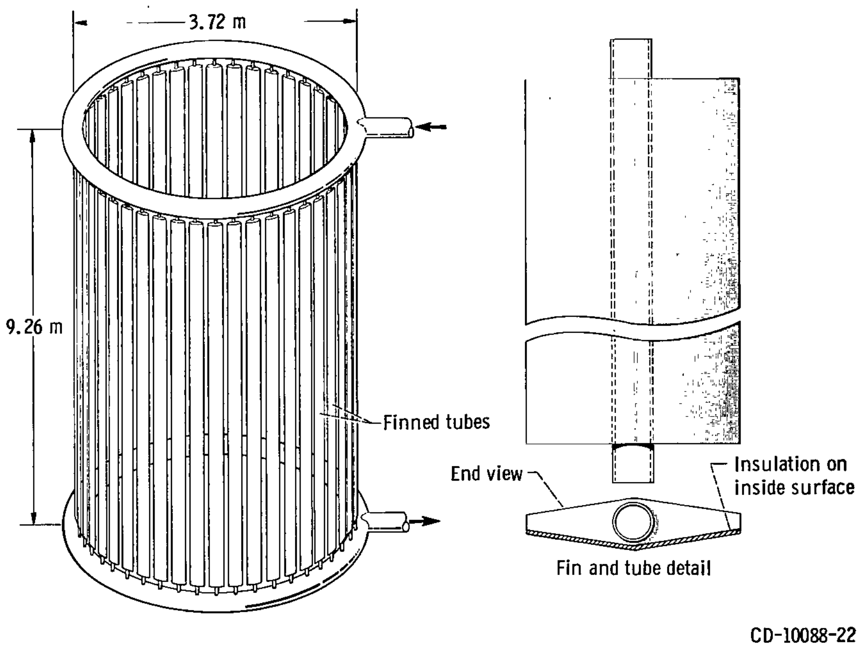


Figure 1. - Assumed design of SNAP-8 radiator.

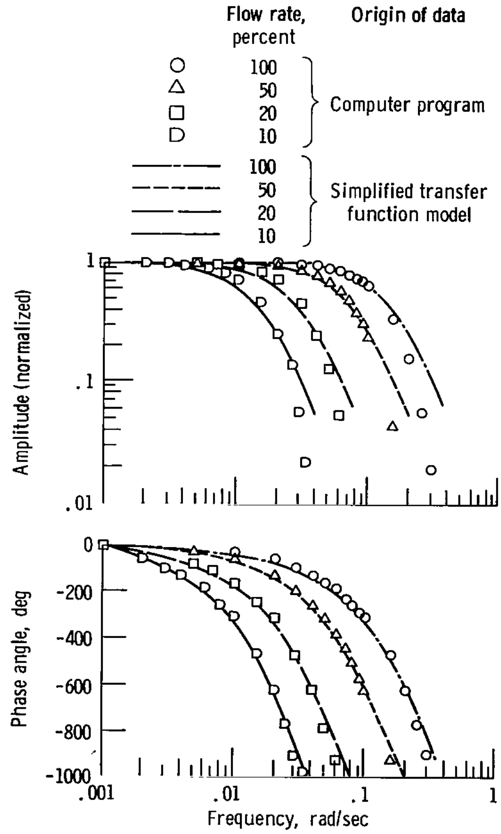
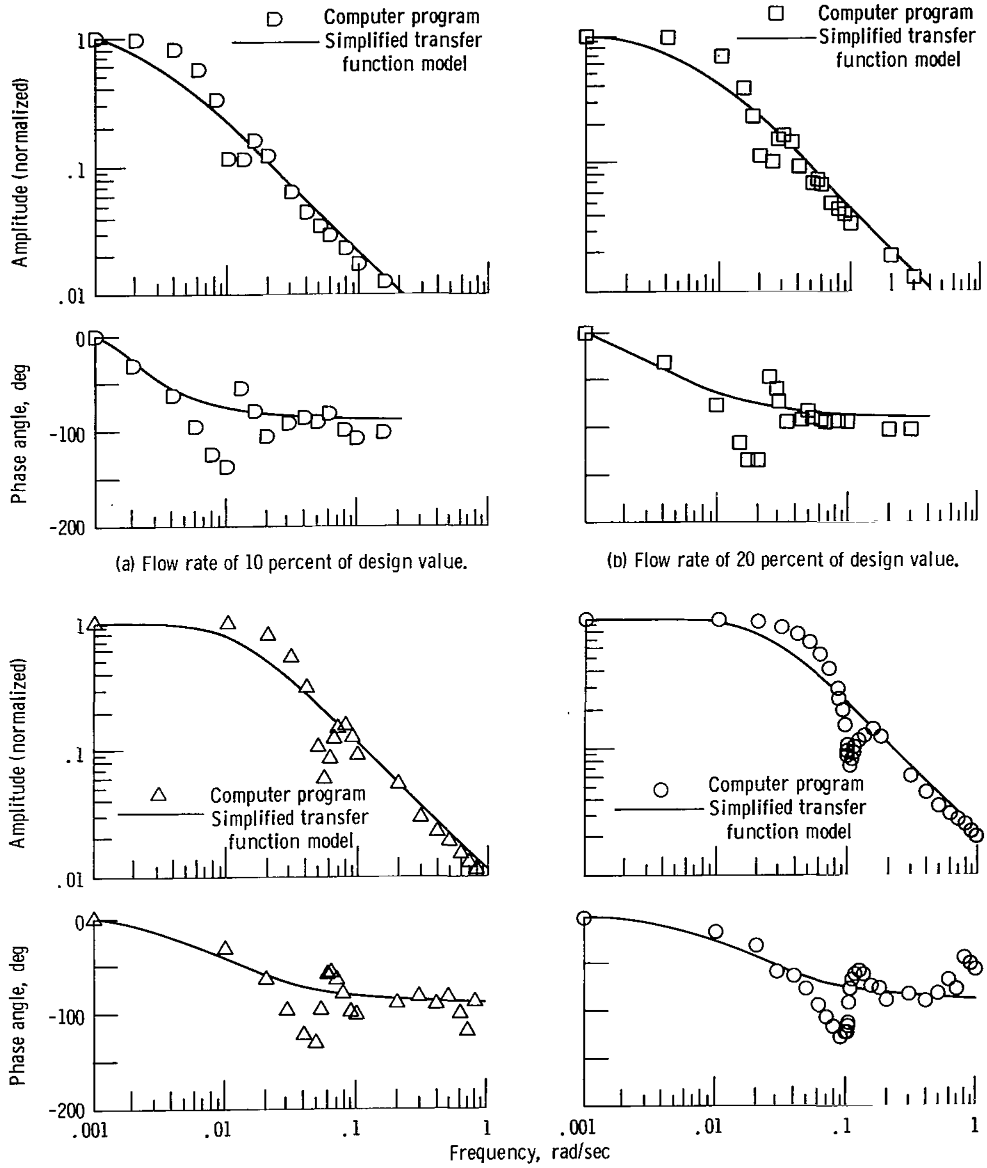


Figure 2. - Frequency response of fluid outlet temperature to fluid inlet temperature for various percentages of design flow rate.



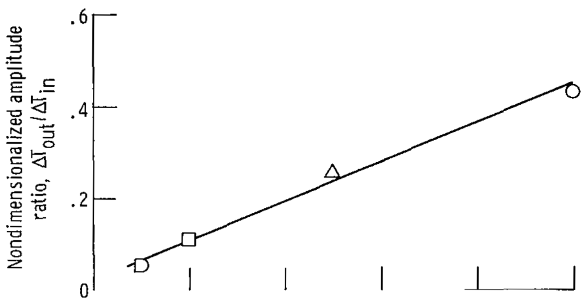
(a) Flow rate of 10 percent of design value.

(b) Flow rate of 20 percent of design value.

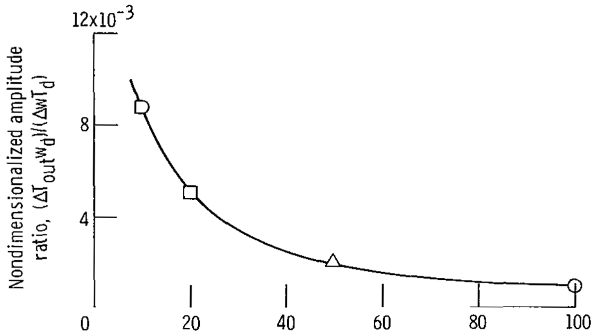
(c) Flow rate of 50 percent of design value.

(d) Flow rate of 100 percent of design value.

Figure 3. - Frequency response of fluid outlet temperature to inlet flow rate for various percentages of design flow rate.



(a) For perturbations in inlet temperature.



(b) For perturbations in inlet flow rate.

Figure 4. - Steady-state amplitude ratios against flow rate for perturbations in inlet temperature and inlet flow rate. Design flow rate, 4.54 kilograms per second; inlet fluid temperature, 619.0 k.

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