TECHNICAL AND ECONOMIC ASSESSMENT OF PHASE CHANGE AND THERMOCHEMICAL ADVANCED THERMAL ENERGY STORAGE (TES) SYSTEMS

EPRI EM-256
(Research Project 788-1)

Final Report

Volume II:

Phase Change TES Sizing
Computer Program

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ABSTRACT

This document describes the computer program used in conceptual studies of phase change thermal energy storage systems. The model assumes the phase change media is contained in a tube-in-bath configuration. The program has been used in conjunction with, but is not necessarily limited to, a high temperature, gas-cooled solar power plant. The program represents a computer implementation of the engineering equations used to estimate the size and cost of a given phase change storage system design concept. Herein is a description of the model including a description of the inputs and outputs of the program.

ACKNOWLEDGEMENTS

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Section 1.

INTRODUCTION AND SUMMARY

Analytical models and computer programs which mechanize these models have been developed to support the sizing and performance analysis of the phase change and chemical energy storage systems. Each of the three major models presented in this volume and volumes III and IV has been programmed in Fortran for the IBM 370.

The math model for sizing the phase change storage system (Volume II) performs the basic function of initial thermal sizing, conceptual configuration sizing, and preliminary cost estimating. The math model for the sizing of the CES system (Volume III) includes the chemical analysis, initial thermal sizing for the reactor and fractionating column, preliminary cost estimating, and overall configuration synthesis. The plant operation math model described in Volume IV is the result of a major modification to a similar program developed during the EPRI Solar Receiver Program RP377-1.

The analytical basis and overall program structure for each of these three computer programs is presented in Section 2.0 of each volume respectively. The input, output, operating instructions, and Fortran listings for each of the three Fortran programs are also included.

This report contains a description of the phase change thermal energy storage sizing model developed in conjunction with storage concepts evaluated in Volume I of this report.

The purpose of this document is to describe the program from a user's point-of-view as an aid to the engineer wishing to size and cost phase change storage systems. The program has been coded in standard IBM FORTRAN IV language using EBCDIC card format. The program encompasses about 2,000 cards and is totally self-contained in batch execution.

Figure 1-1 shows the program logic flow at the main program level. The separate logic blocks represent subroutines that execute the functions described in the figure.

The program assumes a storage system configuration as shown schematically in Figure 1-2. The phase change storage media is contained in an underground insulated vessel. The helium working fluid is dispersed and collected by manifolds. The storage media is contained as a bath immersing the helium tubes. A vertical flow arrangement is used with hot helium entering the top manifold during charging and the cold helium entering the bottom manifold during discharging.

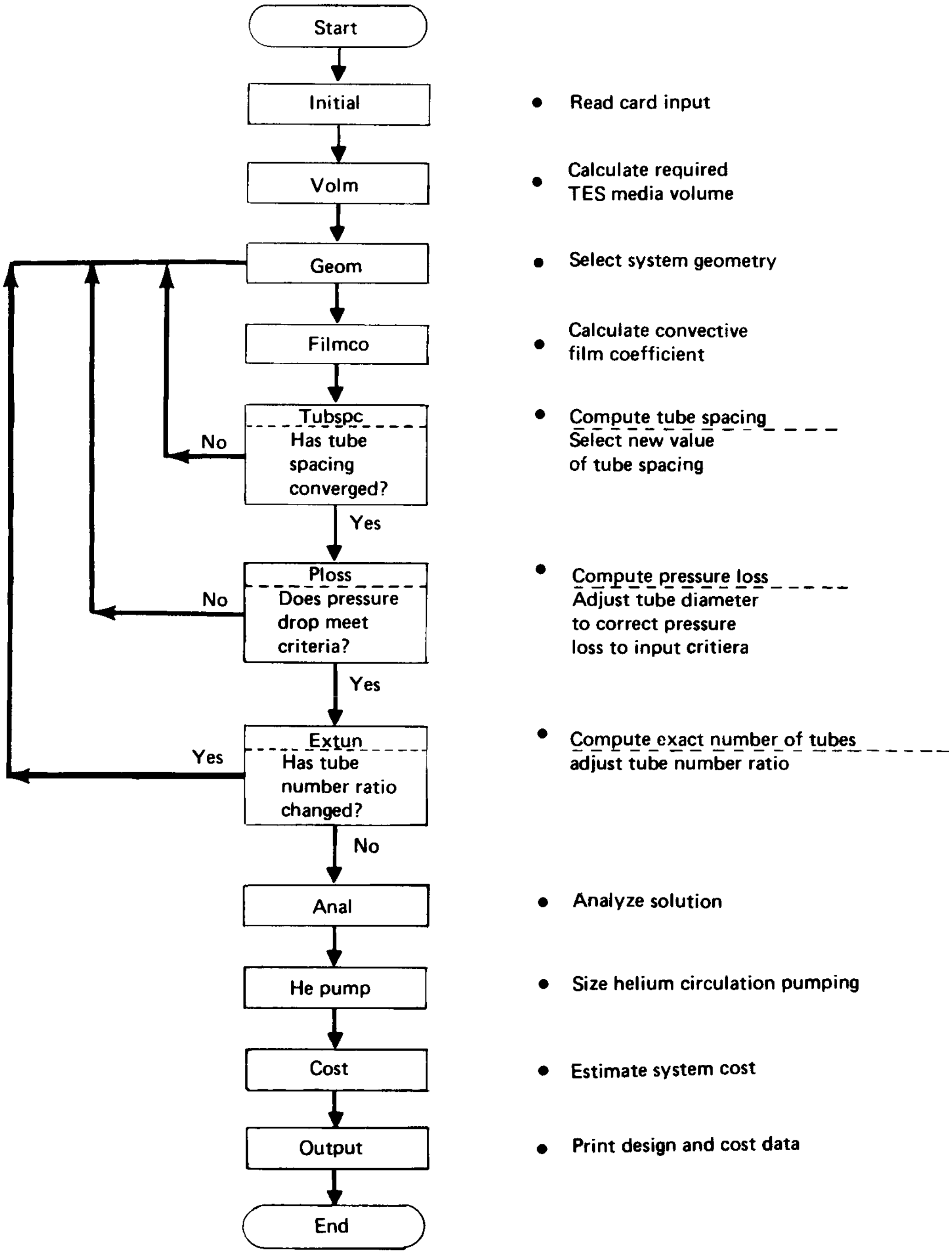


Figure 1-1. Designation Molten Salt Heater Sizing Math Model Structure

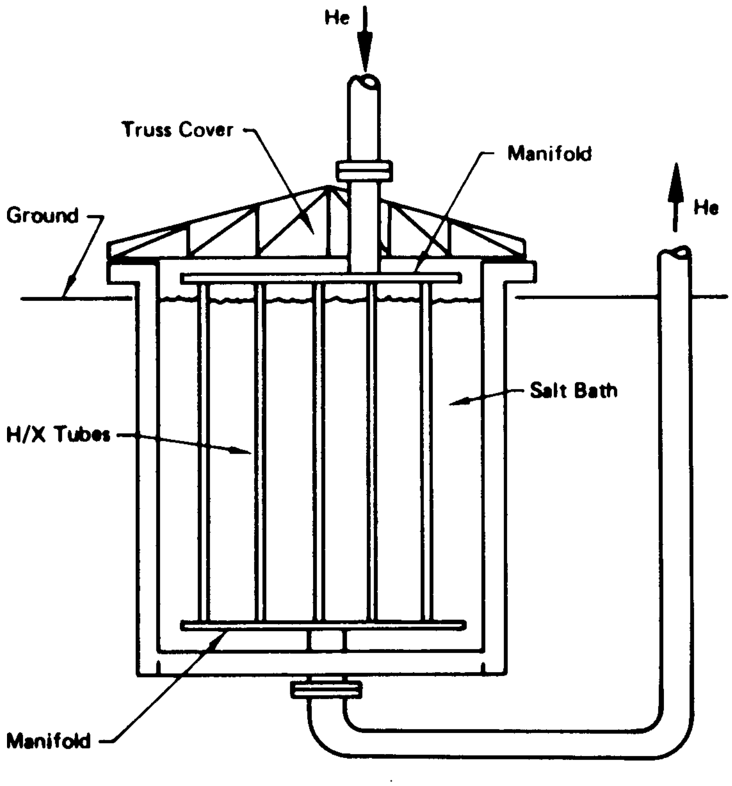


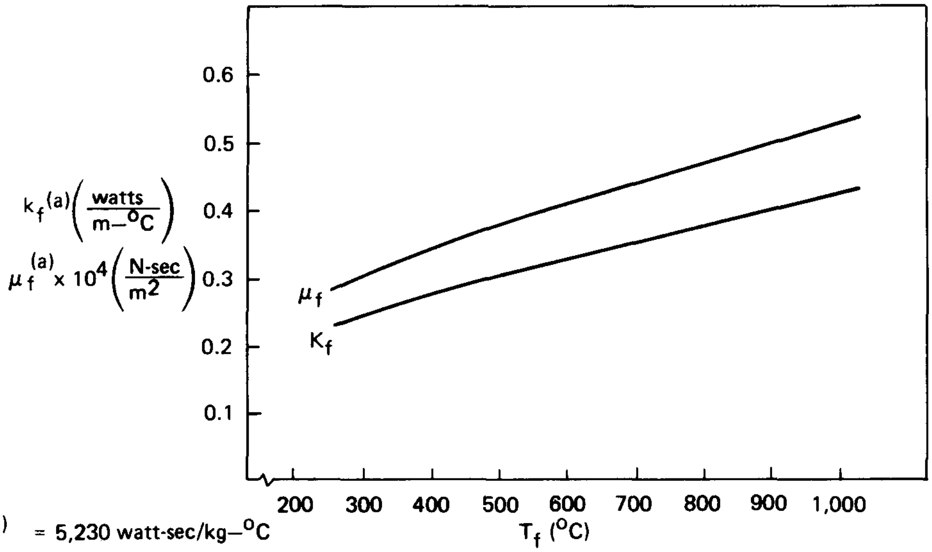
Figure 1-2. Phase Change Thermal Energy Storage Concept

Section 2.

TECHNICAL DESCRIPTION

This section reports on the details of the Phase Change Sizing math model. The purpose of this model is to physically size a phase change thermal energy storage device given a set of consistent performance requirements and operating conditions. Cost estimates of system components are made on the basis of the sizing results. This section includes a presentation of the analytical basis of the math model.

The inputs to the analysis include TES system performance requirements and operating conditions, storage media and working fluid material properties, and storage vessel wall and heat exchanger tubing mechanical restrictions. The performance requirements and operating conditions are obtained from the plant operations math model and include the storage time, discharge rate, heat exchanger NTU value, TES system temperatures, temperature swing of the media, mass flow rates, turbine efficiencies, system pressure and pressure drop criterion. Helium is used as the working fluid, and its thermophysical properties of interest for this analysis include thermal conductivity, density, viscosity, heat capacity and specific heat ratio. The values assumed for helium and the data sources are shown in Figure 2-1. The required material properties of the salt eutectic used as the storage media include thermal conductivity, density, solid and liquid heat capacity, heat of fusion, and melt temperature. The value of heat of fusion for the salt is a very important concern. Some of the heat of fusion values are experimentally determined values; others are calculated values. The calculated values have the Kirchhoff correction included.[1] The details of this correction are presented in Appendix I. The key physical parameter input into the analysis is a characteristic vessel dimension. For a vessel with a square cross-section the dimension is the inside width; for a circular cross-section, the dimension is the inside diameter.



- $C_{P_f}{}^{(a)} = 5{,}230$ watt-sec/kg—°C
- $\gamma_f = 1.67$
- $\rho_f = \dfrac{P}{\frac{R}{AW} \times T_f}$, $R = 8.314 \times 10^3 \dfrac{\text{watt-sec}}{\text{kg-mole} - {}^oC}$, AW = 4 kg/kg-mole

Data source:

(a) Von Cederberg, V.N., Popov, N. V., Morosova, N.A., "Thermodynamic Properties of Helium in the Range of 0° to 3,000°C and 0.2 to 200 Bar," Moscow Power Institute, 1969

Figure 2-1. Thermophysical Properties of Helium

The outputs of the analysis include geometrical data (tubing diameter, tubing thickness, intertube spacing, vessel height, vessel wall thicknesses, etc.), required quantities of TES media, tubing, and container vessel materials, required size of helium pump circulation system, and cost estimates of the components.

2.1 MATHEMATICAL METHODS

The structure of the math model analysis is represented by Figure 1-1. This diagram shows the flow diagram for the computer model; however, it allows a presentation of the details of the analysis. The steps of the analysis are represented by the subroutine blocks shown in the Figure. The details of each block are presented below.

INITIAL

The purpose of this block is to set up the input data and make any initializations or preliminary calculations required by the remainder of the analysis. An example of a preliminary calculation is the selection of the proper value of helium thermal conductivity and viscosity given an average helium temperature (see Figure 2-1). A detailed list of the required inputs for the analysis is shown in Figure 2-2. The source of the values is also indicated.

VOLM

The calculation of the required volume of salt eutectic is carried out in this block. The required thermal energy E is found from:

$$E = \frac{P_D \tau}{\eta_T} \qquad (1)$$

where P_D = discharge power, τ = storage time and η_T = turbine efficiency at the average helium temperature $T_{f_{avg}}$.

The mass of media m required to store this thermal energy is given by

$$m = \frac{E}{xh + C_p(\ell)\,\Delta T - (T_m - T_o)\,\Delta C_p} \qquad (2)$$

where h = heat of fusion, $C_p(l)$ = liquid heat capacity, $\Delta C_p = C_p(l) - \overline{C_p(s)}$, the difference between liquid and solid heat capacity, T_m = melt temperature, T_o = initial temperature of storage system, ΔT = effective temperature swing of the media, x = effective portion of salt that undergoes a change of phase. ΔT and x are determined from the plant operation model. $\overline{C_p(S)}$ is an average value over the temperature range T_o to T_m. The solid heat capacity of the salt can be expressed as follows

$$C_p(S) = a + bT + cT^{-2} \qquad (3)$$

The final term is negligible in most cases, accounting for about 1/2% of the total value. Using the first two terms, the average Cp(s) can be found from

$$\overline{C_p(S)} = \frac{1}{T_m - T_o} \int_{T_o}^{T_m} C_p(S)\, dT$$

$$= a + \frac{b}{2}(T_m - T_o) \qquad (4)$$

Parameter	Description	Units	Source
$\dot{m}$	Mass flow rate	kg/sec	POP*
$\dot{m}_c$	Charge condition mass flowrate	kg/sec	POP
ΔT	Temperature drop across TES media	^oC	POP
$(\Delta T)_{pp}$	Pinch point temperature drop	^oC	POP
η_T	Turbine efficiency	–	POP
X	Fraction of heat of fusion utilized	–	POP
NTU	Number of transfer units	–	POP
P_D	Discharge rate	Watts	POP
t	Storage time	Sec	POP
Tf_{avg}	Average working fluid temperature	^oC	POP
T_o	Initial storage temperature	^oC	POP
α	Fractional pressure drop criterion	–	OCS**
α_1	Fractional pressure drop heater + receiver	–	OCS
p	System pressure	N/m^2	OCS
T_i	Heater inlet temperature	^oC	OCS
C_p (l)	Salt heat capacility (liquid)	Watt-sec/kg-^oC	Material properties
a_1	Salt heat capacity coefficient (solid)	Watt-sec/kg-^oC	↓
b_1	Salt heat capacity coefficient (solid)	Watt-sec/kg-$(^oC)^2$	↓
ρ	Salt density	kg/m^3	↓
h	Salt heat of fusion	Watt-sec/kg	↓
k	Salt thermal conductivity	Watt/m-^oK	↓
T_m	Salt melt temperature	^oK	↓
Cp_f	Working fluid heat capacity	Watt-sec/kg-^oK	↓
ρ_f	Working fluid density	kg/m^3	↓
μ_f	Working fluid viscosity	$N\text{-}sec/m^2$	↓
k_f	Working fluid thermal conductivity	Watt/m-^oC	↓
γ_f	Working fluid specific heat ratio	–	↓
η_C	Helium pump efficiency	–	Design specifications
H_t	Maximum tubing length manufactured	m	↓
S	Maximum allowable stress in tubing material	N/m^2	↓
D	Vessel characteristic dimension	m	↓
j	= 1 triangular tube spacing = 0 square tube spacing		↓
k	= 1 circular vessel cross section = 0 square vessel cross section		↓
a	Ratio of wall clearance to intertube spacing		↓
CM	Manifold cost allowance	%	Cost data
Cm_{t1}	Cost per m^3 of tubing metal volume	$\$/m^3$	↓
Cm_{t2}	Cost per m of tubing length	\$/m	↓
C_{TES}	Cost per m^3 of TES media	$\$/m^3$	↓
C_{VW}	Cost per m^2 of vessel wall	$\$/m^2$	↓
C_w	Cost per weld	\$/weld	↓

*Plant operation program

**Operating condition specification

Figure 2-2. Inputs to Phase Change Math Model Analysis

The required salt volume V is found from

$$V = \frac{m}{\rho} \tag{5}$$

where ρ = salt density

GEOM

This block does a major portion of the geometric calculations. The most important calculation is the estimate of the tube number n_T. This estimate is calculated by considering the packing density of a given tubing spacing pattern. Figure 2-3 shows the two spacing patterns considered. Defining the packing density $\bar{\rho}$ as the ratio of the salt volume to total available volume, we have

$$\bar{\rho} = 1 - a_c \frac{d^2}{(d + 2\delta)^2} \tag{6}$$

and

$$a_c = \begin{cases} \pi/4, & \text{square tube spacing} \\ \frac{\sqrt{3}\,\pi}{9} & \text{triangular tube spacing} \end{cases} \tag{7}$$

The tube number is proportional to the ratio of the vessel cross-sectional area Av, the tube cross-sectional area $\pi\, d^2/_4$, and the packing density $\bar{\rho}$

$$n_T \propto (1 - \bar{\rho}) \frac{A_v}{\frac{\pi d^2}{4}}$$

Since

$$A_v = b_c D^2 \tag{8}$$

where

$$b_c = \begin{cases} 1, & \text{square vessel cross section} \\ \frac{\pi}{4}, & \text{circular vessel cross section} \end{cases} \tag{9}$$

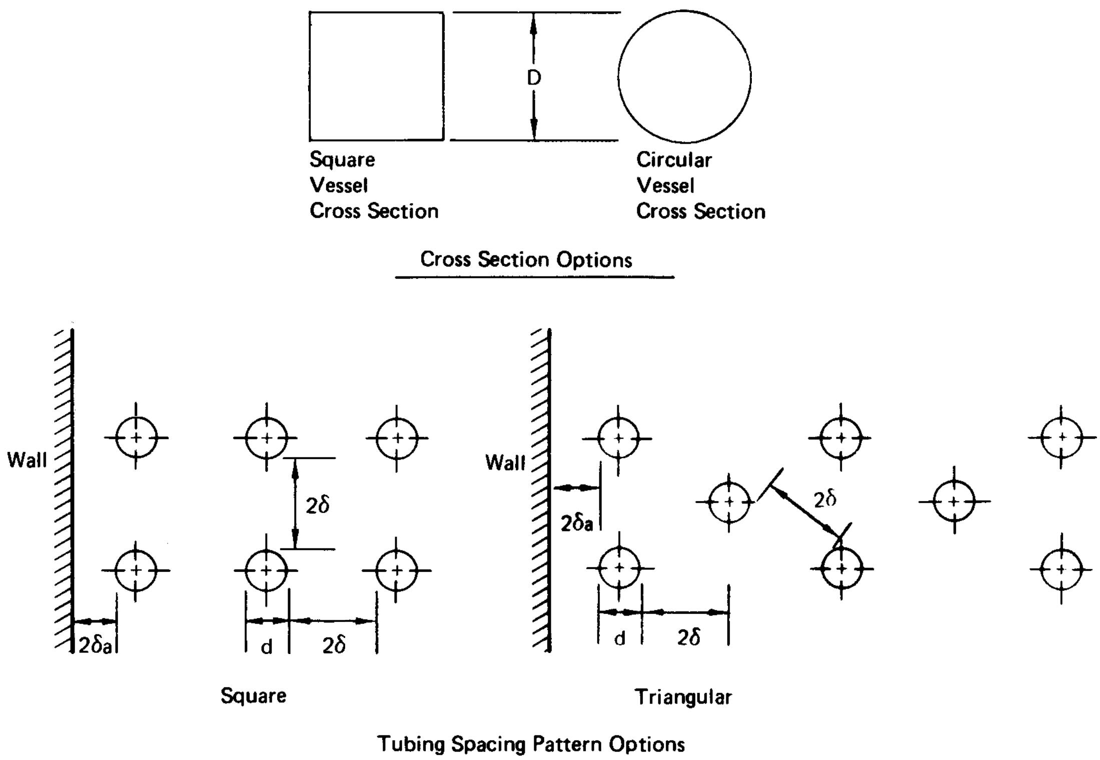


Figure 2-3. Geometrical Options

then

$$n_T = C_1 \frac{4\ b_c}{\pi}\ a_c \frac{D^2}{(d + 2\delta)^2} \qquad (10)$$

The constant C_1 is used to correct the n_T value to the actual vessel design. Because a certain minimum spacing must be chosen between the outer tubes and the vessel inner wall (see Figure 2-3), not all the area of the vessel cross-section is available for the heat exchanger.

Another important geometric calculation is the determination of the vessel height H. Assuming the salt volume is contained entirely in the heat exchanger portion of the vessel; i.e., no salt in the manifold heat regions, the height of vessel to contain the desired amounts of salt volume and tubing is given by

$$H_1 = \frac{4}{\pi} \frac{V}{(\frac{4}{\pi} b_c D^2 - n_T d^2)} \qquad (11)$$

There is also a requirement for enough tubing surface area to provide adequate heat transfer from/to the helium flow and the salt TES media. This required surface area A is expressed as a desired UA - value, U being the effective unit thermal conductance. The UA - value is usually expressed as

$$UA = \dot{m}\ C_p\ NTU \qquad (12)$$

where $\dot{m}$ - mass flowrate at critical charge or discharge condition, Cp = heat capacity of helium, NTU = number of transfer units. The NTU - value is a measure of the heat exchanger effectiveness ε

$$\varepsilon = 1-e^{-NTU} = \frac{T_E - T_I}{T_m - T_I} \qquad (13)$$

where T_E = system exit temperature, T_I = system inlet temperature, and T_m = melt temperature. The NTU - value is an input given from the plant performance math model. The heat exchange surface area is given by

$$A = n_T\ \pi dH$$

Therefore, the required vessel height for the desired heat exchange is

$$H_2 = \frac{\dot{m}\ C_p\ NTU}{\pi d\ \ n_T}\ \frac{1}{U} \qquad (14)$$

A consistent design is obtained when $H_1 = H_2$. The parameter that is varied to cause this consistency to occur is the tube half spacing δ. Since Eqn (14) requires a unit thermal conductance value, which is also dependent upon d and δ, the initial pass through GEOM picks up default values of C_1, d, and δ. The calculations of (13) and (14) are skipped until the U is calculated later in the analysis. As shown in Figure 1-1, an iterative process is required to simultaneously satisfy $H_1 = H_2$ and calculate the unit thermal conductance U.

FILMCO

This block has the important function of accurately predicting the convective heat transfer coefficient h. The tubing wall thickness t is calculated from

$$t = 0.75\ \frac{pd}{S} \qquad (15)$$

where p = helium pressure, S = allowable stress in tubing metal = 3.9 x 10^7 N/m^2 (5600 psi) for Inconel 617 at 816°C (1500°F). This thickness value contains a 50% safety factor over the minimum allowable thickness. The flow velocity U_f through each tube is given by

$$U_f = \frac{\dot{m}}{n_T} \frac{4}{\rho_f \pi (d - 2t)^2} \qquad (16)$$

where ρ_f = helium density. The Reynolds number Re and Prandtl number Pr are given below

$$Re = \frac{U_f (d - 2t)}{\mu_f/\rho_f} \qquad (17)$$

$$Pr = \frac{C_{Pf} \mu_f}{k_f} \qquad (18)$$

where μ_f = helium viscosity, k_f = helium thermal conductivity.

The Nusselt number Nu is related to the convective film coefficient by

$$h = Nu \frac{k_f}{(d - 2t)} \qquad (19)$$

Nu has been experimentally correlated [4] with Re and Pr at expected temperatures by

$$Nu = 0.0215 \, Re^{0.8} Pr^{0.6} \qquad (20)$$

This correlation has been shown to give Nu values accurate to 5%.

TUBSPC

This block calculates the tube half spacing δ and the unit thermal conductance U. A new value of tube half spacing is calculated from equating Eqns (11) and (14) to yield

$$\delta^* = 1/2 \left\{ \left[C_1 a_c d^2 + \frac{4 d c_1 a_c V}{\dot{m} C_p NTU} \right]^{1/2} - d \right\} \qquad (21)$$

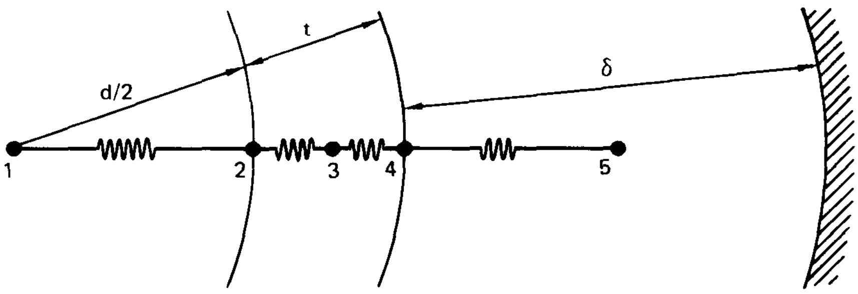
If the new and old half spacing values are not sufficiently close, control passes back to GEOM. This process continues until a consistent δ is found.

The unit thermal conductance is used to calculate the heat transfer between the helium flow and the storage media

$$Q = U\,(T_{He} - T_{SALT})$$

where $U = (R_{total}\ A_i)^{-1}$, R_{total} = total thermal resistance, A_i = tube inside surface area. The unit thermal conductance is calculated by lumping the masses of the helium, tube wall and storage media into nodes (see Figure 2-4). Halfway between the tubes is an adiabatic surface, so that U can be found from

$$U = \frac{1}{R_{total}\ A_2} = \frac{1}{A_2[R_{12}+R_{23}+R_{34}+R_{45}]} \qquad (22)$$



$$U = \frac{1}{R_{total}\ A_2} = \left\{ A_2[R_{12} + R_{23} + R_{34} + R_{45}] \right\}^{-1}$$

$$R_{ij} = \frac{r_j - r_i}{k_{ij}\ A_{ij}}, \text{ (CONDUCTION)}$$

$$= \frac{1}{h_{ij}\ A_{ij}}, \text{ (CONVECTION)}$$

Figure 2-4. Unit Thermal Conductance Nodal Model

The thermal resistances are found from

$$R_{ij} = \frac{r_j - r_i}{k_{ij}\ A_{ij}} \quad \text{for conduction}$$

$$= \frac{1}{h_{ij}\ A_{ij}} \quad \text{for convection} \qquad (23)$$

substitution and simplification gives

$$U = \left\{ \frac{1}{h} + \frac{(d - 2t)}{2\ k_w} \left[\ln\left(\frac{\frac{\sqrt{2}}{2}\sqrt{d^2 + (d - 2t)^2}}{(d - 2t)} \right) + \ln\left(\frac{\sqrt{2}\ d}{\sqrt{d^2 + (d - 2t)^2}} \right) \right] + \frac{(d - 2t)}{2\,k} \ln\left(\frac{\frac{\sqrt{2}}{2}\sqrt{d^2 + (d + 2\delta)^2}}{d} \right) \right\}^{-1} \quad (24)$$

A check on the adequacy of using a lumped node approach over the exact solution was made for a planar geometry. The details of those calculations are shown in Appendix II. The results from those calculations indicate that the lumped node approach can provide accurate values for the unit thermal conductance for a wide range of conditions.

One concern that remains with this lumped node approach used to obtain the unit thermal conductance is the value of the salt thermal conductivity. Presently an average value is assumed to handle variations caused by differences between solid and molten salt properties. If there is a substantial difference between solid and molten salt thermal conductivity values, the average thermal conductivity approach may produce misleading data. During the ERDA portion of this study, the effects of the salt melt face propagation on the charge/discharge characteristics of the phase change device will be considered in detail.

PLOSS

This block calculates the pressure drop through the heat exchanger. The ratio of the pressure drop to the system pressure is given by [2]

$$\frac{\Delta p}{p} = \frac{1}{2} f U_f^2 \ \frac{H}{(d - 2t)} \quad (25)$$

The friction factor f for flow through smooth tubes is given by the Blasius formula

$$f = \frac{0.3164}{Re^{1/4}} \quad (26)$$

The pressure ratio of Eqn. (25) is compared to a desired criterion, e.g., 4%. If the ratio is significantly different, the tubing diameter d is changed and control passes back to the GEOM routine as shown in Figure 2-1. A new tube half spacing is found and a new pressure drop ratio calculated. This process continues until both the consistent tube spacing requirement and pressure drop criterion are satisfied.

The pressure drop calculated herein so far accounts only for the heat exchanger portion. Plans are to later include the manifold pressure drop contribution. Initial estimates indicate that the contribution is an additional 0.5%.

EXTUN

This block calculates the exact tube number n_T' which will fit in a given vessel cross-section. This involves actually counting the number of tubes that will fit in a vessel with a given spacing pattern. This n_T' is used to update the numerical constant C_1 used in the GEOM routine. As will be shown, this additional correction is necessary to accurately give the tube number for a given configuration.

As was indicated in the discussion of the GEOM routine, the exact tube number that can be placed in a vessel with a specified tubing spacing pattern depends on the specification of the minimum distance allowed between the outer tubes and the vessel wall. As shown in Figure 2-5 this minimum distance can be specified by giving the value for the parameter a, which is defined as the ratio of this minimum distance to the intertube spacing distance 2δ. Most calculations so far have proceeded with a = 1. The maximum number of tubes that can be placed along the centerline of the vessel with a dimension D is given by

$$m_1 = \text{INTEGER}\left(\frac{D - 2a\delta}{\ell_1}\right) \qquad (27)$$

where ℓ_1 = centerline to centerline tube spacing = $d + 2\delta$

Defining $$D^* = 2\,(m_1 + a)\,\delta + m_1 d$$

and $$\overline{\alpha} = \frac{D-D^*}{2} \qquad (28)$$

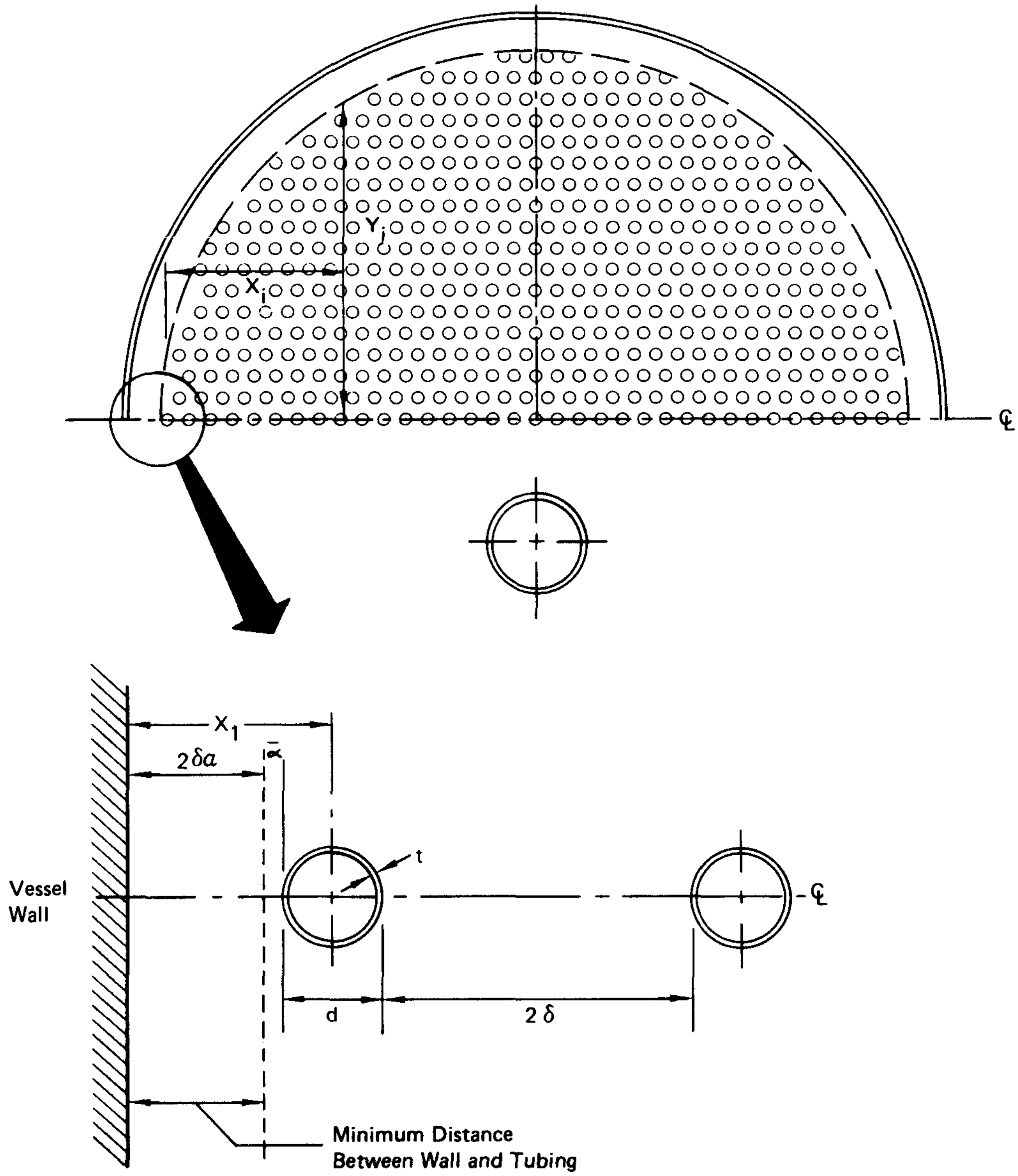


Figure 2-5. Tube Number Calculation Schematic

the distance between the vessel wall and the centerline of the closest tube is given by

$$x_1 = 2\delta a + \overline{\alpha} + \frac{d}{2} \qquad (29)$$

With these initial setups, the tube number is calculated by determining the distance Y from the centerline to the minimum distance line at points regularly spaced along the vessel centerline. The Y- values are divided by the distance between tubes, the integer value of the quotient taken, and the integer values sumed. By the use of symmetry, twice the integer value sum plus m_1 yields the tube number n_T'. This procedure obviously allows the calculation of n_T' for any symmetrical vessel where Y can be specified as a function of the distance along its centerline.

In order to accomplish this summation for either a square or cylindrical vessel and either a square or triangular tube spacing pattern, a logic pattern was set up (see Figure 2-6). For a square tube spacing, the following parameters were defined

$$\begin{aligned} \overline{m} &= m_1 \\ \overline{b} &= 1 \\ \overline{B} &= \ell_1 \\ A_i &= 0, \text{ for all } i \end{aligned} \qquad (30)$$

For a triangular spacing

$$\begin{aligned} \overline{m} &= 2m_1 - 1 \\ \overline{b} &= 1/2 \\ \overline{B} &= \frac{\sqrt{3}}{2}\ell_1 \\ A_i &= \begin{cases} 0, & \text{for odd } i \\ 1, & \text{for even } i \end{cases} \end{aligned} \qquad (31)$$

The points along the centerline are given by

$$x_i = x_1 + (i-1)\,\overline{b}\,\ell_1 \qquad (32)$$

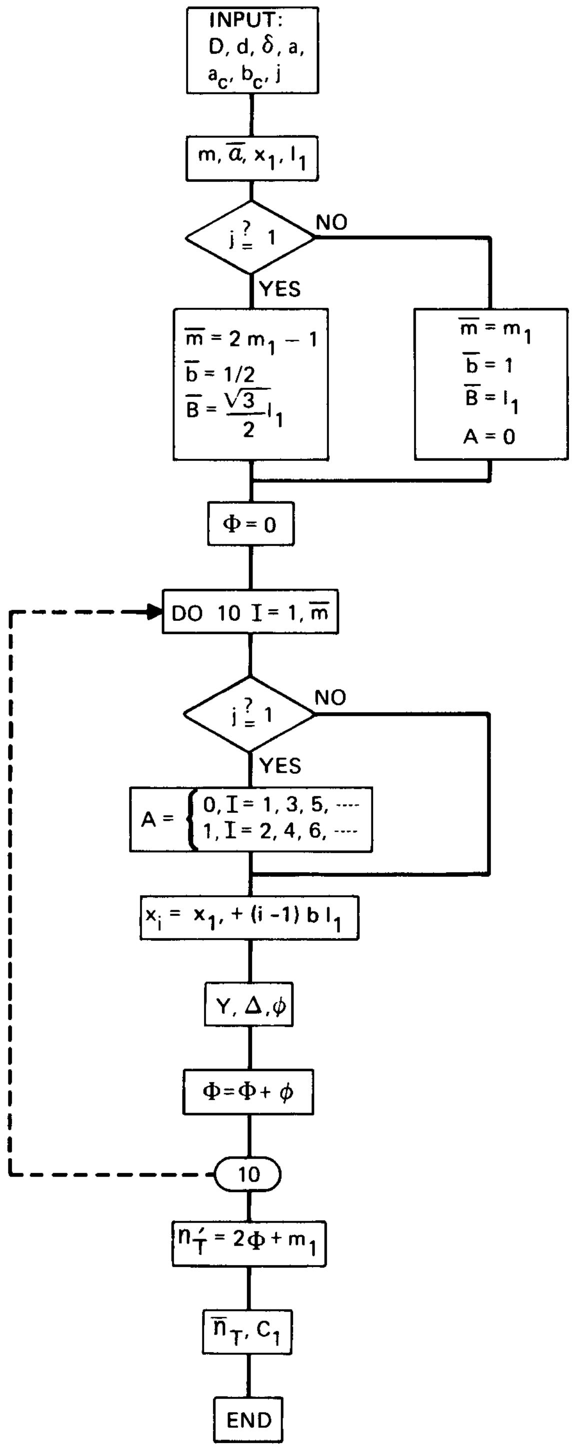


Figure 2-6. Logic Diagram for Exact Tube Number Calculation

The distance Y_i is given by

$$Y_i = \begin{cases} \sqrt{\overline{R}^2 - (x_i - \overline{R} - x_1)^2}, \text{ circular cross section} \\ \overline{R}, \text{ square cross section} \end{cases} \quad (33)$$

where

$$\overline{R} = 1/2D - 2\delta a - \overline{\alpha}$$

The Y_i value is divided by the distance between tubes $\overline{B}$ to give

$$\Delta_i = \frac{Y_i}{\overline{B}} \quad (34)$$

The integer sum is then given by

$$\Phi = \sum_{i=1}^{\overline{m}} \left\{ \text{INTEGER } [\overline{b} \; (\Delta_i - A_i)] + A_i \right\} \quad (35)$$

Then, the tube number n_T' is given by

$$n_T' = m_1 + 2\Phi \quad (36)$$

The numerical constant C_1 is updated by

$$C_1 = \frac{n_T'}{\overline{n}_T} \quad (37)$$

where $\overline{n}_T = \frac{4}{\pi} \; b_c a_c \frac{D^2}{(d + 2\delta)^2}$

The importance of calculating the exact tube number n_T' and updating C_1 is shown in Table 2-1. As can be seen, basing the tube number solely on the packing fraction approach produces significant variations with the actual number of tubes that can be physically placed in a vessel.

Table 2-1
COMPARISON OF TUBE NUMBER CALCULATIONS

$d = 0.01$ m, $\delta = 0.03$ m, $a = 1.0$

	D (meters)	Square vessel square spacing	Square vessel triangular spacing	Circular vessel square spacing	Circular vessel triangular spacing
C_1	5	.988	1.526	.994	1.513
n_T'		5041	5993	3981	4665
C_1	10	1.002	1.152	1.004	1.518
n_T'		20449	23513	16099	18731

ANAL

This block analyzes the solution to provide data needed to calculate cost estimates. The total length of heat exchanger tubing required is

$$\ell = n_T H \tag{38}$$

The volume of tubing metal V_m is given by

$$V_m = \pi \ell \, (dt - t^2) \tag{39}$$

The number of welds n_w required to produce the length of tubes required is

$$n_w = n_T \text{ INTEGER } \left(\frac{H}{H_t}\right) \tag{40}$$

where H_t = maximum manufactured tube length. At present, the vessel container wall cost estimate is based on the surface area A_s of the vessel

$$A_s = \pi DH$$

It is planned to include the detailed design calculations for the vessel container wall at a later date.

HEPUMP

This block sizes the helium circulation system pump. During charging of the TES system, the helium pump will circulate the helium through the receiver and the storage system. The compressor is sized to recoup the pressure losses in both the receiver and storage system. A schematic of its location is given in Figure 2-7. Defining the compressor efficiency by

$$\eta_C = \frac{\left(\frac{Po_3}{Po_2}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\frac{To_3}{To_2} - 1} \tag{41}$$

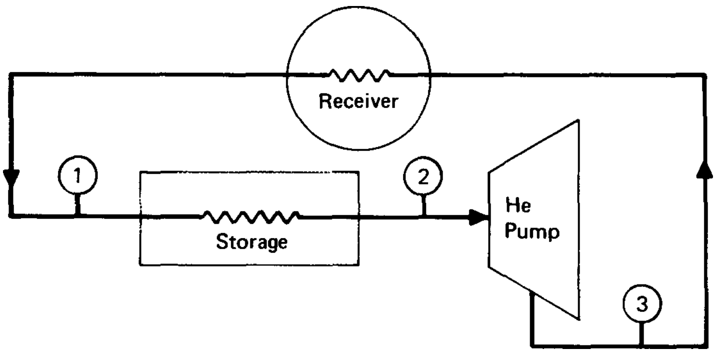


Figure 2-7. Simplified Schematic of Storage Charging Cycle

the required work rate W_c from the compressor is given by

$$W_c = \dot{m}_c C_p (To_3 - To_2)$$

$$= \frac{\dot{m}_c C_p To_2}{\eta_c}\left[\left(\frac{Po_3}{Po_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{42}$$

where $\dot{m}_c$ = critical charging mass flowrate, γ = specific heat ratio, and $(\ )_o$ indicates stagnation flow conditions.

The stagnation pressure p_o is given by

$$p_o = p + 1/2\ \rho_f U_f^2$$

Since the static pressure p is >> the dynamic pressure $1/2\ \rho_f U_f^2$, $p_o \approx p$ or stagnation conditions ≈ static conditions. Using $p_1 = p_2 + (\Delta p)_T$ where $(\Delta p)_T$ is pressure drop through receiver and TES system.

$$W_c = \frac{\dot{m} C_p T_2}{\eta_C}\left[\left(\frac{1}{1-\alpha_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

where

$$\alpha_1 = \frac{(\Delta p)_T}{p}$$

The temperature T_2 can be found from

$$\frac{T_3}{T_2} = 1 + \frac{1}{\eta_C}\left[\left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \qquad (43)$$

and

$$T_3 = T_1 - (\Delta T)_{PP}$$

where $T_1 \equiv$ TES inlet temperature = 816°C (1500°F), $(\Delta T)_{PP}$ = pinch point temperature delta = 111°C (200°F).

Substitution and simplification yields

$$W_C = \frac{\dot{m}_c\, C_p\, [T_1 - (\Delta T)_{PP}][(\frac{1}{1-\alpha_1})^{\frac{\gamma-1}{\gamma}} - 1]}{\left\{\eta_C + (\frac{1}{1-\alpha_1})^{\frac{\gamma-1}{\gamma}} - 1\right\}} \qquad (44)$$

To cost a compressor of this rating, a number of existing compressors were surveyed. Table 2-2 shows the findings. It was decided to scale the 0.8 MW compressor using the following relation [3]

$$C_{HP} = \frac{210 \times 10^{-3}}{\left(\frac{W_C}{8 \times 10^5}\right)^{0.4}} \qquad (45)$$

where C_{HP} is the \$/watt for the pump.

COST

This block assembles the various design data to form cost estimates of the various components. The cost account structure is shown in Figure 2-8.

Table 2-2
EXAMPLES OF AVAILABLE COMPRESSORS

Manufacturer	Inlet temp (°C)	Pressure ratio	Rating (MW)	Cost ($/kW)
Ingersol-Rand	45	8	15	250
Ingersol-Rand	39	150	10	250
Turbonetics	294	1.27	0.3	223
Elliot	316	1.18	0.8	210

Account	Quantity (units)	Unit cost (units)	Cost (M$)
TES media	V (m^3)	C_{TES} ($/$m^3$)	$C_{TES} \cdot V$
Storage container			
*Vessel outer wall	V_{ow} (m^3)	C_{ow} ($/$m^3$)	$C_{ow} \cdot V_{ow}$
*Insulating Brick	V_e (m^3)	C_I ($/$m^3$	$C_I \cdot V_I$
*Liner	V_R (m^3)	C_e ($/$m^3$)	$C_e \cdot V_e$
*Roof		C_R ($/$m^3$)	$C_R \cdot V_R$
Heat exchanger			
Metal volume	V_m (m^3)	$C_{m_{t_1}}$ ($/$m^3$)	$C_{m_{t_1}} \cdot V_m$
Tubing length	ℓ (m)	$C_{m_{t_2}}$ ($/m)	$C_{m_{t_2}} \cdot \ell$
Number of welds	η_W	C_W ($/weld)	$C_W \cdot \eta_W$
Manifold allowance			C_M
Helium circulation pump	W_C (MW)	C_{HP} ($/MW)	$C_{HP} \cdot W_C$
Total			$C_T = \Sigma$

*Presently expressed as lumped value for vessel wall

Figure 2-8 Cost Account Structure

The unit costs for the various components and their data sources are listed in Table 2-3.

2.2 RECOMMENDATIONS

Although the phase change sizing math model is working well, additional calculational steps will be added under the ERDA portion of the study. An

Table 2-3
TYPICAL UNIT COST VALUES

Material	Unit cost value	Data source
TES media NaF/ZnF_2	$2{,}170 \$/m^3$ (0.42 $/lbm)	1
Storage container	$4{,}100 \$/m^2$	2
Heat exchanger		
Metal volume	$99{,}000. \$/m^3$	3
Tubing length	4.92 $/m	3
Number of welds	12.00 $/weld	4
Helium circulation system	From Hepump	5

1. Pennwalt Data, April 1976, FOB Inyokern, California
2. Based on an estimate of container cost for a square vessel cross section, metal wall and liner, insulating brick, and truss roof
3. Based on estimates from Huntington Alloys, Huntington, W.Va.
4. Manufacturing estimate
5. Data produced in Hepump subroutine

important addition will be the incorporation of vessel wall sizing calculations into the ANAL subroutine.

This will allow a point design calculation to be made for the vessel wall, increasing the accuracy of the storage container cost account.

Another very important addition will be the addition of the manifold sizing and costing calculations. This addition will require the selection of a particular manifolding concept and the quantifying of the sizing calculations. It is expected that this sizing will significantly affect the choice of heat exchanger tube number, diameter, wall thickness, etc.

Other additions include the capacity to handle finned heat exchanger tubing and radiation enhanced salt thermal conductivity. Both of these additions will allow the quantifying of their influence on the phase change system sizing and cost estimates.

Finally, it is expected that the phase change sizing model can be modified slightly to allow consideration of the sizing of a sensible heat TES system. The requirements of such a modification will be explored.

2.3 REFERENCES FOR SECTION 2.0

1. Bramlette, T. T., et al, "Survey of High Temperature Thermal Energy Storage" Sandia Labs, Albuquerque, N. M., March 1976.

2. Schlichting, H., Boundary Layer Theory, McGraw-Hill, N. Y., 1968, p. 12.

3. Boeing Coordination Sheet, "Turbomachinery Costs," K-6161-GLV-079.

4. Kays, W. M. Convective Heat and Mass Transfer, McGraw-Hill, N. Y., 1966, p. 173.

Section 3.

INPUT DESCRIPTION

The following is a description of the input variables and how to prepare them to initialize the Molten Salt TES Math Model. All inputs are defined and listed at the beginning of each case. The variables given are FORTRAN names.

3.1 NAMELIST

The inputs to the Molten Salt Thermal Energy Math model are completely on cards. All variables have default values built in which may be overriden by standard IBM/NAMELIST statements. The inputs are free field separated by commas (,). Card column one (1) may not be used, however.

Input for a given case is initiated by the symbol &INPUT, and computation is started when the symbol &END is encountered. For example, input changes are started with a card as follows:

&INPUT√DT = 300.0, CW = 10.0, ...

Input is terminated and case execution begins with the following:

. . . . , XK = 5.0, TØ = 700.00√&END

Where √ represents a blank space. Any variable defined in Section 2.2 may be changed for a given case. Once an input has been modified, it will remain the same for all following cases or until changed again. Figure 3-1 is an example from a recent study.

3.2 INPUT VARIABLES

The inputs are listed here primarily for identification purposes. For a detailed explanation of their significance, refer to Section 2.

```
&INPUT NTU=4.0,DT=200.0,EFFT=0.326,HC=516000.0,TI=1089.0,TAVG=786.0
       DMT=196.0,DMTC=150.0,EFFC=0.9,EFFT1=0.442,CPL=937.0,CPS=937.0
       TMELT=913.0,DT1=111.0,
       NTU=5.7,DT=267.0,EFFT=0.332,HC=539000.0,TO=778.0
       VCD=12.3,ISHAPE=0,IJ=0 &END
&INPUT XK=2. &END
&INPUT XK=7. &END
&INPUT XK=10. &END
```


Case Input

Figure 3-1.

Variable	Default Value		Definition
CDR	0.9		Charge to discharge power ratio
CM	20.0		Manifold allowance in heat exchanger cost - %
CMT1	99000.0		Cost per cubic meter of tubing metal volume - $/meters^3
CMT2	4.92		Cost per meter of tubine metal length - $/meter
CPL	1204.0		Salt heat capacity (liquid) Watt-sec/kg-°K
CPSA	814.1		Salt heat capacity coefficient (solid) - Watt-sec/kg-°K
CPSB	0.2825		Salt heat capacity coefficient (solid) - Watt-sec/kg-°K^2
CSR	1.0		Ratio of wall clearance to inter-tube spacing
CTES	2170.0		Cost per cubic meter of TES media - $/meter^3
CVW	4100.0		Cost per square meter of wall materials - $/meter^2
CW	12.0		Cost per weld - $/weld
DEN	2339.0		Salt density - kg/meter^3
DMT	195.0		Total mass flow rate - kg/sec
DMTC	195.0		Charge condition mass flow rate-kg/sec
DPØ	0.04		Pressure drop criteria
DPØ1	0.07		Pressure drop in heater plus receiver
DT	246.0		Temperature change across the system - °K
DT1	111.0		Pinch point temperature change - °K
EFFC	0.4		Helium circulation system compressor efficiency
EFFT	0.4		Turbine efficiency
HC	5.98×10^5		Salt latent heat of fusion - Watt-sec/kg
HT	6.1		Longest tube length manufactured - meters
IJ	0	=	1 for hexagonal tube spacing
		=	0 for rectangular tube spacing
IPRINT	1		Print indicator
		=	1 Print interim calculations
			0 Print only final results
ISHAPE	0	=	1 for cylindrical vessel crossection
		=	0 for square vessel crossection
NTU	3.0		Number of thermal units

Variable	Default Value	Definition
PD	5.0×10^7	Discharge rate - Watts
PRESS	3.45×10^6	System pressure - Newtons/meter^2
STRESS	3.86×10^7	Allowable stress in tubing material - Newtons/meter^2
TAU	21600.0	Storage time - seconds
TAVG	786.0	Average heater temperature - °K
TI	1111.0	Heater inlet temperature - °K
TMELT	908.0	Salt melt temperature - °K
TØ	833.0	Initial storage temperature - °K
VCD	11.28	Vessel diameter - meters
VIS	0.0017	Salt viscosity - Newton-sec/meter^2
XK	4.3	Salt thermal conductivity - Watts/meter - °K

The program contains several variables which are computed internally, but initial values are needed as a beginning for their iterative solution. If the user wishes to change the starting value and perhaps speed problem solution these are available as inputs.

Variable	Default Value	Definition
C1I	0.98	Ratio of actual to calculated tube numbers
TDI	0.1	Tube diameter - meters
TSI	0.028	Tube spacing - meters

Section 4.

OPERATING INSTRUCTIONS

The computer program exists in the form of card decks and is executed in the batch mode. The source cards are coded in FORTRAN IV language and are compatible with IBM 360/370 computer systems.

Conversion to other computer systems should not be difficult if required. The program uses only standard FORTRAN instructions and there is no machine dependent software used and no known numerical significance concerns. The program should readily adapt to Remote Job Entry (RJE) or time sharing terminals.

4.1 CONTROL CARDS

The program is executed by standard FORTRAN compile, LINKEDIT, and GØ steps run in sequence with IBM Job Control Language (JCL).

In order to resolve installation dependent system difference, JCL procedures (PROCS) exist at all IBM facilities for accomplishing the execution sequence. The example shown below illustrates one of the PROCS used at Boeing System 370 computers and will be similar if not identical elsewhere.

COLUMN 1

```
Card 1        //√EXEC√FØRTHCLG
Card 2        //FORT.SYSIN√DD√*

                ( FORTRAN    )
                (   SOURCE   )
                (            )
Card n        /*
Card n+1      // GØ.SYSIN√DD√*

                ( NAMELIST   )
                (   STATEMENTS)
                (            )
Card last     /*
```

4.2 TIME AND OUTPUT ESTIMATES

The run time for a given case will vary somewhat depending on the number of program iterations required. Experience has shown a typical average to be about 0.2 seconds of central processor time per case. This estimate was obtained using Boeing IBM/370 computers. The FORTRAN compilation required 3.7 seconds and the LINKEDIT step about 0.5 seconds. Obviously, optimum use is achieved when as many cases as possible are grouped together in one program execution. The program generates 3 to 4 pages of output per case, excluding the subroutine compilations.

Section 5.

OUTPUT DESCRIPTION

Output from the Molten Salt Heater Sizing Model consists of (1) the inputs for the case with working fluid properties, (2) the vessel geometry, and (3) the cost data. An output option (IPRINT=1) will cause the program to generate internal output from subroutine EXTUN. The following example is the first case shown in Figure 3-1.

```
          **** INPUTS ****

CDR     =         0.900     CHARGE/DISCHARGE RATIO
CM      =        20.000     MANIFOLD ALLOWANCE IN HEAT EXCHANGER COST - %
CMT1    =     99000.000     COST PER M**3 OF TUBING METAL VOLUME - $/M**3
CMT2    =         4.920     COST PER M OF TUBING METAL LENGTH - $/M
CPL     =       937.000     SALT HEAT CAPICITY (LIQUID) - WATT-SEC/KGM-DEGK
CPSA    =       814.100     SALT HEAT CAP COEFF (SOLID) - WATT-SEC/KGM-DEGK
CPSB    =         0.282     SALT HEAT CAP COEFF (SOLID) - WATT-SEC/KGM-DEGK**2
CSR     =         1.000     RATIO OF WALL CLEARANCE TO INTERTUBE SPACING
CTES    =      2170.000     COST PER M**3 OF TES MEDIA - $/M**3
CVW     =      4100.000     COST PER M**2 OF WALL MATERIALS - $/M**2
CW      =        12.000     COST PER WELD - $/WELD
DEN     =      2339.000     SALT DENSITY - KGM/M**3
DMT     =       196.000     TOTAL MASS FLOW RATE - KGM/SEC
DMTC    =       150.000     CHARGE CONDITION MASS FLOW RATE - KGM-SEC
DPO     =         0.040     PRESSURE DROP CRITERIA
DPO1    =         0.070     PRESSURE DROP IN HEATER + RECIEVER
DT      =       267.000     TEMPERATURE CHANGE ACROSS SYSTEM - DEG K
DT1     =       111.000     PINCH POINT TEMPERATURE CHANGE - DEG K
EFFC    =         0.900     HELIUM CIRCULATION SYSTEM COMPRESSOR EFFICIENCY
EFFT    =         0.332     TURBINE EFFICIENCY
HC      =    539000.000     SALT LATENT HEAT OF FUSION - WATT-SEC/KGM
HT      =         6.100     LONGEST TUBE LENGTH MANUFACTURED - M
IJ      =         0         = 1 HEXAGONAL SPACING OF TUBES
                            = 0 RECTANGULAR SPACING OF TUBES
IPRINT  =         1         PRINTING INDICATOR = 1 PRINT INTERIM CALCULATIONS
                                               = 0 PRINT ONLY FINAL RESULTS
ISHAPE  =         0         = 1 CYLINDRICAL VESSEL CROSSECTION
                            = 0 SQUARE VESSEL CROSSECTION
NTU     =         5.700     NO. OF THERMAL UNITS
PD      =  50000000.000     DISCHARGE RATE - WATTS
PRESS   =   3450000.000     SYSTEM PRESSURE - N/M**2
STRESS  =  38600000.000     ALLOWABLE STRESS IN TUBING MATERAL - N/M**2
TAU     =     21600.000     STORAGE TIME - SEC
TAVG    =       786.000     AVERAGE HEATER TEMPERATURE - DEG K
TI      =      1089.000     HEATER INLET TEMPERATURE - DEG K
TMELT   =       913.000     SALT MELT TEMPERATURE - DEG K
TO      =       778.000     INITIAL STORAGE TEMPERATURE - DEGK
VCD     =        12.300     VESSEL DIAMETER - METERS
VIS     =         0.001700  SALT VISCOSITY - N-SEC/M**2
XK      =         4.300     SALT THERMAL CONDUCTIVITY - WATTS/M-DEGK

          **** INITIAL DEFAULT VALUES ****

C1      =         0.980     RATIO OF ACTUAL TO CALC. TUBE NUMBERS
TD      =         0.100     TUBE DIAMETER - METERS
TS      =         0.028     TUBE SPACING - METERS

          **** HELIUM PROPERTIES AT T =    786.00 ****

XKF     =         0.305     THERMAL CONDUCTIVITY - WATTS/M-DEGK
DENF    =         1.524     DENSITY - KGM/M**3
VISF    =         0.000038  VISCOSITY - N-SEC/KGM-DEGK
CPF     =      5230.000     HEAT CAPACITY - WATT-SEC/KGM-DEGK
GAMMA   =         1.670     RATIO OF SPECIFIC HEATS
```

MI	ALP	XI	MB	SBB	XBB	IPC	NTP
184	0.008	0.070	184	1.000	0.066	16744	33672

VESSEL CROSSECTIONAL SHAPE IS SQUARE
TUBE SPACING PATTERN IS SQUARE

VESSEL CHARACTERISTIC DIMENSION	12.30 METERS
TUBE OUTER DIAMETER	0.00964 METERS
TUBE HALF SPACING	0.02840 METERS
TUBE WALL THICKNESS	0.00065 METERS
TUBE NUMBER	33579
VESSEL HEIGHT	12.09 METERS
HEIGHT/DIAMETER RATIO	0.98
ACTUAL CALCULATED TUBE NO. RATIO	0.98
PRESSURE DROP	3.99 PERCENT
FLUID FLOW VELOCITY	69.95 M/SEC
REYNOLDS NUMBER	23604.98
PRANDTL NUMBER	0.65
NUSSELT NUMBER	52.13
FILM COEFFICIENT	1905.65 WATT/M**2-K
UNIT CONDUCTANCE	476.60 WATT/M**2-K
REQUIRED THERMAL ENERGY	903.61 MEGAWATT-HRS
REQUIRED TES MEDIA MASS	4196558.00 KGM
REQUIRED TES MEDIA VOLUME	1794.17 M**3
TUBING METAL VOLUME	7.41 M**3
NUMBER OF WELDS IN TUBING	33579
TUBING VOLUME	29.61 M**3
DISTANCE FROM WALL TO TUBE C/L	0.07003 METERS
CONSISTANCY RELATION	1.00267
CONVERGENCE CONDITION	1.00278
UA VALUE	5.84 MEGAWATTS/K
REQUIRED HELIUM PUMP SIZE	24.38 MEGAWATTS

**** COST SUMMARY ****

ACCOUNT	QUANTITY	UNIT COST ($/Q)	COST (M$)
TES MEDIA (M**3)	1794.17	2170.00	3.89
STORAGE CONTAINER (M**2)	594.66	4100.00	2.44
HEAT EXCHANGER			
METAL VOLUME (M**3)	7.41	99000.00	0.73
TUBING LENGTH (M)	204831.88	4.92	1.01
NUMBER OF WELDS (NO.)	33579	12.00	0.40
MANIFOLD ALLOWANCE (20%)			0.43
HELIUM CIRCULATION SYSTEM (MW)	24.38	53531.47	1.31
TOTAL			10.21

Section 6.

PROGRAM LISTINGS

```
      BLOCK DATA
C
      COMMON/SALT/C(500)
C
      DATA C      / 500*0.0/
C
      EQUIVALENCE (PI          ,C(  56))
C
      DATA PI     /3.14159 /
C
      EQUIVALENCE (NTU         ,C(   1)),(PD          ,C(   2))
      EQUIVALENCE (TAU         ,C(   3)),(CDR         ,C(   4))
      EQUIVALENCE (TI          ,C(   5)),(DT          ,C(   6))
      EQUIVALENCE (DMT         ,C(   7)),(EFFT        ,C(   8))
      EQUIVALENCE (PRESS       ,C(   9)),(DPO         ,C(  10))
      EQUIVALENCE (XKF         ,C(  11)),(DENF        ,C(  12))
      EQUIVALENCE (VISF        ,C(  13)),(CPF         ,C(  14))
      EQUIVALENCE (XK          ,C(  15)),(DEN         ,C(  16))
      EQUIVALENCE (VIS         ,C(  17)),(CPL         ,C(  18))
      EQUIVALENCE (CPS         ,C(  19)),(HC          ,C(  20))
      EQUIVALENCE (TMELT       ,C(  21)),(XKW         ,C(  22))
      EQUIVALENCE                        (STRESS      ,C(  24))
      EQUIVALENCE (HT          ,C(  25)),(CTES        ,C(  26))
      EQUIVALENCE (CMT1        ,C(  27)),(CMT2        ,C(  28))
      EQUIVALENCE (CMW         ,C(  29)),(CW          ,C(  30))
      EQUIVALENCE (IPRINT      ,C(  31)),(IJ          ,C(  32))
      EQUIVALENCE (CSR         ,C(  33))
      EQUIVALENCE (TDI         ,C(  85)),(TSI         ,C(  86))
      EQUIVALENCE (C1I         ,C(  87))
      EQUIVALENCE (DMTC        ,C(  70)),(EFFC        ,C(  65))
      EQUIVALENCE (CVW         ,C(  68))
      EQUIVALENCE (TAVG        ,C(  88)),(EFFT1       ,C(  89))
      EQUIVALENCE (DT1         ,C(  90)),(DPO1        ,C(  91))
      EQUIVALENCE (CM          ,C(  92))
      EQUIVALENCE (TO          ,C(  94)),(CPSA        ,C(  95))
      EQUIVALENCE (CPSB        ,C(  96))
C
      EQUIVALENCE (VTES        ,C(  34)),(TD          ,C(  35))
      EQUIVALENCE (TS          ,C(  36)),(VCD         ,C(  37))
      EQUIVALENCE (C1          ,C(  38)),(ISHAPE      ,C(  39))
```

```
C
      REAL NTU
C
      DATA NTU,PD,TAU,CDR     / 3.0       ,50000000.,21600.0  ,0.9       /
      DATA TI,DT,DMT,EFFT     / 1111.0    ,246.00   ,195.0    ,0.4       /
      DATA PRESS,DPO,XKF,DENF/ 3450000.0,0.04     ,0.3839   ,1.472     /
      DATA VISF,CPF,XK,DEN    /  4.794E-5,5230.0   ,4.3      ,2339.0    /
      DATA VIS,CPL,CPS,HC     / 0.0017    ,1204.0   ,1204.0   ,598000.0 /
      DATA TMELT,XKW          / 908.0     ,23.3     /
      DATA STRESS,HT,CTES,CM /   3.86E+7,6.1      ,2170.0   , 20.0      /
      DATA CMT1,CMT2,CMW,CW   / 99000.0  ,4.92     ,9500.0   ,12.0      /
      DATA IPRINT,IJ,CSR,CVW /         1,        0,1.0      ,4100.0    /
      DATA TAVG,EFFT1,DT1,DPO1/786.0     ,0.442    ,111.0    ,0.07      /
C
      DATA VTES,TD,TS,VCD     / 1150.0    ,0.0427   ,0.02975  ,11.28     /
      DATA C1,ISHAPE          / 0.98      ,        0/
      DATA TO,CPSA,CPSB       / 833.0     ,814.1    ,0.2825   /
C
      DATA DMTC,EFFC          / 195.0     ,0.4      /
C
      DATA TDI,TSI,C1I        / 0.1       ,0.028    ,0.98     /
C
      END
```

```
      COMMON/SALT/C(500)
C
      EQUIVALENCE (IPASS      ,C(  55))
      EQUIVALENCE (IPASS1     ,C(  58))
      EQUIVALENCE (IPASS2     ,C(  59))
      EQUIVALENCE (IPASS3     ,C(  60))
C
      CALL ERRSET(208,1000,-1,1)
      CALL ERRSET(209,1000,-1,1)
      CALL ERRSET(217,1   ,-1,1)
C
      WRITE(6,1000)
C
      DIMENSION AC    (20)
C
  100 READ(5,1010,END=200)AC
      WRITE(6,1020)AC
C
      GO TO 100
C
  200 REWIND 5
C
C**** OPERATING CONDITIONS INITIALIZATION
C
  300 CALL INITAL(&800)
C
C**** CALCULATE REQUIRED TES MEDIA VOLUME
C
      CALL VOLM
C
C**** SELECT SYSTEM GEOMETRY
C
      IPASS=0
C
      IPASS1=0
      IPASS2=0
      IPASS3=0
C
  500 CALL GEOM
C
```

```
      IPASS=IPASS+1
C
C**** CALCULATE CONVECTIVE FILM COEFFICIENT
C
      CALL FILMCO
C
C**** CALCULATE TUBE SPACING
C
      IPASS1=IPASS1+1
C
      IF(IPASS1.GT.20)CALL UABEND(1)
C
      CALL TUBSPC(&500)
C
C**** PRESSURE LOSS CALCULATION
C
      IPASS1=0
C
      IPASS2=IPASS2+1
C
      IF(IPASS2.GT.100)CALL UABEND(2)
C
      CALL PLOSS(&500)
C
      IPASS2=0
C
      IPASS3=IPASS3+1
C
      IF(IPASS3.GT.10)CALL UABEND(3)
C
      CALL EXTUN(&500)
C
C**** ANALYZE SOLUTION
C
      CALL ANAL
C
C**** SIZE HELIUM CIRCULATION PUMPING
C
      CALL HEPUMP
C
```

```
C**** COST ESTIMATE CALCULATIONS
C
      CALL COST
C
C**** PRINT CASE OUTPUT
C
      CALL OUTPUT
C
      GO TO 300
C
  800 STOP
C
 1000 FORMAT('1')
 1010 FORMAT(20A4)
 1020 FORMAT(1X,20A4)
      END
```

```
      SUBROUTINE ANAL
C
      COMMON/SALT/C(500)
C
      EQUIVALENCE (NT           ,C(   41)),(TD           ,C(   35))
      EQUIVALENCE (HF           ,C(   42)),(TWT          ,C(   47))
      EQUIVALENCE (PI           ,C(   56))
      EQUIVALENCE (VL           ,C(   40)),(VT           ,C(   57))
      EQUIVALENCE (HT           ,C(   25))
      EQUIVALENCE (VW           ,C(   63)),(TL           ,C(   66))
      EQUIVALENCE (VM           ,C(   61)),(NW           ,C(   62))
      EQUIVALENCE (VCD          ,C(   37)),(ISHAPE       ,C(   39))
C
      VM=PI*FLOAT(NT)*VL*(TD*TWT-TWT**2)
C
      NW=NT*INT(VL/HT)
C
      IF(ISHAPE.EQ.0)VW=4.0*VCD*VL
      IF(ISHAPE.EQ.1)VW= PI*VCD*VL
C
C**** VOLUME OCCUPIED BY TUBES
C
      VT=FLOAT(NT)*VL*PI*TD**2/4.0
C
      TL=FLOAT(NT)*HT
C
      RETURN
      END
```

```
      FUNCTION CBRT(X)
C
      IF(X.LT.0.0) GO TO 10
C
      CBRT=X**0.3333333
      RETURN
C
   10 XL=-X
C
      CBRT=-XL**0.3333333
      RETURN
C
      END
```

```
      SUBROUTINE COST
C
      COMMON/SALT/C(500)
C
      EQUIVALENCE (CTES        ,C(  26)),(CMT1        ,C(  27))
      EQUIVALENCE (CMT2        ,C(  28)),(CMW         ,C(  29))
      EQUIVALENCE (CW          ,C(  30)),(VTES        ,C(  34))
      EQUIVALENCE (VM          ,C(  61)),(NT          ,C(  41))
      EQUIVALENCE (NW          ,C(  62)),(VW          ,C(  63))
      EQUIVALENCE (TL          ,C(  66)),(CHP         ,C(  67))
      EQUIVALENCE (PCP         ,C(  69)),(CVW         ,C(  68))
      EQUIVALENCE (CCTES       ,C(  78)),(CCVW        ,C(  79))
      EQUIVALENCE (CPHX1       ,C(  80)),(CPHX2       ,C(  81))
      EQUIVALENCE (CPHX3       ,C(  82)),(CCHP        ,C(  83))
      EQUIVALENCE (CTOTAL      ,C(  84))
      EQUIVALENCE (CM          ,C(  92)),(CCM         ,C(  93))
C
      CCTES=CTES*VTES/1000000.0
C
      CPHX1=CMT1*VM/1000000.0
      CPHX2=CMT2*TL/1000000.0
      CPHX3=CW  *FLOAT(NW)/1000000.0
C
      CCHP=CHP*PCP/1000000.0
C
      CCVW=CVW*VW/1000000.0
C
      CCM =CM*(CPHX1+CPHX2+CPHX3)/100.0
C
      CTOTAL=CCTES+CPHX1+CPHX2+CPHX3+CCHP+CCVW+CCM
C
      RETURN
      END
```

```
      SUBROUTINE CUBIC(A,B,C,D,ANS)
      P=B/A
      Q=C/A
      R=D/A
      P3=P/3.
      AA=(3.*Q-P**2)/3.
      BB=(2.*P**3-9.*P*Q+27.*R)/27.
      TER=AA**3/27.
      TERM=BB**2/4.+TER
      IF(ABS(TERM).GT.0.0  )GO TO 10
C
C**** THREE REAL ROOTS, TWO EQUAL
C
      AB=2.*CBRT(-BB/2.)
      ABB=-AB/2.
C
C**** SELECT POSITIVE ROOT
C
      ANS=AMAX1(AB-P3,ABB-P3)
      RETURN
   10 IF(TERM.LT.0.)GO TO 20
C
C**** ONE REAL ROOT, TWO CONJUGATE IMAGINARY ROOTS
C
      STERM=SQRT(TERM)
      AAA=CBRT(-BB/2.+STERM)
      BBB=CBRT(-BB/2.-STERM)
C
C**** SELECT REAL ROOT
C
      ANS=AAA+BBB-P3
      RETURN
C
C**** THREE REAL, UNEQUAL ROOTS
C
   20 STER=SQRT(-TER)
      THETA=ACOS(-BB/2./STER)
      TE=2.*SQRT(-AA/3.)
      THETA3=THETA/3.
      X1=TE*COS(THETA3)-P3
```

```
          X2=TE*COS(THETA3+2.09439)-P3
          X3=TE*COS(THETA3+4.18879)-P3
C
C**** SELECT SMALLEST POSITIVE ROOT
C
      ANS=AMAX1(X1,X2,X3)
      IF(X1.GT.0.)ANS=AMIN1(ANS,X1)
      IF(X2.GT.0.)ANS=AMIN1(ANS,X2)
      IF(X3.GT.0.)ANS=AMIN1(ANS,X3)
      RETURN
      END
```

```
      SUBROUTINE EXTUN(*)
C
      COMMON/SALT/C(500)
C
      EQUIVALENCE (VCD         ,C(  37)),(TD          ,C(  35))
      EQUIVALENCE (CSR         ,C(  33)),(IJ          ,C(  32))
      EQUIVALENCE (IPRINT      ,C(  31)),(TS          ,C(  36))
      EQUIVALENCE (ISHAPE      ,C(  39)),(BC          ,C(  51))
      EQUIVALENCE (NT          ,C(  41)),(C1          ,C(  38))
      EQUIVALENCE (AC          ,C(  52)),(IPASS3      ,C(  60))
      EQUIVALENCE (PI          ,C(  56))
      EQUIVALENCE (X1          ,C(  74)),(C1C1P       ,C(  76))
C
C**** THIS ROUTINE COMPUTES THE EXACT TUBE NUMBER
C
      IF(IPASS3.EQ.1)C1P=C1
C
C**** INITIALIZATION
C
      M1 =INT((VCD-2.0*CSR*TS)/(TD+2.0*TS))
      XL1=TD+2.0*TS
      DST=2.0*(FLOAT(M1)+CSR)*TS+FLOAT(M1)*TD
      ALP=(VCD-DST)/2.0
      X1 =2.0*TS*CSR+ALP +TD/2.0
C
      IF(IJ.NE.1)GO TO 100
C
      MB =2*M1-1
      SBB=1.0/2.0
      XBB=SQRT(3.0)/2.0*XL1
C
      GO TO 200
C
  100 MB =M1
      SBB=1.0
      XBB=XL1
C
  200 IPC=0
C
      DO 500 I=1,MB
```

```
C
      A=IJ*MOD(I+1,2)
C
      XI=X1+FLOAT(I-1)*SBB*XL1
C
      RB=0.5*VCD-2.0*TS*CSR-ALP
C
      YXI=RB
C
      IF(ISHAPE.EQ.1)YXI=SQRT(RB**2-(XI-RB-X1)**2)
C
      DELTA=YXI/XBB
C
      IP=INT(SBB*(DELTA-A))+INT(A)
C
  500 IPC=IPC+IP
C
      NTP=2*IPC+M1
C
      IF(IPRINT.EQ.0)GO TO 600
C
      IF(IPASS3.EQ.1)WRITE(6,1000)
C
      WRITE(6,1010)M1,ALP,X1,MB,SBB,XBB,IPC,NTP
C
  600 NTB=4.0*BC/PI*AC*VCD**2/(TD+2.0*TS)**2
C
      C1 =FLOAT(NTP)/FLOAT(NTB)
C
      C1C1P=C1/C1P
C
      IF(ABS((C1-C1P)/C1).LT.0.05)RETURN
C
      C1P=C1
C
      RETURN 1
C
 1000 FORMAT('1     M1        ALP          X1          MB          SBB    '
     X        ,'    XBB       IPC          NTP    '/)
 1010 FORMAT( 1X,I6,4X,2F10.3,I6,4X,2F10.3,I6,4X,I6)
```

```
C
      END
```

```
      SUBROUTINE FILMCO
C
      COMMON/SALT/C(500)
C
      EQUIVALENCE (NT          ,C(  41)),(HF          ,C(  42))
      EQUIVALENCE (VISF        ,C(  13)),(STRESS      ,C(  24))
      EQUIVALENCE (PRESS       ,C(   9)),(TD          ,C(  35))
      EQUIVALENCE (VF          ,C(  43)),(RE          ,C(  44))
      EQUIVALENCE (PR          ,C(  45)),(XNU         ,C(  46))
      EQUIVALENCE (TWT         ,C(  47))
      EQUIVALENCE (DENF        ,C(  12)),(CPF         ,C(  14))
      EQUIVALENCE (XKF         ,C(  11)),(DMT         ,C(   7))
      EQUIVALENCE (PI          ,C(  56))
C
C**** THIS ROUTINE COMPUTES THE FLUID FILM COEFFICIENT
C
C
C**** TUBE WALL THICKNESS
C
      TWT=PRESS/STRESS*TD/2.0*1.5
C
C**** FLOW VELOCITY
C
      VF=DMT/FLOAT(NT)*4.0/DENF/PI/(TD-2.0*TWT)**2
C
C**** REYNCLDS NUMBER
C
      RE=VF*(TD-2.0*TWT)/VISF*DENF
C
C**** PRANDTL NUMBER
C
      PR=CPF*VISF/XKF
C
C**** NUSSELT NUMBER
C
      XNU=0.0215*RE**0.8*PR**0.6
C
C**** FILM COEFFICIENT
C
      HF=XNU*XKF/(TD-2.0*TWT)
```

```
C
      RETURN
      END
```

```
      SUBROUTINE GEOM
C
      COMMON/SALT/C(500)
C
      EQUIVALENCE (NTU         ,C(   1)),(DMT          ,C(   7))
      EQUIVALENCE (CPF         ,C(  14)),(TD           ,C(  35))
      EQUIVALENCE (ISHAPE      ,C(  39))
      EQUIVALENCE (C1          ,C(  38)),(VL           ,C(  40))
      EQUIVALENCE (TD          ,C(  35)),(TS           ,C(  36))
      EQUIVALENCE (VCD         ,C(  37)),(UC           ,C(  48))
      EQUIVALENCE (B           ,C(  50)),(IJ           ,C(  32))
      EQUIVALENCE (AC          ,C(  52)),(BC           ,C(  51))
      EQUIVALENCE (VTES        ,C(  34))
      EQUIVALENCE (NT          ,C(  41))
      EQUIVALENCE (PI          ,C(  56))
      EQUIVALENCE (IPASS       ,C(  55))
      EQUIVALENCE (HDR         ,C(  72)),(VLVLC        ,C(  75))
C
      REAL NTU
C
      BC=1.0
C
      IF(ISHAPE.EQ.1)BC=PI/4.0
C
      AC=PI/4.0
C
      IF(IJ.EQ.1)AC=PI*SQRT(3.0)/9.0
C
      NT   =C1*4.0*BC/PI*AC*VCD**2/(TD+2.0*TS)**2
C
      IF(IPASS.EQ.1)RETURN
C
C**** SELECT VESSEL LENGTH
C
      B=NTU*DMT*CPF
C
      VL=B/PI/TD/FLOAT(NT)/UC
C
      VLC=4.0/PI*VTES/(4.0/PI*BC*VCD**2-FLOAT(NT)*TD**2)
C
```

```
      HDR=VL/VCD
      VLVLC=VL/VLC
C
      RETURN
      END
```

```
      SUBROUTINE HEPUMP
C
      COMMON/SALT/C(500)
C
      EQUIVALENCE (TI          ,C(   5)),(CPF         ,C(  14))
      EQUIVALENCE (DPO         ,C(  10)),(PCP         ,C(  69))
      EQUIVALENCE (GAMMA       ,C(  64)),(CHP         ,C(  67))
      EQUIVALENCE (EFFC        ,C(  65)),(DMTC        ,C(  70))
      EQUIVALENCE (TAVG        ,C(  88)),(EFFT1       ,C(  89))
      EQUIVALENCE (DT1         ,C(  90)),(DPO1        ,C(  91))
C
C**** COMPUTE REQUIRED HE PUMPING COMPRESSOR POWER & COST
C
      T1=TI-DT1
C
      PCP1=DMTC*CPF*T1      *((1.0/(1.0-DPO1))**((GAMMA-1.0)/GAMMA)-1.0)
      PCP=PCP1/(EFFC+(1.0/(1.0-DPO1))**((GAMMA-1.0)/GAMMA)-1.0)
C
      CHP =210.0/(PCP/800000.0)**0.4*1.0/1000.0
C
      RETURN
      END
```

```
      SUBROUTINE INITAL(*)
C
      COMMON/SALT/C(500)
C
      EQUIVALENCE (NTU          ,C(   1)),(PD          ,C(   2))
      EQUIVALENCE (TAU          ,C(   3)),(CDR         ,C(   4))
      EQUIVALENCE (TI           ,C(   5)),(DT          ,C(   6))
      EQUIVALENCE (DMT          ,C(   7)),(EFFT        ,C(   8))
      EQUIVALENCE (PRESS        ,C(   9)),(DPO         ,C(  10))
      EQUIVALENCE (XKF          ,C(  11)),(DENF        ,C(  12))
      EQUIVALENCE (VISF         ,C(  13)),(CPF         ,C(  14))
      EQUIVALENCE (XK           ,C(  15)),(DEN         ,C(  16))
      EQUIVALENCE (VIS          ,C(  17)),(CPL         ,C(  18))
      EQUIVALENCE (CPS          ,C(  19)),(HC          ,C(  20))
      EQUIVALENCE (TMELT        ,C(  21)),(XKW         ,C(  22))
      EQUIVALENCE (ISPACE       ,C(  23)),(STRESS      ,C(  24))
      EQUIVALENCE (HT           ,C(  25)),(CTES        ,C(  26))
      EQUIVALENCE (CMT1         ,C(  27)),(CMT2        ,C(  28))
      EQUIVALENCE (CMW          ,C(  29)),(CW          ,C(  30))
      EQUIVALENCE (IPRINT       ,C(  31)),(IJ          ,C(  32))
      EQUIVALENCE (CSR          ,C(  33))
      EQUIVALENCE (VCD          ,C(  37))
      EQUIVALENCE (ISHAPE       ,C(  39))
      EQUIVALENCE (CVW          ,C(  68)),(EFFC        ,C(  65))
      EQUIVALENCE (DMTC         ,C(  70))
      EQUIVALENCE (VTES         ,C(  34)),(TD          ,C(  35))
      EQUIVALENCE (TS           ,C(  36)),(C1          ,C(  38))
      EQUIVALENCE (TDI          ,C(  85)),(TSI         ,C(  86))
      EQUIVALENCE (C1I          ,C(  87))
      EQUIVALENCE (TAVG         ,C(  88)),(EFFT1       ,C(  89))
      EQUIVALENCE (DT1          ,C(  90)),(DPO1        ,C(  91))
      EQUIVALENCE (CM           ,C(  92))
      EQUIVALENCE (TO           ,C(  94)),(CPSA        ,C(  95))
      EQUIVALENCE (CPSB         ,C(  96))
C
      REAL NTU
C
C     CDR            CHARGE/DISCHARGE RATIO
C     CM             MANIFOLD ALLOWANCE IN HEAT EXCHANGER COST - %
C     CMT1           COST PER M**3 OF TUBING METAL VOLUME - $/M**3
```

```
C      CMT2           COST PER M OF TUBING METAL LENGTH - $/M
C      CPL            SALT HEAT CAPICITY (LIQUID) - WATT-SEC/KGM-DEGK
C      CPSA           SALT HEAT CAP COEFF (SOLID) - WATT-SEC/KGM-DEGK
C      CPSB           SALT HEAT CAP COEFF (SOLID) - WATT-SEC/KGM-DEGK**2
C      CSR            RATIO OF WALL CLEARANCE TO INTERTUBE SPACING
C      CTES           COST PER M**3 OF TES MEDIA - $/M**3
C      CVW            COST PER M**2 OF WALL MATERIALS - $/M**2
C      CW             COST PER WELD - $/WELD
C      DEN            SALT DENSITY - KGM/M**3
C      DMT            TOTAL MASS FLOW RATE - KGM/SEC
C      DMTC           CHARGE CONDITION MASS FLOW RATE - KGM-SEC
C      DPO            PRESSURE DROP CRITERIA
C      DPO1           PRESSURE DROP IN HEATER + RECIEVER
C      DT             TEMPERATURE CHANGE ACROSS SYSTEM - DEG K
C      DT1            PINCH POINT TEMPERATURE CHANGE - DEG K
C      EFFC           HELIUM CIRCULATION SYSTEM COMPRESSOR EFFICIENCY
C      EFFT           TURBINE EFFICIENCY
C      HC             SALT LATENT HEAT OF FUSION - WATT-SEC/KGM
C      HT             LONGEST TUBE LENGTH MANUFACTURED - M
C      IJ             = 1 HEXAGONAL SPACING OF TUBES
C                     = 0 RECTANGULAR SPACING OF TUBES
C      IPRINT         PRINTING INDICATOR = 1 PRINT INTERIM CALCULATIONS
C                                        = 0 PRINT ONLY FINAL RESULTS
C      ISHAPE         = 1 CYLINDRICAL VESSEL CROSSECTION
C                     = 0 SQUARE VESSEL CROSSECTION
C      NTU            NO. OF THERMAL UNITS
C      PD             DISCHARGE RATE - WATTS
C      PRESS          SYSTEM PRESSURE - N/M**2
C      STRESS         ALLOWABLE STRESS IN TUBING MATERAL - N/M**2
C      TAU            STORAGE TIME - SEC
C      TAVG           AVERAGE HEATER TEMPERATURE - DEG K
C      TI             HEATER INLET TEMPERATURE - DEC K
C      TMELT          SALT MELT TEMPERATURE - DEG K
C      TO             INITIAL STORAGE TEMPERATURE - DEGK
C      VCD            VESSEL DIAMETER - METERS
C      VIS            SALT VISCOSITY - N-SEC/M**2
C      XK             SALT THERMAL CONDUCTIVITY - WATTS/M-DEGK
C
C      ******  DEFAULT VALUES  ******
C
```

```
C      C1              DEFAULT VALUE OF RATIO OF ACTUAL/CALC TUBE NO
C      TD              DEFAULT VALUE OF TUBE DIAMETER - M
C      TS              DEFAULT VALUE OF TUBE SPACING - M
C
      DIMENSION ID1  (13),ID2  (13),ID3  (13),ID4  (13),ID5  (13)
      DIMENSION ID6  (13),ID7  (13),ID8  (13),ID9  (13),ID10 (13)
      DIMENSION ID11 (13),ID12 (13),ID13 (13),ID14 (13),ID15 (13)
      DIMENSION ID16 (13),ID17 (13),ID18 (13),ID19 (13),ID20 (13)
      DIMENSION ID21 (13),ID22 (13),ID23 (13),ID24 (13),ID25 (13)
      DIMENSION ID26 (13),ID27 (13),ID28 (13),ID29 (13),ID30 (13)
      DIMENSION ID31 (13),ID32 (13),ID33 (13),ID34 (13),ID35 (13)
      DIMENSION ID36 (13),ID37 (13),ID38 (13),ID39 (13),ID40 (13)
C
      DIMENSION ID291(13),ID301(13),ID311(13)
C
      DATA ID1  /'  NO. OF THERMAL UNITS                                   '/
      DATA ID2  /'  DISCHARGE RATE - WATTS                                 '/
      DATA ID3  /'  STORAGE TIME - SEC                                     '/
      DATA ID4  /'  CHARGE/DISCHARGE RATIO                                 '/
      DATA ID5  /'  HEATER INLET TEMPERATURE - DEG K                       '/
      DATA ID6  /'  TEMPERATURE CHANGE ACROSS SYSTEM - DEG K               '/
      DATA ID7  /'  TOTAL MASS FLOW RATE - KGM/SEC                         '/
      DATA ID8  /'  CHARGE CONDITION MASS FLOW RATE - KGM-SEC              '/
      DATA ID9  /'  HELIUM CIRCULATION SYSTEM COMPRESSOR EFFICIENCY        '/
      DATA ID10 /'  TURBINE EFFICIENCY                                     '/
      DATA ID11 /'  SYSTEM PRESSURE - N/M**2                               '/
      DATA ID12 /'  PRESSURE DROP CRITERIA                                 '/
      DATA ID13 /'  MANIFOLD ALLOWANCE IN HEAT EXCHANGER COST - %          '/
      DATA ID14 /'  SALT THERMAL CONDUCTIVITY - WATTS/M-DEGK               '/
      DATA ID15 /'  SALT DENSITY - KGM/M**3                                '/
      DATA ID16 /'  SALT VISCOSITY - N-SEC/M**2                            '/
      DATA ID17 /'  SALT HEAT CAPICITY (LIQUID) - WATT-SEC/KGM-DEGK        '/
      DATA ID18 /'  SALT HEAT CAP COEFF (SOLID) - WATT-SEC/KGM-DEGK        '/
      DATA ID19 /'  SALT LATENT HEAT OF FUSION - WATT-SEC/KGM              '/
      DATA ID20 /'  SALT MELT TEMPERATURE - DEG K                          '/
      DATA ID21 /'  ALLOWABLE STRESS IN TUBING MATERAL - N/M**2            '/
      DATA ID22 /'  LONGEST TUBE LENGTH MANUFACTURED - M                   '/
      DATA ID23 /'  COST PER M**3 OF TES MEDIA - $/M**3                    '/
      DATA ID24 /'  COST PER M**3 OF TUBING METAL VOLUME - $/M**3          '/
      DATA ID25 /'  COST PER M OF TUBING METAL LENGTH - $/M                '/
```

```
      DATA ID26 /'  INITIAL STORAGE TEMPERATURE - DEGK                      '/
      DATA ID27 /'  COST PER WELD - $/WELD                                  '/
      DATA ID28 /'  COST PER M**2 OF WALL MATERIALS - $/M**2                '/
      DATA ID29 /'  PRINTING INDICATOR = 1 PRINT INTERIM CALCULATIONS '/
      DATA ID291/'                     = 0 PRINT ONLY FINAL RESULTS   '/
      DATA ID30 /'  = 1 HEXAGONAL SPACING OF TUBES                          '/
      DATA ID301/'  = 0 RECTANGULAR SPACING OF TUBES                        '/
      DATA ID31 /'  = 1 CYLINDRICAL VESSEL CROSSECTION                      '/
      DATA ID311/'  = 0 SQUARE VESSEL CROSSECTION                           '/
      DATA ID32 /'  RATIO OF WALL CLEARANCE TO INTERTUBE SPACING            '/
      DATA ID33 /'  VESSEL DIAMETER - METERS                                '/
      DATA ID34 /'  TUBE DIAMETER - METERS                                  '/
      DATA ID35 /'  TUBE SPACING - METERS                                   '/
      DATA ID36 /'  RATIO OF ACTUAL TO CALC. TUBE NUMBERS                   '/
      DATA ID37 /'  AVERAGE HEATER TEMPERATURE - DEG K                      '/
      DATA ID38 /'  SALT HEAT CAP COEFF (SOLID) - WATT-SEC/KGM-DEGK**2'/
      DATA ID39 /'  PINCH POINT TEMPERATURE CHANGE - DEG K                  '/
      DATA ID40 /'  PRESSURE DROP IN HEATER + RECIEVER                      '/
C
      NAMELIST/INPUT/NTU   ,PD    ,TAU   ,CDR   ,TI    ,DT    ,DMT
     X              ,EFFT  ,PRESS ,DPO   ,XKF   ,DENF  ,VISF  ,CPF
     X              ,XK    ,DEN   ,VIS   ,CPL   ,CPS   ,HC    ,TMELT
     X              ,XKW   ,ISHAPE,STRESS,HT    ,CTES  ,CMT1  ,CMT2
     X              ,CMW   ,CW    ,IPRINT,IJ    ,CSR   ,VCD   ,DMTC
     X              ,EFFC  ,CVW   ,TAVG  ,EFFT1 ,DT1   ,DPO1  ,CM
     X              ,TO    ,CPSA  ,CPSB  ,C1I   ,TDI   ,TSI
C
      READ(5,INPUT,END=800)
C
      WRITE(6,1005)
C
      WRITE(6,1040)CDR   ,ID4
      WRITE(6,1130)CM    ,ID13
      WRITE(6,1240)CMT1  ,ID24
      WRITE(6,1250)CMT2  ,ID25
      WRITE(6,1170)CPL   ,ID17
      WRITE(6,1180)CPSA  ,ID18
      WRITE(6,1380)CPSB  ,ID38
      WRITE(6,1320)CSR   ,ID32
      WRITE(6,1230)CTES  ,ID23
```

```
      WRITE(6,1280)CVW   ,ID28
      WRITE(6,1270)CW    ,ID27
      WRITE(6,1150)DEN   ,ID15
      WRITE(6,1070)DMT   ,ID7
      WRITE(6,1080)DMTC  ,ID8
      WRITE(6,1120)DPO   ,ID12
      WRITE(6,1370)DPO1  ,ID40
      WRITE(6,1060)DT    ,ID6
      WRITE(6,1360)DT1   ,ID39
      WRITE(6,1090)EFFC  ,ID9
      WRITE(6,1100)EFFT  ,ID10
      WRITE(6,1190)HC    ,ID19
      WRITE(6,1220)HT    ,ID22
      WRITE(6,1300)IJ    ,ID30,ID301
      WRITE(6,1290)IPRINT,ID29,ID291
      WRITE(6,1310)ISHAPE,ID31,ID311
      WRITE(6,1010)NTU   ,ID1
      WRITE(6,1020)PD    ,ID2
      WRITE(6,1110)PRESS ,ID11
      WRITE(6,1210)STRESS,ID21
      WRITE(6,1030)TAU   ,ID3
      WRITE(6,1340)TAVG  ,ID37
      WRITE(6,1050)TI    ,ID5
      WRITE(6,1200)TMELT ,ID20
      WRITE(6,1260)TD    ,ID26
      WRITE(6,1330)VCD   ,ID33
      WRITE(6,1160)VIS   ,ID16
      WRITE(6,1140)XK    ,ID14
C
      TD=TDI
      TS=TSI
      C1=C1I
C
      WRITE(6,1500)
      WRITE(6,1530)C1    ,ID36
      WRITE(6,1510)TD    ,ID34
      WRITE(6,1520)TS    ,ID35
C
C**** COMPUTE WORKING FLUID PROPERTIES
C
```

```
      CALL PROPFL
C
      RETURN
C
  800 RETURN 1
C
 1005 FORMAT('1          **** INPUTS ****',/)
 1010 FORMAT(' NTU    = ',F13.3,3X,13A4)
 1020 FORMAT(' PD     = ',F13.3,3X,13A4)
 1030 FORMAT(' TAU    = ',F13.3,3X,13A4)
 1040 FORMAT(' CDR    = ',F13.3,3X,13A4)
 1050 FORMAT(' TI     = ',F13.3,3X,13A4)
 1060 FORMAT(' DT     = ',F13.3,3X,13A4)
 1070 FORMAT(' DMT    = ',F13.3,3X,13A4)
 1080 FORMAT(' DMTC   = ',F13.3,3X,13A4)
 1090 FORMAT(' EFFC   = ',F13.3,3X,13A4)
 1100 FORMAT(' EFFT   = ',F13.3,3X,13A4)
 1110 FORMAT(' PRESS  = ',F13.3,3X,13A4)
 1120 FORMAT(' DPO    = ',F13.3,3X,13A4)
 1130 FORMAT(' CM     = ',F13.3,3X,13A4)
 1140 FORMAT(' XK     = ',F13.3,3X,13A4)
 1150 FORMAT(' DEN    = ',F13.3,3X,13A4)
 1160 FORMAT(' VIS    = ',F13.6,3X,13A4)
 1170 FORMAT(' CPL    = ',F13.3,3X,13A4)
 1180 FORMAT(' CPSA   = ',F13.3,3X,13A4)
 1190 FORMAT(' HC     = ',F13.3,3X,13A4)
 1200 FORMAT(' TMELT  = ',F13.3,3X,13A4)
 1210 FORMAT(' STRESS = ',F13.3,3X,13A4)
 1220 FORMAT(' HT     = ',F13.3,3X,13A4)
 1230 FORMAT(' CTES   = ',F13.3,3X,13A4)
 1240 FORMAT(' CMT1   = ',F13.3,3X,13A4)
 1250 FORMAT(' CMT2   = ',F13.3,3X,13A4)
 1260 FORMAT(' TO     = ',F13.3,3X,13A4)
 1270 FORMAT(' CW     = ',F13.3,3X,13A4)
 1280 FORMAT(' CVW    = ',F13.3,3X,13A4)
 1290 FORMAT(' IPRINT = ',I9,4X,3X,13A4,/26X,13A4)
 1300 FORMAT(' IJ     = ',I9,4X,3X,13A4,/26X,13A4)
 1310 FORMAT(' ISHAPE = ',I9,4X,3X,13A4,/26X,13A4)
 1320 FORMAT(' CSR    = ',F13.3,3X,13A4)
 1330 FORMAT(' VCD    = ',F13.3,3X,13A4)
```

```
 1340 FORMAT(' TAVG    = ',F13.3,3X,13A4)
 1360 FORMAT(' DT1     = ',F13.3,3X,13A4)
 1370 FORMAT(' DPQ1    = ',F13.3,3X,13A4)
 1380 FORMAT(' CPSB    = ',F13.3,3X,13A4)
 1500 FORMAT(/ '                **** INITIAL DEFAULT VALUES ****',/)
 1510 FORMAT(' TD      = ',F13.3,3X,13A4)
 1520 FORMAT(' TS      = ',F13.3,3X,13A4)
 1530 FORMAT(' C1      = ',F13.3,3X,13A4)
C
      END
```

```
      SUBROUTINE OUTPUT
C
      COMMON/SALT/C(500)
C
      EQUIVALENCE (ISHAPE     ,C(  39)),(IJ          ,C(  32))
      EQUIVALENCE (VCD        ,C(  37)),(TD          ,C(  35))
      EQUIVALENCE (TS         ,C(  36)),(TWT         ,C(  47))
      EQUIVALENCE (NT         ,C(  41)),(C1          ,C(  38))
      EQUIVALENCE (VF         ,C(  43)),(RE          ,C(  44))
      EQUIVALENCE (PR         ,C(  45)),(XNU         ,C(  46))
      EQUIVALENCE (HF         ,C(  42)),(UC          ,C(  48))
      EQUIVALENCE (VM         ,C(  61)),(VT          ,C(  57))
      EQUIVALENCE (VTES       ,C(  34)),(NW          ,C(  62))
      EQUIVALENCE (B          ,C(  50))
      EQUIVALENCE (HDR        ,C(  72)),(VLVLC       ,C(  75))
      EQUIVALENCE (X1         ,C(  74)),(C1C1P       ,C(  76))
      EQUIVALENCE (RTE        ,C(  71))
      EQUIVALENCE (DP         ,C(  73))
      EQUIVALENCE (XM         ,C(  77))
      EQUIVALENCE (CCTES      ,C(  78)),(CCVW        ,C(  79))
      EQUIVALENCE (CPHX1      ,C(  80)),(CPHX2       ,C(  81))
      EQUIVALENCE (CPHX3      ,C(  82)),(CCHP        ,C(  83))
      EQUIVALENCE (CTOTAL     ,C(  84))
      EQUIVALENCE (VW         ,C(  63)),(CTES        ,C(  26))
      EQUIVALENCE (CVW        ,C(  68)),(CMT1        ,C(  27))
      EQUIVALENCE (CMT2       ,C(  28)),(CW          ,C(  30))
      EQUIVALENCE (CHP        ,C(  67)),(PCP         ,C(  69))
      EQUIVALENCE (TL         ,C(  66))
      EQUIVALENCE (VL         ,C(  40))
      EQUIVALENCE (CM         ,C(  92)),(CCM         ,C(  93))
C
      DIMENSION ISO   (6),IJO   (6)
C
      DATA ISO  /'SQUA','RE  ','    ','CYLI','NDRI','CAL '/
      DATA IJO  /'SQUA','RE  ','    ','HEXA','GONA','L   '/
C
      WRITE(6,1000)
C
      IF(ISHAPE.EQ.0)IS1=1
      IF(ISHAPE.EQ.1)IS1=4
```

```
      IF(IJ    .EQ.0)IS2=1
      IF(IJ    .EQ.1)IS2=4
C
      WRITE(6,1010)ISO(IS1),ISO(IS1+1),ISO(IS1+2)
      WRITE(6,1020)IJO(IS2),IJO(IS2+1),IJO(IS2+2)
C
      WRITE(6,1030)VCD
      WRITE(6,1040)TD
      WRITE(6,1050)TS
      WRITE(6,1060)TWT
      WRITE(6,1070)NT
      WRITE(6,1080)VL
      WRITE(6,1090)HDR
      WRITE(6,1110)C1
C
      DPO=DP*100.0
C
      WRITE(6,1100)DPO
C
      WRITE(6,1120)VF
      WRITE(6,1130)RE
      WRITE(6,1140)PR
      WRITE(6,1150)XNU
      WRITE(6,1160)HF
      WRITE(6,1170)UC
C
      RTO=RTE/1000000.0/3600.0
C
      WRITE(6,1180)RTO
      WRITE(6,1190)XM
      WRITE(6,1200)VTES
      WRITE(6,1210)VM
C
      WRITE(6,1220)NW
      WRITE(6,1230)VT
      WRITE(6,1240)X1
      WRITE(6,1250)VLVLC
      WRITE(6,1260)C1C1P
C
      BO=B/1000000.0
```

```
C
      WRITE(6,1270)BO
C
      PCPO=PCP/1000000.0
      CHPC=CHP*1000000.0
C
      WRITE(6,1280)PCPO
C
      WRITE(6,1500)
      WRITE(6,1510)
C
      ICCM= CM+0.0001
C
      WRITE(6,1520)VTES,CTES,CCTES
      WRITE(6,1530)VW,CVW,CCVW
      WRITE(6,1540)
      WRITE(6,1550)VM,CMT1,CPHX1
      WRITE(6,1560)TL,CMT2,CPHX2
      WRITE(6,1570)NW,CW,CPHX3
      WRITE(6,1575)ICCM,CCM
      WRITE(6,1580)PCPO,CHPO,CCHP
      WRITE(6,1590)CTOTAL
C
      RETURN
C
 1000 FORMAT('1')
 1010 FORMAT('OVESSEL CROSSECTIONAL SHAPE IS ',3A4)
 1020 FORMAT(' TUBE SPACING PATTERN IS ',3A4)
 1030 FORMAT('OVESSEL CHARACTERISTIC DIMENSION    ',F13.2,' METERS')
 1040 FORMAT(' TUBE OUTER DIAMETER                ',F13.5,' METERS')
 1050 FORMAT(' TUBE HALF SPACING                  ',F13.5,' METERS')
 1060 FORMAT(' TUBE WALL THICKNESS                ',F13.5,' METERS')
 1070 FORMAT(' TUBE NUMBER                        ',I13)
 1080 FORMAT(' VESSEL HEIGHT                      ',F13.2,' METERS')
 1090 FORMAT(' HEIGHT/DIAMETER RATIO              ',F13.2)
 1100 FORMAT(' PRESSURE DROP                      ',F13.2,' PERCENT')
 1110 FORMAT(' ACTUAL CALCULATED TUBE NO. RATIO   ',F13.2)
 1120 FORMAT('OFLUID FLOW VELOCITY                ',F13.2,' M/SEC')
 1130 FORMAT(' REYNOLDS NUMBER                    ',F13.2)
 1140 FORMAT(' PRANDTL NUMBER                     ',F13.2)
```

```
 1150 FORMAT(' NUSSELT NUMBER                                 ',F13.2)
 1160 FORMAT(' FILM COEFFICIENT                               ',F13.2,' WATT',
     X       '/M**2-K')
 1170 FORMAT(' UNIT CONDUCTANCE                               ',F13.2,' WATT',
     X       '/M**2-K')
 1180 FORMAT(' REQUIRED THERMAL ENERGY                        ',F13.2,' MEGAWATT',
     X       '-HRS')
 1190 FORMAT(' REQUIRED TES MEDIA MASS                        ',F13.2,' KGM')
 1200 FORMAT(' REQUIRED TES MEDIA VOLUME                      ',F13.2,' M**3')
 1210 FORMAT(' TUBING METAL VOLUME                            ',F13.2,' M**3')
 1220 FORMAT(' NUMBER OF WELDS IN TUBING                      ',I13)
 1230 FORMAT(' TUBING VOLUME                                  ',F13.2,' M**3')
 1240 FORMAT(' DISTANCE FROM WALL TO TUBE C/L                 ',F13.5,' METERS')
 1250 FORMAT(' CONSISTANCY RELATION                           ',F13.5)
 1260 FORMAT(' CONVERGENCE CONDITION                          ',F13.5)
 1270 FORMAT(' UA VALUE                                       ',F13.2,' MEGAWATTS',
     X       '/K  ')
 1280 FORMAT(' REQUIRED HELIUM PUMP SIZE                      ',F13.2,' MEGAWATTS')
C
 1500 FORMAT('1          **** COST SUMMARY ****')
 1510 FORMAT('0ACCOUNT',30X,'QUANTITY      UNIT COST ($/Q)  COST (M$)')
 1520 FORMAT('0TES MEDIA (M**3)                   ',3F15.2)
 1530 FORMAT('0STORAGE CONTAINER (M**2)           ',3F15.2)
 1540 FORMAT('0HEAT EXCHANGER                     ')
 1550 FORMAT('     METAL VOLUME (M**3)            ',3F15.2)
 1560 FORMAT('     TUBING LENGTH (M)              ',3F15.2)
 1570 FORMAT('     NUMBER OF WELDS (NO.)          ',I15,2F15.2)
 1575 FORMAT('     MANIFOLD ALLOWANCE (',I2,'%) ',30X,F15.2)
 1580 FORMAT('0HELIUM CIRCULATION SYSTEM (MW)',3F15.2)
 1590 FORMAT('0TOTAL                              ',30X,F15.2)
C
      END
```

```
      SUBROUTINE PLOSS(*)
C
      COMMON/SALT/C(500)
C
      EQUIVALENCE (DPO         ,C(  10)),(VL          ,C(  40))
      EQUIVALENCE (VF          ,C(  43)),(RE          ,C(  44))
      EQUIVALENCE (DENF        ,C(  12)),(PRESS       ,C(   9))
      EQUIVALENCE (TD          ,C(  35)),(TWT         ,C(  47))
      EQUIVALENCE (HT          ,C(  25)),(UC          ,C(  48))
      EQUIVALENCE (IPASS2      ,C(  59))
      EQUIVALENCE (DP          ,C(  73))
C
      F=0.3164/RE**0.25
C
C**** PRESSURE LOSS
C
      DP =0.5*DENF/PRESS*VF**2*F*VL/(TD-2.0*TWT)
C
      IF(IPASS2.GT.1)GO TO 50
C
      IF(DP.LT.DPO)ISTEP=1
      IF(DP.LT.DPO)STEP=0.9
      IF(DP.GT.DPO)ISTEP=2
      IF(DP.GT.DPO)STEP=1.1
C
   50 GO TO (100,200,300),ISTEP
C
  100 IF(DP.GT.DPO)GO TO 300
C
      TDP=TD
      TDP=TD
      DPP=DP
      TD =TD*STEP
C
      RETURN 1
C
  200 IF(DP.LT.DPO)GO TO 300
C
      TDP=TD
      TDP=TD
```

```
      DPP=DP
      TD =TD*STEP
C
      RETURN 1
C
  300 TDPR=TD+(TDP-TD)*(DP-DPO)/(DP-DPP)
C
      DPP=DP
      TDP=TD
      TD=TDPR
C
      IF(ABS((TDP-TDPR)/TDPR).LT.0.001)GO TO 400
C
      ISTEP=3
C
      RETURN 1
C
  400 RETURN
C
      END
```

```
      SUBROUTINE PROPFL
C
      COMMON/SALT/C(500)
C
      EQUIVALENCE (TI         ,C(   5)),(PRESS      ,C(   9))
      EQUIVALENCE (DENF       ,C(  12)),(VISF       ,C(  13))
      EQUIVALENCE (CPF        ,C(  14)),(GAMMA      ,C(  64))
      EQUIVALENCE (XKF        ,C(  11))
      EQUIVALENCE (TAVG       ,C(  88))
C
      DIMENSION TA    (6)
      DIMENSION XKFA  (6)
      DIMENSION VISFA (6)
C
      DATA TA   /555.56   ,694.56   ,833.33   ,972.22   ,1111.11 ,1255.55 /
      DATA XKFA /0.2386   ,0.2801   ,0.3182   ,0.3545   ,0.3839   ,0.4150   /
      DATA VISFA/2.976E-5,3.472E-5,3.926E-5,4.381E-5,4.794E-5,5.208E-5/
C
      DATA NPTS /    6/
C
      GAMMA=1.67
      CPF  =5230.0
C
      R=8314.0
      AW=4.0
C
      DENF=PRESS/R/TI*AW
C
      XKF =TABLE1(TA,XKFA ,NPTS,TAVG)
      VISF=TABLE1(TA,VISFA,NPTS,TAVG)
C
      DIMENSION ID1  (13),ID2  (13),ID3  (13),ID4  (13),ID5  (13)
C
      DATA ID1  /'  THERMAL CONDUCTIVITY - WATTS/M-DEGK                  '/
      DATA ID2  /'  DENSITY - KGM/M**3                                   '/
      DATA ID3  /'  VISCOSITY - N-SEC/KGM-DEGK                           '/
      DATA ID4  /'  HEAT CAPACITY - WATT-SEC/KGM-DEGK                    '/
      DATA ID5  /'  RATIO OF SPECIFIC HEATS                              '/
C
      WRITE(6,1000)TAVG
```

```
      WRITE(6,1010)XKF    ,ID1
      WRITE(6,1020)DENF   ,ID2
      WRITE(6,1030)VISF   ,ID3
      WRITE(6,1040)CPF    ,ID4
      WRITE(6,1050)GAMMA  ,ID5
C
 1000 FORMAT('0           **** HELIUM PROPERTIES AT T =',F10.2,' ****'/)
 1010 FORMAT(' XKF     = ',F13.3,3X,13A4)
 1020 FORMAT(' DENF    = ',F13.3,3X,13A4)
 1030 FORMAT(' VISF    = ',F13.6,3X,13A4)
 1040 FORMAT(' CPF     = ',F13.3,3X,13A4)
 1050 FORMAT(' GAMMA   = ',F13.3,3X,13A4)
C
      RETURN
      END
```

```
      FUNCTION TABLE1(X,Y,N,AX)
      DIMENSION X(1),Y(1)
C
      I=1
      IF(AX-X(I))40,40,80
   40 I=2
      GO TO 110
   80 IF(I-N)100,90,90
   90 SL=(Y(N)-Y(N-1))/(X(N)-X(N-1))
      TABLE1=SL*(AX-X(N))+Y(N)
      RETURN
  100 I=I+1
      IF(AX-X(I))110,110,80
  110 SL=(Y(I)-Y(I-1))/(X(I)-X(I-1))
      TABLE1=SL*(AX-X(I-1))+Y(I-1)
      RETURN
      END
```

```
      SUBROUTINE TUBSPC(*)
C
      COMMON/SALT/C(500)
C
      EQUIVALENCE (HF          ,C(  42)),(TWT         ,C(  47))
      EQUIVALENCE (UC          ,C(  48)),(TD          ,C(  35))
      EQUIVALENCE (XK          ,C(  15)),(TST         ,C(  49))
      EQUIVALENCE (B           ,C(  50)),(BC          ,C(  51))
      EQUIVALENCE (AC          ,C(  52)),(VTES        ,C(  34))
      EQUIVALENCE (TS          ,C(  36)),(IPASS       ,C(  55))
      EQUIVALENCE (HF          ,C(  42)),(C1          ,C(  38))
      EQUIVALENCE (IPASS       ,C(  55))
      EQUIVALENCE (PI          ,C(  56))
      EQUIVALENCE (XKW         ,C(  22))
C
      DATA TSP   /  0.0/
C
C**** THIS ROUTINE COMPUTES TUBE SPACING - TS
C
C
      IF(IPASS.GT.1)GO TO 100
C
C**** MAKE INITAL ESTIMATE OF TS
C
      A1=2.0/XK
      A2=2.0*TD/XK+4.0*(1.0/HF-TST/XKW)
      A3=TD**2/2.0/TD+4.0*TD*(1.0/HF-TST/XKW)-PI*AC*TD**2/4.0/BC/2.0/XK
      A4=TD**2*(1.0/HF+TWT/XKW)-PI*AC*TD**2/4.0/BC-PI*TD*AC*VTES/B/BC
C
      CALL CUBIC(A1,A2,A3,A4,TS)
C
C
  100 T1=TD-2.0*TWT
      T2=SQRT(TD**2+T1**2)
C
      XL1=ALOG(T2/T1/2.0**0.5)
      XL2=ALOG(2.0**0.5*TD/T2)
C
      T3=SQRT(TD**2+(TD+2.0*TS)**2)
C
```

```
      XL3=ALOG(T3/TD/2.0**0.5)
C
C**** COMPUTE UNIT CONDUCTANCE
C
      UC=1.0/(1.0/HF+T1/2.0/XKW*(XL1+XL2)+T1/2.0/XK*XL3)
C
      TD2S2=C1*AC*TD**2+(4.0*TD*C1*AC*VTES)/B*UC
C
      TS =(SQRT(TD2S2)-TD)/2.0
C
      IF(ABS((TS-TSP)/TS).LT.0.00005)RETURN
C
      TSP=TS
C
      RETURN 1
C
      END
```

```
      SUBROUTINE VOLM
C
      COMMON/SALT/C(500)
C
      EQUIVALENCE (PD          ,C(   2)),(TAU         ,C(   3))
      EQUIVALENCE (EFFT        ,C(   8)),(HC          ,C(  20))
      EQUIVALENCE (VTES        ,C(  34)),(DEN         ,C(  16))
      EQUIVALENCE (CPL         ,C(  18)),(CPS         ,C(  19))
      EQUIVALENCE (DT          ,C(   6))
      EQUIVALENCE (RTE         ,C(  71))
      EQUIVALENCE (XM          ,C(  77))
      EQUIVALENCE (TO          ,C(  94)),(CPSA        ,C(  95))
      EQUIVALENCE (CPSB        ,C(  96))
      EQUIVALENCE (TMELT       ,C(  21))
C
C**** COMPUTE REQUIRED TES MEDIA VOLUME
C
C**** REQUIRED THERMAL ENERGY (RTE)
C
      RTE=PD*TAU/EFFT
C
C**** TES MEDIA MASS
C
      DCP=CPL-CPSA-CPSB/2.0*(TMELT-TO)
C
      XM=RTE/(HC+CPL*DT-(TMELT-TO)*DCP)
C
C**** TES MEDIA VOLUME
C
      VTES=XM/DEN
C
      RETURN
      END
```

1117 CARDS

APPENDIX I

KIRCHKOFF CORRECTION TO EUTECTIC HEAT OF FUSION

The heat of fusion for molten salt eutectics are often calculated on the basis of a mole average of the heat of fusion of the constituent salts. Significant errors can be encountered for eutectic melt temperatures significantly removed from the constituent salt melt temperatures. Kirchkoff's Law can be applied to correct the eutectic salt heat of fusion. Kirchkoff's Law can be stated as:

> If a reaction originally takes place at a temperature T_1 and has a heat of reaction of H_{T1} at that temperature, then the heat of reaction at some other temperature T_2 is given by

$$\Delta H_{T_2} = \Delta H_{T_1} + \int_{T_1}^{T_2} \Delta C_p \, dT \qquad \text{(I-1)}$$

Applying this law to a two-component eutectic salt yields (I-2)

$$h_e = x_A h_A + x_B h_B + X_A \int_{T_e}^{T_A} (C_{PA}(S) - C_{PA}(\ell))dT + X_B \int_{T_e}^{T_B} (C_{PB}(S) - C_{PB}(\ell))dT$$

where h_A, h_B ≡ component salt heats of fusion, T_A, T_B ≡ component salt melt temperatures, $Cp_A(s)$, $Cp_B(s)$ solid heat capacity of components, $Cp_A(\ell)$, $Cp_B(\ell)$ ≡ liquid heat capacity of components, T_e ≡ eutectic melt temperature, X_A, X_B ≡ mole fraction of component salts in eutectic mixture.

The heat capacity can be expressed as

$$C_p = a + bT + cT^{-2} \qquad \text{(I-3)}$$

Defining I by

$$I = X\int_{Te}^{T} C_p \, dT = X\int_{T_e}^{T} (a+bT+cT^{-2})dT$$

$$= X\left[a\,(T-T_e) + \frac{b}{2}(T^2 - T_e^2) + c\,(T_e^{-1} - T^{-1})\right]$$

Then eqn. (I-2) yields

$$h_e = x_A h_A + x_B h_B + I_A^S - I_A^\ell + I_B^S - I_B^\ell \qquad (I-4)$$

Values for h, a, b, c for various salts are available in the literature.* Characteristically, b, c are zero for liquid component salts.

This same methodology should be extendable to three component eutectic mixtures:

$$h_e = x_A h_A + x_B h_B + x_C h_C + I_A^S - I_A^\ell + I_B^S - I_B^\ell + I_C^S - I_C^\ell \qquad (I-5)$$

Sample results for calculation on a two-component salt are shown below:

Table I-1
SAMPLE RESULTS

Salt	Melt temperature	Molecular weight	a_s	$b_s \times 10^3$	$c_s \times 10^{-5}$	$C_p (\ell)$	h	x
	(^oC)	(g/mole)	$\left(\frac{cal}{mole\ ^oC}\right)$	$\left(\frac{cal}{mole\ (^oC)^2}\right)$	$\left(\frac{cal\ (^oC)^2}{mole}\right)$	$\left(\frac{cal}{mole\ ^oC}\right)$	$\left(\frac{cal}{mole}\right)$	(%)
NaF	1268	41.99	10.4	3.88	-0.33	16.4	8030	40.5
KF	1131	58.1	11.88	2.22	-0.72	16.0	6750	59.5
40.5 NaF/ 59.5 KF	983	51.58					6860	

The heat of fusion of the 40.5 NaF/59.5KF eutectic expressed on a per-unit mass basis is 133 cal/g. This value is 7 cal/g or 5% less than the mole average heat of fusion. In general, this method of correction has produced satisfactory results for eutectic heats of fusion.** For candidate fluoride salts where experimental data were not available on the eutectic heat of fusion, the Kirchkoff correction was applied to data on the component salts.

A check on the correction accuracy for the type of salts considered in this study was made by applying Eqn. (I-4) to a salt with experimental heat of fusion data. For the eutectic 67 LiF/33M_gF_2, Dr. Schroder, from the Philips

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*"Molten Salt Chemistry," Interscience, N.Y., 1964, p. 141.

**Bramlette, et al, "Survey of High Temperature Thermal Energy Storage," Sandia Labs, Albuquerque, N.M., March 1976.

Labs in Aachen, Germany, has measured at 746°C melt temperature the heat of fusion value to be 217 cal/g. The mole average heat of fusion is 235 cal/g and the Kirchkoff correction is 13 cal/g, yielding a calculated heat of fusion of 222 cal/g. Comparison shows for this salt, the Kirchkoff correction is too small. This implies that, although the Kirchkoff correction can be used to provide approximate heat of fusion data, a detailed TES design with a specific salt will require experimental verification of the salt thermophysical properties.

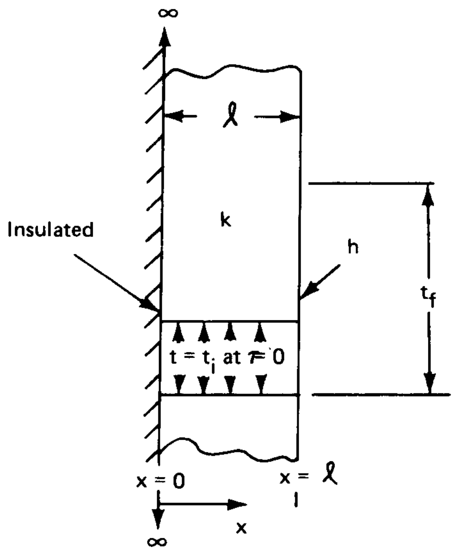
APPENDIX II

UNIT THERMAL CONDUCTANCE ANALYSIS

The heat transfer from/to the helium flow to/from the storage media for the sensible heat and phase change TES systems has been modeled as a one-dimensional problem. For the purpose of the initial presentation, a planar heat flow model has been adopted. This approach greatly simplifies the presentation and leads to a conclusion that applies equally well to the radial heat flow problem.

At a given axial position in the storage device, the heat flow from the working fluid into the storage media is substantially a one-dimensional problem. The working fluid temperature varies with time at a given axial location and the media simply responds to that temperature change. Symmetrical adiabatic surfaces develop between the uniformly heated tubes which further reduces the problem to the classical case of the semi-infinite plate uniformly heated on one side and insulated on the other. Any basic heat transfer text treats this transient problem. There is an exact solution to this problem, but it is complex in the general case. Over a wide range of parameters of practical interest in our problem, these solutions can be avoided by the adoption of a single node approximation. The accuracy of this approach is demonstrated in the following paragraphs by comparison to the step change response characteristic of the partial differential equation.

Under the above conditions, the one-dimensional temperature distribution within the media shown below must satisfy the following partial differential equations.



$$\frac{\partial^2 t}{\partial x^2} = 1/\alpha \frac{\partial t}{\partial \tau}$$

where:

α = storage media thermal diffisuvity

In addition, the following initial and boundary conditions apply:

$$t - t_f = t_i - t_f \text{ at } \tau = 0 \qquad \text{(II-1)}$$

$$\frac{\partial}{\partial x}(t-t_f) = 0 \text{ at } x = 0 \text{ for all } \tau \qquad \text{(II-2)}$$

$$-k \frac{\partial 2(t-t_f)}{\partial x^2} = h\,(t-t_f) \text{ at } x = \ell \qquad \text{(II-3)}$$

The solution to the partial differential equation with these boundary and initial conditions is obtained by the separation of variables technique and is as follows:

$$\frac{t-t_f}{t_i-t_f} = 2\sum_{n=1}^{\infty} \left(\frac{\sin \lambda n\,\ell}{\lambda n\,\ell + \sin \lambda n\,\ell \cos \lambda n\,\ell}\right) e^{-\lambda_n^2 \alpha \tau} \cos \lambda_n x \qquad \text{(II-4)}$$

The λ_n satisfy the transcendental equation

$$\cot \lambda_n\,\ell = \frac{k}{n}\lambda_n \qquad \text{(II-5)}$$

and are referred to as the eigenvalues.

The condition of concern in our problem is the heat flux rate at the surface which is given by

$$q = -k \left(\frac{\partial (t - t_f)}{\partial x} \right)_{x = \ell} \tag{II-6}$$

Then by defining the unit thermal conductance as,

$$U = \frac{q}{(t_o - t_f)} \tag{II-7}$$

U can be written in terms similar to equation (4) as follows:

$$u = \frac{k}{\ell} \frac{\sum_{n=1}^{\infty} \left(\frac{N_n \sin^2 N_n}{N_n + \sin N_n \cos N_n} \right) e^{-N_n^2 N_{Fo}}}{\sum_{n=1}^{\infty} \left(\frac{\sin N_n}{N_n + \sin N_n \cos N_n} \right) e^{-N_n^2 N_{Fo}}} \tag{II-8}$$

and the eigenvalues (N_n) now satisfy the expression,

$$N_n \tan N_n - N_{Bi} = 0 \tag{II-9}$$

The non-dimensional quantities that have been introduced in equations (II-8) and (II-9) are the Fourier Number (N_{F_o}) and the Biot number (N_{Bi}) which are defined as follows:

$$N_{Fo} = \frac{\alpha \tau}{\ell^2}$$

$$N_{Bi} = \frac{h\ell}{k}$$

The Fourier number is a measure of the degree heating or cooling effects have penetrated the plate and the Biot number is indicative of the resistance to heat transfer at the surface of the plate compared to its internal resistance.

For our particular problem, $\frac{N_{Fo}}{\tau}$ runs about 3.0 and N_{Bi} runs about 4-5. The data presented below include variations in N_{Bi} from 1.0 to 10.0 and variations in N_{Fo} from .3 to 5.0. Since the time response in the axial heat transfer problem is about .5 hour, considerations of longer times here are of little significance.

The solution for the unit thermal conductance in equation (II-9) is a complex series solution. Fortunately, the series converges rather rapidly and satisfactory accuracy is obtained by considering only five terms. A chart of the eigenvalues for the first five terms is shown as a function of the Biot number in Figure II-1. Final results for the exact unit thermal conductance given in equation (II-8) are presented in Figure II-2. The single node approximation to the unit thermal conductance is shown for comparison with the exact data. The accuracy of the single node approximation is obviously very good.

The final conclusion applies equally well to the lateral heat flow problem in cylindrical coordinates. Specifically, the lateral heat flow problem can be adequately represented by a single thermal node approximation if that node is taken as the centroid of the thermal mass of the storage media enclosed by the adiabatic surface of symmetry between the heat exchanger tubes. The derivation and presentation of the resultant unit thermal conductance in cylindrical coordinates are given in Section 2.0 of this volume.

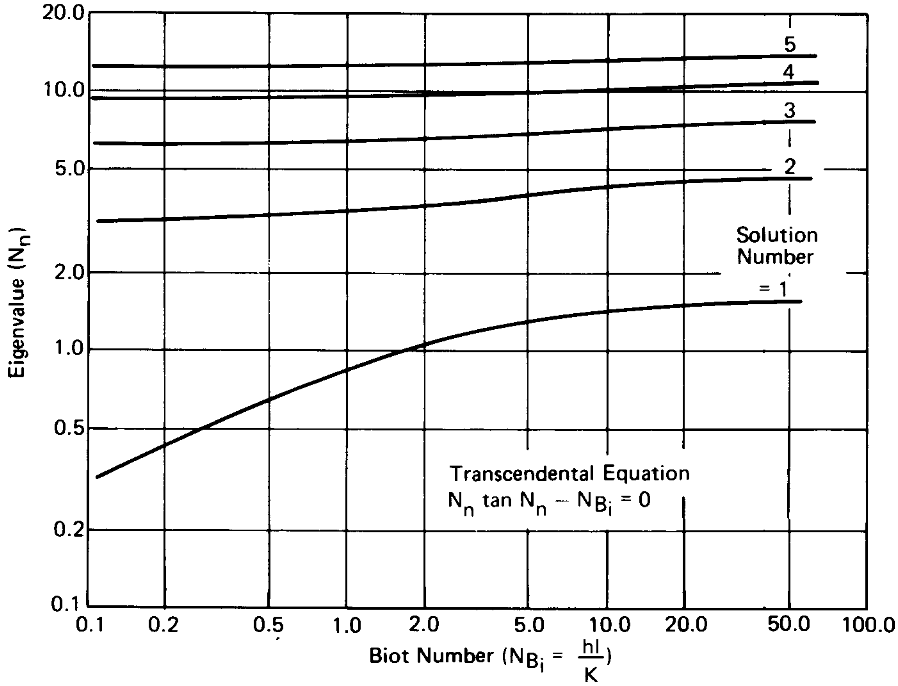


Figure II-1. Exact Unit Thermal Conductance Eigenvalues

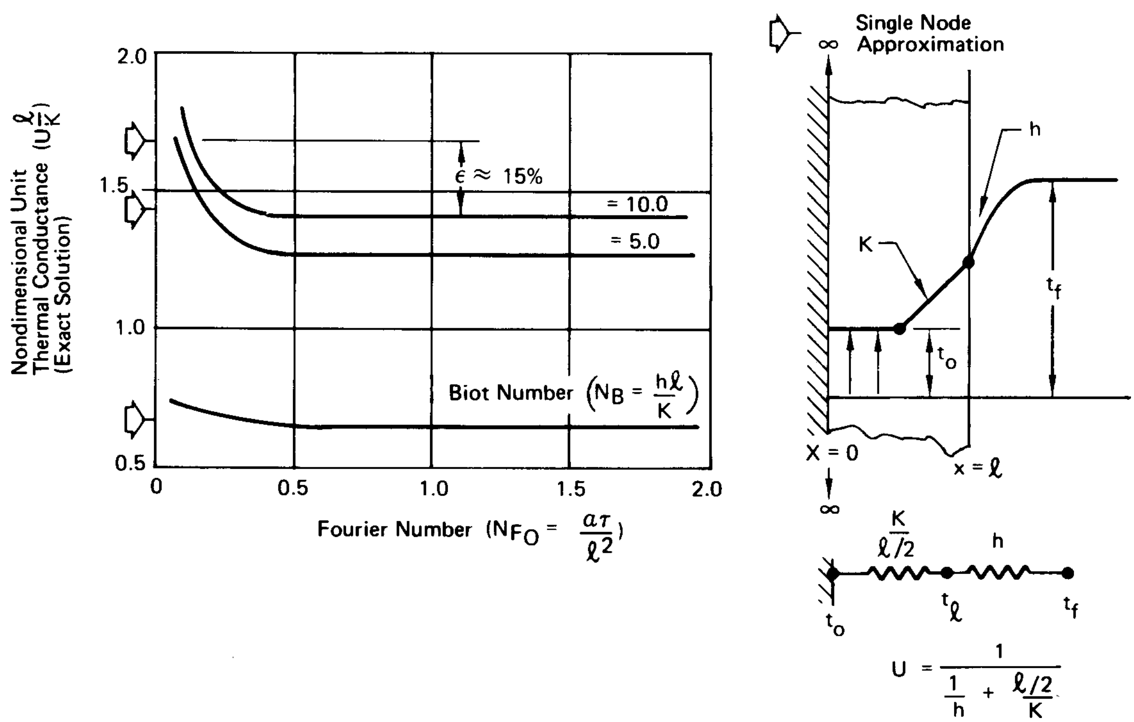


Figure II-2. Single Node Unit Thermal Conductance Accuracy