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SUBJECT: Design and Simulation of the First Blanket Zone of the DEMO Fusion Device

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ABSTRACT

An evaluation of the proposed design for the first blanket zone of the DEMO fusion device at Oak Ridge National Laboratory was performed by determining temperature profiles for a number of possible design geometries. Only one design configuration was acceptable and further evaluated by determining two-dimensional steady state temperature and tritium concentration profiles within the unit. The transient response of this design during periods of plasma shutdown was also determined to evaluate the maximum and minimum possible stress on the stainless steel cooling tubes. The preponderance of unacceptable designs of those investigated led to the recommendation that future studies consider only modules less than 25 cm thick and coolant temperature rises less than 67°C.

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1. SUMMARY

A new blanket design for the DEMO Fusion Device has been proposed at Oak Ridge National Laboratory. The design incorporates the feature of ease of replacement and the ability to reduce neutron flux, recover thermal energy, and breed tritium as fuel. The removable sections (or modules) are composed of a series of stainless steel U-tubes enclosing lithium.

Collisions of the neutrons with the lithium produce tritium. A series of niobium capillary tubes are placed within the module creating a wall which is effectively adiabatic and highly permeable to tritium. Thus the tritium can be removed and recovered as it diffuses through the tube.

This project investigated the temperature and tritium concentration profiles for possible configuration of this module during steady state operation and during transient periods of plasma shutdown.

A computer program was written which applied an overall energy balance to various possible cassette designs and calculated the coolant temperature profile and the various design parameters including heat transfer coefficients, Reynolds numbers, and position of the niobium wall. One hundred sixty possible module configurations were studied by application of the overall energy balance. To limit the number of cases, a one-dimensional approximation to the two-dimensional steady state temperature profile within the lithium was developed by assuming that plasma flux variation along the length of the module was negligible. Applying maximum temperature and temperature difference criteria to these cases revealed only one case which met the criteria. HEATING5, a computer program developed at ORNL, was used with the coolant temperature profile already produced to generate the temperature profile through the lithium within the cassette for this chosen case. The inputs to HEATING5 were then modified to produce a steady state tritium concentration profile. Integration of this profile led to determination of the amount of tritium within the module.

To evaluate the stress on the cooling tubes during transient periods of plasma shutdown, HEATING5 was again used, this time to obtain a solution for the transient behavior. Since HEATING5 is not designed to solve systems containing flowing fluids, it could only be used to determine the maximum and minimum temperature differences across the cooling tubes. This placed upper and lower bounds on the stress.

It was concluded that cassettes greater than 25-cm thick and coolant temperature rises greater than 67°C result in unacceptable blanket designs.

2. INTRODUCTION

2.1 Background

Tokamak-type fusion devices are characterized by a toroidal, D-shaped plasma. The plasma is maintained in its toroidal shape by magnetic fields from supercooled magnets surrounding the system. A region, called the blanket, is contained between the plasma and the magnets. Its purpose is to reduce neutron flux and recover the kinetic energy of the neutrons and to breed tritium as shown in Eqs. (1) and (2). The blanket contains heat exchanger tubes through which a coolant (either a molten salt or helium) circulates to recover the thermal energy for electric power generation.

$$Li^6 + n \rightarrow H^3 + He + 4.78 \text{ MeV} \tag{1}$$

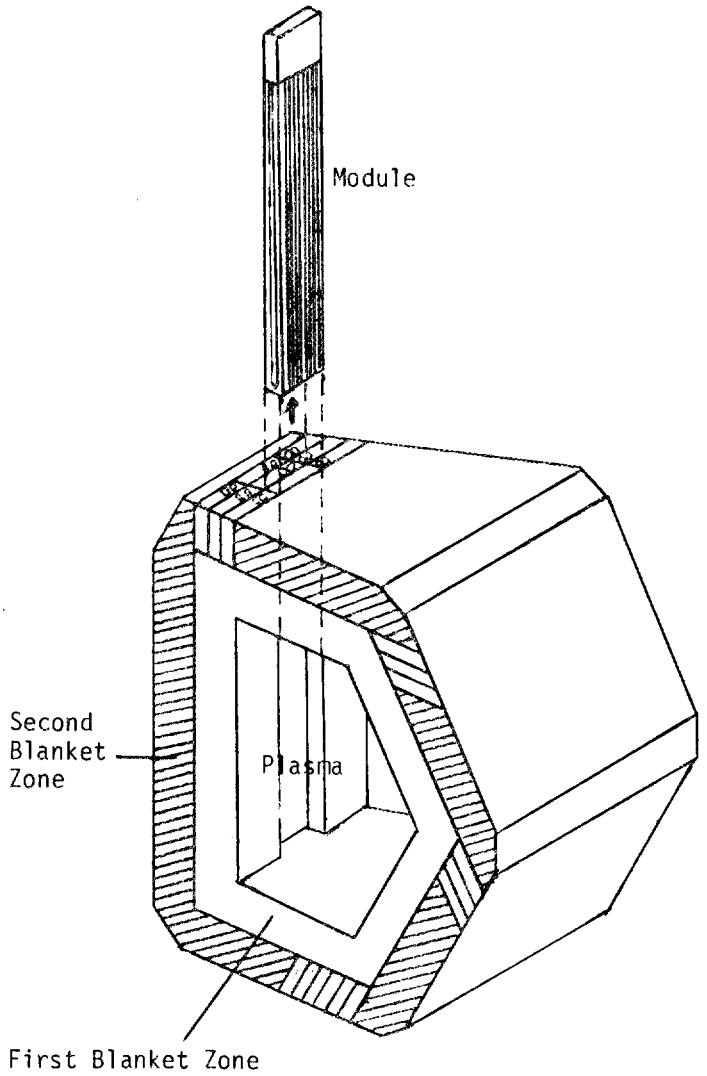
$$Li^7 + n \rightarrow n + H^3 + He - 2.78 \text{ MeV} \tag{2}$$

In addition to a flux of neutrons leaving the plasma, there is also the release of alpha and beta particles. The measure of this flux at the surface of the blanket is called the charged particle loading. This flux not only deteriorates the blanket surface but also releases molecules of blanket material into the plasma. Such impurities severely hinder maintenance of the plasma.

A device called a divertor can be added to the system which, if 100% efficient, would magnetically remove all the charged particles. However, it is beneficial to let some of the particles strike the blanket surface to recover their kinetic energy. Since all the particles are not being removed, a buildup in their concentration occurs. This necessitates a brief period of plasma shutdown of roughly one minute for every 20 min of operation (13). During this time the plasma is purged, then recharged and restarted. The blanket degradation makes it necessary to replace a portion of the blanket zone periodically.

Based on the above criteria, a new design for the blanket has been proposed (14) (Fig. 1). The blanket zone is divided into three sections, each of which is removable. Since the charged particle flux and therefore the corrosion only occurs in the module adjacent to the plasma, the first blanket zone, only these modules must be removed. However, charged particle flux is not the only source of damage to the module. Neutron penetration also damages the modules until the flux is reduced to an acceptable level. This level is generally attained within a blanket thickness of roughly 25 cm (14). The thickness of replaceable sections must then be at least 25 cm.

Figure 2 shows a detailed end view of a module. The module wall is made up of a series of stainless steel U-tubes laid side by side. The



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SECTION OF PROPOSED BLANKET DESIGN

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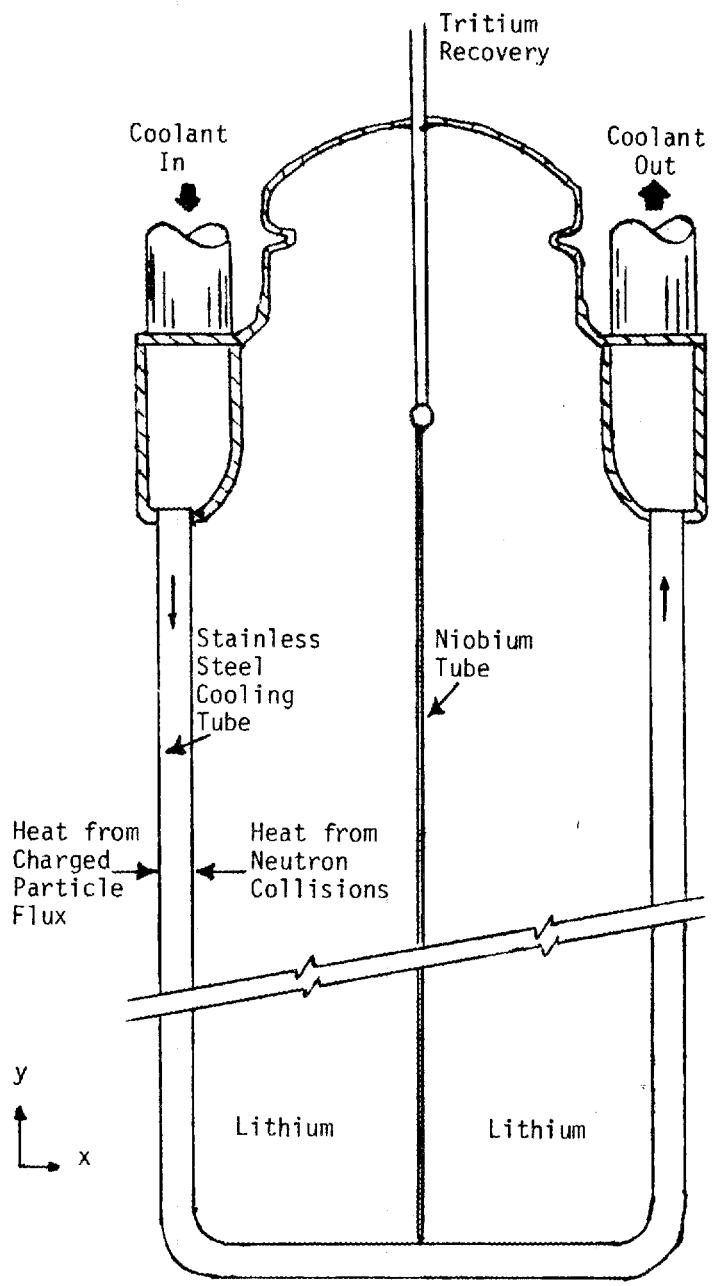

Module Dimensions (m)

Height	4
Width	0.25
Depth	1

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CROSS SECTION OF PROPOSED
BLANKET MODULE DESIGN

DATE	DRAWN BY	FILE NO.	FIG.
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interior of the "U" contains lithium for tritium breeding. To recover the tritium, each module contains a wall of niobium capillary tubes, since niobium is highly permeable to tritium. By drawing a vacuum on the tubes, the tritium is removed from the reactor and recovered. Stainless steel is also permeable to tritium, but it is assumed that the cooling tubes are coated with a material that is impermeable to tritium.

2.2 Objectives

The objectives were:

1. To develop an overall energy balance for the module and to use it as a basis for the design procedure.

2. To determine the steady state temperature profile in the module.

3. To determine the steady state tritium concentration profile in the module.

4. To calculate the thermal stress on the cooling tubes during transient periods of reactor shutdown.

3. APPROACH

3.1 Assumptions

The conceptual model of the module incorporated the following assumptions:

1. The niobium capillary tube acts as an adiabatic wall.

2. The U-tube is coated with a substance which is impermeable to tritium.

3. The tritium concentration on the interior of the niobium wall is zero because the tritium is quickly removed by the vacuum.

4. The partition function of tritium between the lithium and the niobium is 1.0.

5. The coolant physical properties are constant.

3.2 Choice of Variables

The module design parameters included cooling tube inner diameter, coolant temperature change, coolant viscosity, coolant heat capacity, coolant density, charged particle loadings, neutron loading, and niobium wall thickness. To perform a case study of possible module designs using an energy balance program, appropriate choices had to be made for the various parameters, both constant and variable. The choice of constant parameters was based on the proposed design supplied by the ORNL Fusion Energy Division. Coolant physical properties were those for HITEC coolant, and the cooling tubes were considered to be 316 stainless steel. Upper and lower limits exist on the cooling tube diameters that can be used. At the lower limit, pressure drop through the tubes, and thus the required pumping costs become significant. In the limit of larger diameters, while pumping requirements are small, the cooling tubes are becoming a significant fraction of the total module volume. This excludes lithium from being in that volume and reduces the tritium breeding capabilities of the blanket. For this problem, a range of 0.5 to 4.0 cm inside diameter was chosen.

The temperature rise of the coolant between inlet and outlet must be roughly 200°C to supply the necessary driving force for the power generation system downstream of the reactor (13). Within the proposed blanket design, the modules exist in banks of three (Fig. 1). Therefore, this temperature rise may be achieved by running the module coolant systems in series or in parallel. If they are run in series, the coolant outlet from one module will be the inlet to the next, and each module will then supply one third of the 200 or 67°C. In contrast, parallel arrangement requires that each module supply the entire 200°C rise. Thus, 67 and 200°C were the coolant temperature increases investigated.

The charged particle loading can be varied by altering the divertor efficiency (a device to magnetically remove these particles), condition of the plasma, location of the blanket wall, and level of contaminants within the plasma. A range of loadings from 0.1 to 1.0 MW/m^2 then represents the achievable loadings based on variation of the above reactor conditions. These three variable parameters (cooling tube ID, coolant temperature rise, and charged particle loading) are those over which the design engineer has the most control.

3.3 Overall Energy Balance Program

To minimize the thermal stress on the front part of the U-tube, the heat flux into the tube from the plasma side due to charged particle radiation was equated to the heat flux into the tube from the lithium side due to thermal energy generation from neutron collisions with lithium in the front part of the cassette. The front part of the cassette was that which was between the tube on the plasma side and the adiabatic niobium wall. This balance specified the niobium wall position.

The niobium wall placement was calculated in a computer program written by Huxford (6). In addition, this program solved the overall energy balance of the system to find the heat transfer coefficient, coolant flow rate, total cassette power production rate, pressure drop through the coolant tube, and required pumping power. The program was modified in this report to divide the cooling tube into regions and calculate the average coolant temperature in each region at steady state.

3.4 Use of HEATING5 - Steady State Temperature Profile

Knowledge of the average coolant temperatures and of the heat transfer coefficient within the tube allowed a two-dimensional temperature profile within the tube wall and lithium to be determined by application of the steady state energy equation:

$$0 = \frac{\partial}{\partial x}(k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k \frac{\partial T}{\partial y}) + S_n \tag{3}$$

in which x is the horizontal and y is the vertical distance. The appropriate boundary conditions are:

At the interfaces between the coolant and the tubing,

$$h_c(T_c - T_t) = -k_t(\frac{\partial T_t}{\partial x}) \quad \text{horizontal interface} \tag{4}$$

$$h_c(T_c - T_t) = -k_t(\frac{\partial T_t}{\partial y}) \quad \text{vertical interface} \tag{5}$$

At the top of the U-tube material,

$$(\frac{\partial T}{\partial y})_{top} = 0 \tag{6}$$

At the interfaces between the niobium tubes and the lithium,

$$(\frac{\partial T}{\partial x})_{interface} = 0 \tag{7}$$

An ORNL computer program called HEATING5, developed by Doyle Turner *et al.* (11) was available for solving problems of this nature. The cassette was divided into appropriate regions as required by the HEATING5 input requirements, and the temperature profile was determined by HEATING5.

3.5 Use of HEATING5 - Steady State Tritium Concentration Profile

The tritium concentration profile in the lithium was determined in the same manner by use of the steady state equation of continuity:

$$0 = \frac{\partial}{\partial x}\left(D \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D \frac{\partial C}{\partial y}\right) + R \tag{8}$$

with boundary conditions:

$$\left(\frac{\partial C}{\partial x}\right) = \left(\frac{\partial C}{\partial y}\right) = 0 \tag{9}$$

at the interface with the cooling tubes

$$\left(\frac{\partial C}{\partial y}\right)_{top} = 0 \tag{10}$$

at the top of the U-tube and

$$(C)_{interface} = 0 \tag{11}$$

at the interfaces between the niobium tubes and the vacuum. The steady state equation of continuity is analogous to the steady state energy equation. Therefore, HEATING5 was used to solve the concentration profile by replacing conductivity with diffusivity, temperature with concentration, and heat generation with mass generation. Diffusivity is a function of temperature; since temperature varies throughout the cassette, so does diffusivity. However, the data input for HEATING5 only allowed diffusivity to be a constant for each material or to vary with concentration. An approximation was made by considering the lithium and niobium to each contain a number of regions with each region containing a "different" material, and therefore a different constant diffusivity. The diffusivities were calculated from the average steady state temperature in the region. For this reason, the temperature profile must be determined prior to the determination of the concentration profile.

Application of the three computer programs in series (the overall energy balance and the two applications of HEATING5) provided the steady state temperature and concentration profiles.

3.6 Use of HEATING5 - Transient Solution

The final objective, the calculation of thermal stress in the U-tube during the period of reactor shutdown ($\approx$ 1 min for every 20-min run) was achieved by calculating its transient temperature profile. This profile was solved for the maximum possible value of thermal stress with HEATING5 by changing the governing equation to:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k \frac{\partial T}{\partial y}) \tag{12}$$

with the coolant temperature constant and at the maximum value:

$$T_c = T_{c_{max}} \tag{13}$$

thereby making the flux between the lithium and tube a minimum. The transient profile was also calculated to calculate the minimum thermal stress by repeating the above procedure with $T_c = T_{c_{min}}$.

3.7 Design Evaluation Criteria

Since running HEATING5 required a large amount of computer and data preparation time, only a limited number of design cases could be considered. To aid in the selection of these cases, ranges of three important design parameters, cooling tube inner diameter, charged particle loading and coolant temperature change, were run on the overall energy balance program. One criterion which must be met to keep corrosion at an acceptable level is that the tube wall facing the plasma never exceed 400°C. Knowledge of the coolant temperatures and the heat transfer coefficients allowed calculation of this tube wall temperature. This reduced the number of cases which are plausible. Further reduction was accomplished by specifying the maximum allowable temperature gradient across the niobium tube. This required that an approximation of the temperature profile be obtained. This approximation was achieved by a one-dimensional solution which ignored flux in the vertical direction of the U-tube:

$$0 = \frac{\partial}{\partial x}(k \frac{\partial T}{\partial x}) + S \tag{14}$$

If conductivity is assumed to be constant over a small increment, the temperature at the next original position plus the increment could be calculated from the temperature at the original position. A computer program, GRADT, was written to determine a temperature profile by starting at the coolant tube wall, where the temperature was known, and moving across the U-tube in 1-mm increments. The resulting temperature profile yielded the temperature gradient across the niobium tube, thereby eliminating more cases from consideration. The selected cases were then run in the HEATING5 programs previously described and data analysis was performed. A summary of the approach is seen in Fig. 3.

4. RESULTS

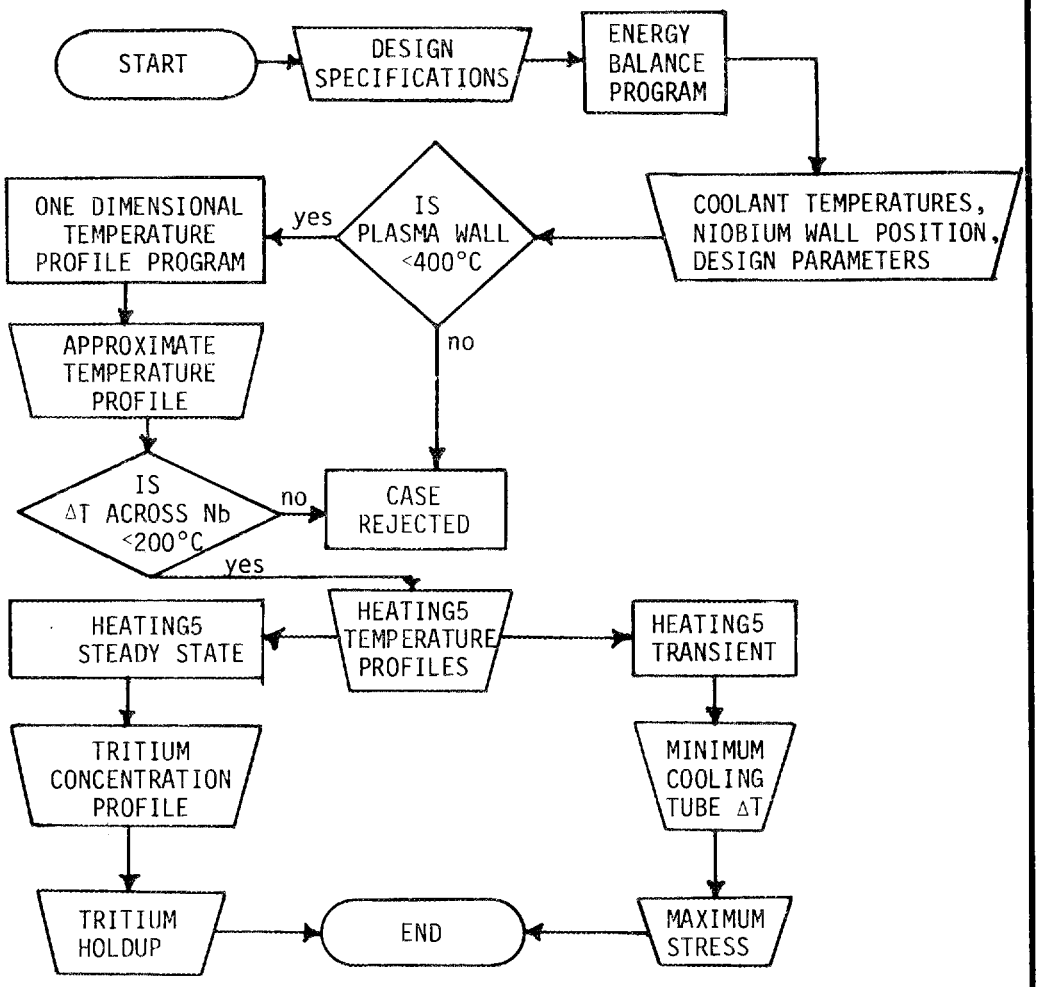
4.1 Overall Energy Balance

A case study was run on the overall energy balance program, ENBAL, to consider a variety of possible cassette designs. The chosen parameters, both constant and variable, are shown in Table 1. For each of the 160 cases considered, a coolant temperature profile and a set of module design parameters were produced. To narrow down the number of cases to be considered further, the various evaluation criteria were applied. The first criterion used was the limit of 400°C on the outer surface of the plasma side cooling tube. The results of this analysis are shown in Tables 2 and 3 for the 67 and 200°C temperature rises, respectively. A significant number of the 200°C cases and many of the 67°C cases were thus eliminated. Those cases which exceeded this 400°C limit are marked with dashes. Wall temperatures for a few of the acceptable cases are shown.

By limiting the temperature difference across the niobium wall to less than 200°C, the number of cases to be considered was reduced more. This was done by running the one-dimensional temperature profile program, GRADT, for a number of the cases. The results of this analysis are shown in Tables 4 and 5 for the 67 and 200°C temperature rise cases, respectively. As can be seen, trends in the results were visible, making it unnecessary to run all the cases. The cases marked with dashes are those that were eliminated by application of the first criterion. Temperature differences for a number of the cases as supplied by GRADT are shown.

In the case of a 200°C coolant temperature rise, all remaining cases surpass this criterion and can be eliminated. From Table 4 it can be seen that only one case, that of a charged particle loading of 1.0 MW/M^2 and a cooling tube inner diameter of 1.0 cm, has a temperature difference of less than 200°C across the niobium wall.

Other relevant output from the overall energy balance included the variation of total module power output with varying cooling tube inside diameter. These results are shown in Fig. 4 for a coolant temperature rise of 67°C and charged particle loadings of 0.1 and 1.0 MW/m^2. The power output for all other charged particle loadings investigated falls



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FLOWSHEET OF SOLUTION PROCEDURE

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Table 1. Parameter Choice for Case Studies

Variable Parameters	
Cooling tube ID	0.5 - 4.0 cm
Charged particle loading	0.1 - 1.0 MW/m^2
Coolant temperature rise	67 and 200°C
Constant Parameters	
Module height	4 m
Module width	1 m
Neutron wall loading	3.14 MW/m^2
Coolant tube thermal conductivity	19 W/m-°K
Coolant properties:	
Specific heat	1.54×10^3 J/kg-°K
Density	1.68×10^3 kg/m^3
Thermal conductivity	0.6 W/m-°K
Viscosity	3.0×10^{-3} Pa·S
Inlet temperature	300°C
Niobium wall OD	0.5 cm

Table 2. Outer **Cooling** Tube Wall Temperatures Facing Plasma
(Coolant Temperature Rise, 67°C)

Charged Particle Load (MW/m^2)	Cooling Tube Inside Diameter (cm)							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
0.1	372.4°C			333.9				345.7
192							363.7	369.4
0.3								391.1
0.4							402.8	-
0.5	340.5				396.0	-	-	-
0.6				395.1	-	-	-	-
0.7			389.4	-	-	-	-	-
0.8			398.5	-	-	-	-	-
0.9		385.5	-	-	-	-	-	-
1.0	367.4	392.2	-	-	-	-	-	-

(-) indicates T > 400°C.

Table 3. Outer Cooling Tube Wall Temperatures Facing Plasma
(Coolant Temperature Rise, 200°C)

Charged Particle Load (MW/m^2)	Cooling Tube Inside Diameter (cm)							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
0.1	334.5°C					398.3	-	-
0.2			392.1	-	-	-	-	-
0.3		397.1	-	-	-	-	-	-
0.4	391.4	-	-	-	-	-	-	-
0.5	-	-	-	-	-	-	-	-
0.6	-	-	-	-	-	-	-	-
0.7	-	-	-	-	-	-	-	-
0.8	-	-	-	-	-	-	-	-
0.9	-	-	-	-	-	-	-	-
1.0	-	-	-	-	-	-	-	-

(-) indicates T > 400°C.

Table 4. Temperature Difference Across 0.5-cm-OD Niobium Wall
(Coolant Temperature Rise, 67°C)

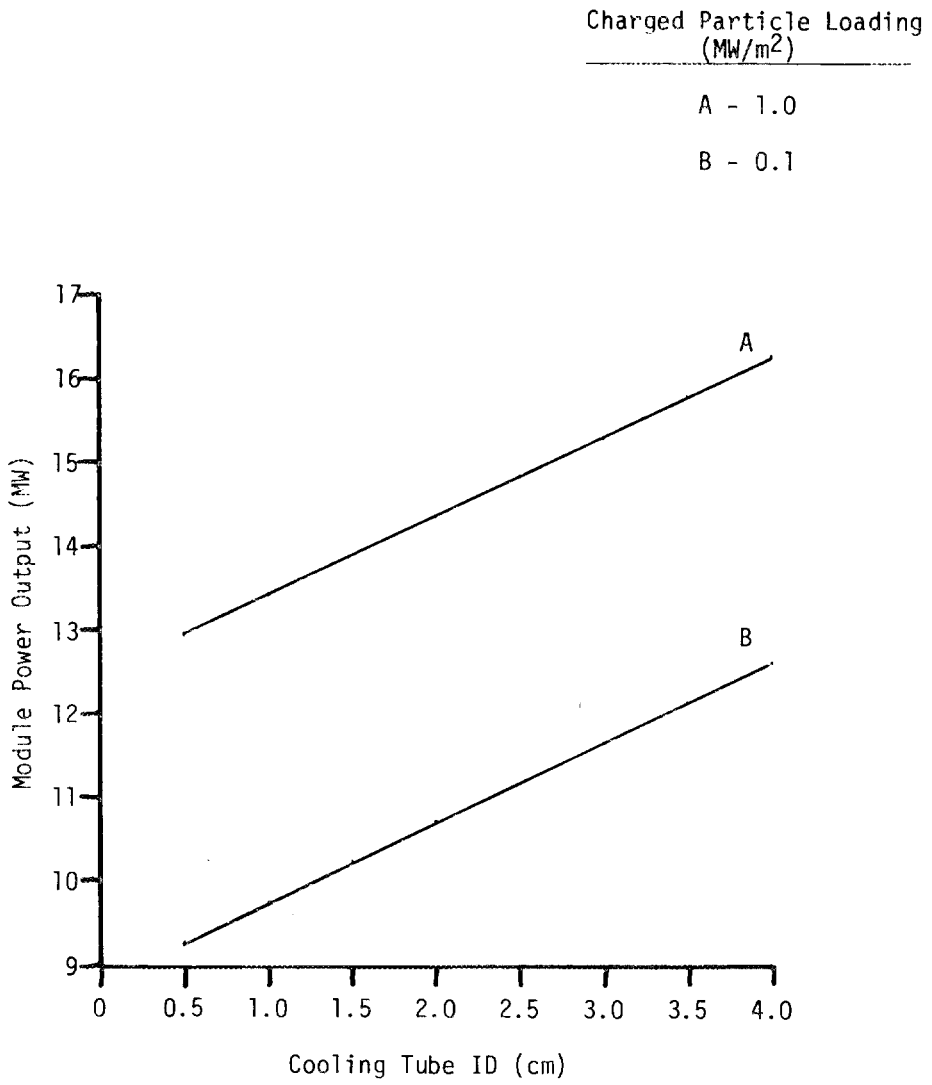
Charged Particle Load (MW/m^2)	Cooling Tube Inside Diameter (cm)							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
0.1	4210°C				2360			1600
0.2								
0.3	3660				1720			
0.4								-
a. 5	2140				1100	-	-	-
0.6					-	-	-	-
Q. 7				-	-	-	-	-
0.8				-	-	-	-	-
0.9		500	-	-	-	-	-	-
1.0	400	195	-	-	-	-	-	-

(-) indicates T > 400°C.

Table 5. Temperature Difference Across 0.5-cm-OD Niobium Wall
(Coolant Temperature Rise, 200°C)

Charged Particle Load (MW/m^2)	Cooling Tube Inside Diameter (cm)							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
0.1	4800°C		3400			2400	-	-
0.2			3100	-	-	-	-	-
0.3		2900	-	-	-	-	-	-
0.4	2800	-	-	-	-	-	-	-
0.5	-	-	-	-	-	-	-	-
0.6	-	-	-	-	-	-	-	-
0.7	-	-	-	-	-	-	-	-
0.8	-	-	-	-	-	-	-	-
0.9	-	-	-	-	-	-	-	-
1.0	-	-	-	-	-	-	-	-

(-) indicates T > 400°C



Coolant Temperature Rise, 67°C

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MODULE POWER OUTPUT VARIATION WITH COOLING TUBE ID AND CHARGED PARTICLE LOADING			
DATE 12-19-76	DRAWN BY JHL	FILE NO. CEPS-X-246	FIG. 4

between these two lines. The effect of variation in the cooling tube inside diameter on the ratio of pumping power to total module power output is shown in Fig. 5.

4.2 Two-Dimensional Temperature Profile

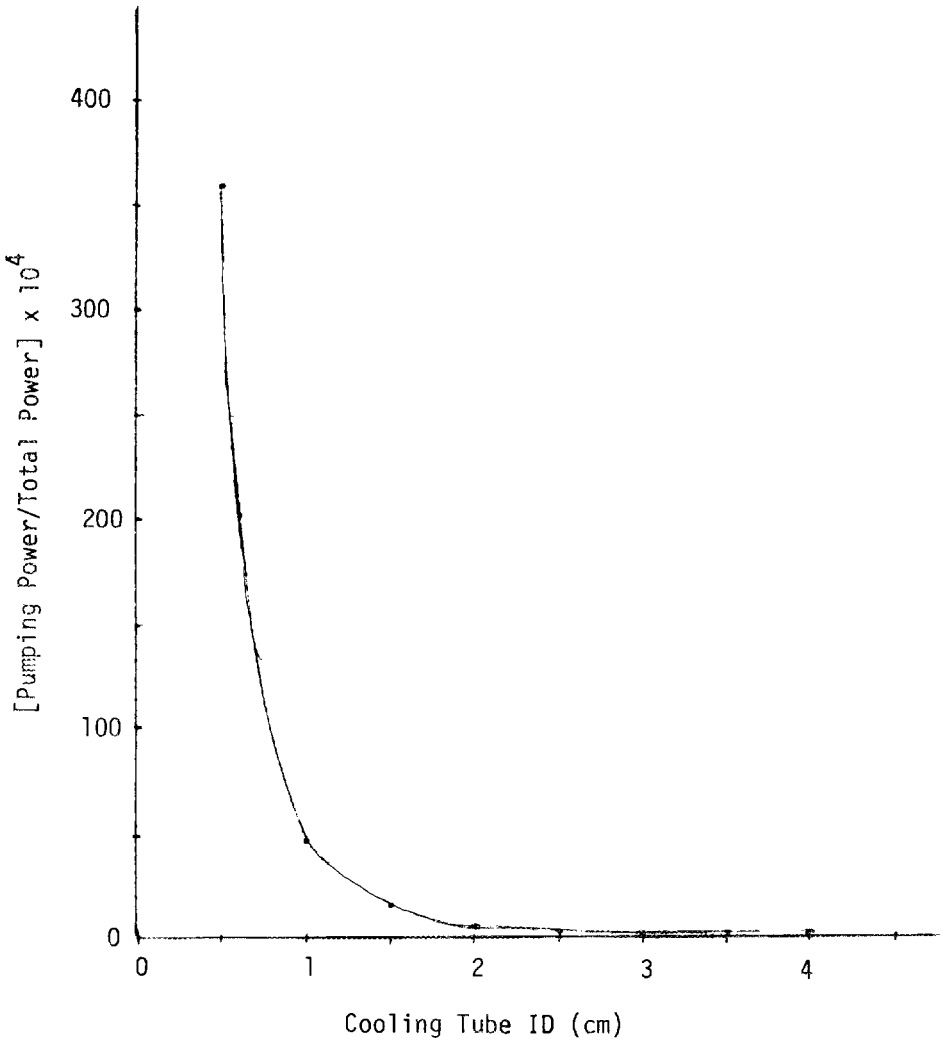
Figure 6 is a plot of the steady state temperature profile through the module operating at 13.2 MW. The results are shown for both the top and the bottom of the module, which are where the upper and lower limits of temperature occur.

4.3 Tritium Concentration Profile

When the inputs to HEATING5 were modified to give the tritium concentration profile as output, the profile obtained is that shown in Fig. 7. This is the concentration variation across the top of the module. Except for the wall concentrations, there is very little (∿4%) change in the tritium concentration for different vertical positions.

4.4 Transient Response

Plots of the temperature profile vs time along a cross-section 2.13 meters from the bottom of the U-tube during both simulations are presented in the following figures. The temperature profiles produced during the first, minimum cooling, simulation are shown in Figs. 8 through 10. The temperature profiles produced during the second, maximum cooling, simulation are shown in Figs. 11 and 12. The upper curves in Figs. 8 and 11 represent the temperature profiles at the tube wall face adjacent to the lithium on the left side of the U-tube. The temperature profiles at the wall face adjacent to the coolant on the left side of the U-tube are presented as the bottom curves in Figs. 8 and 11. The analogous temperature profiles for the right side of the U-tube are presented in Figs. 9 and 12. The temperature profiles on the left and right sides of the niobium wall are presented as the lower and upper curves, respectively, of Fig. 10. Since the temperature profiles at the niobium wall are nearly identical for both simulations, only one plot is shown. The resulting temperature changes at the six locations described above during the transient simulations are summarized in Table 6.



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PUMPING POWER TO TOTAL POWER RATIO
AS A FUNCTION OF
COOLING TUBE INNER DIAMETER

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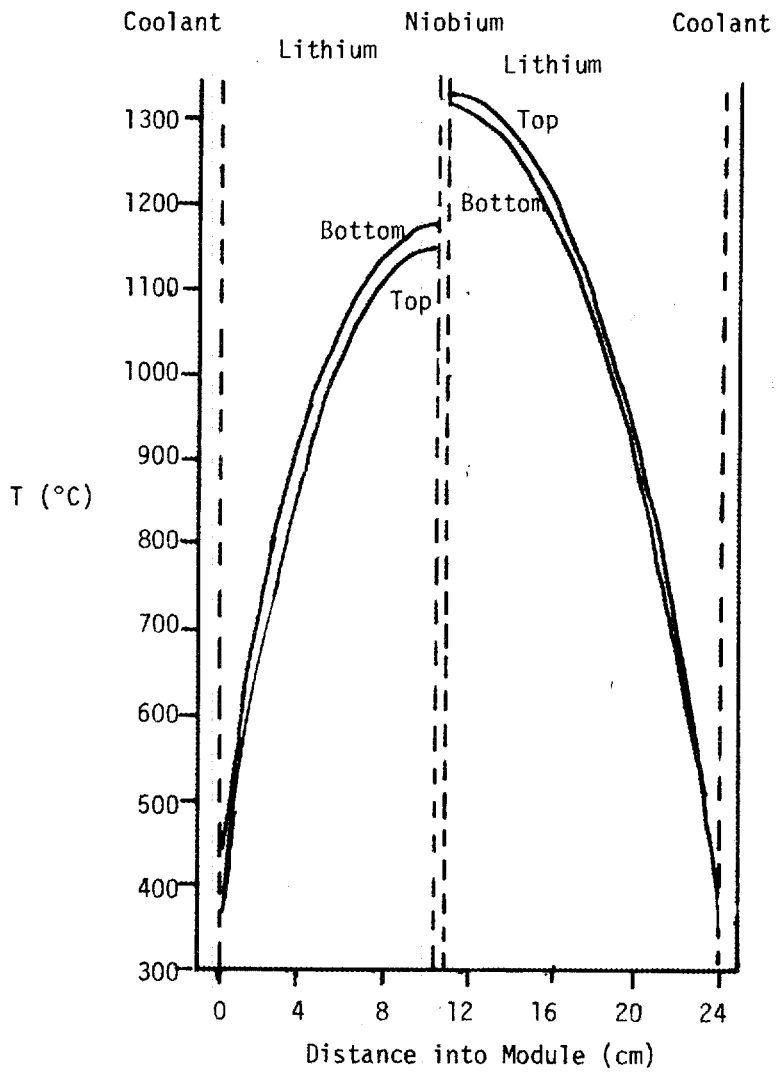

Charged Particle Loading = 1.0 MW/m^2
Cooling Tube ID = 1.0 cm
Coolant Temperature Rise = 67°C

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HEATING5 STEADY STATE
TEMPERATURE PROFILE

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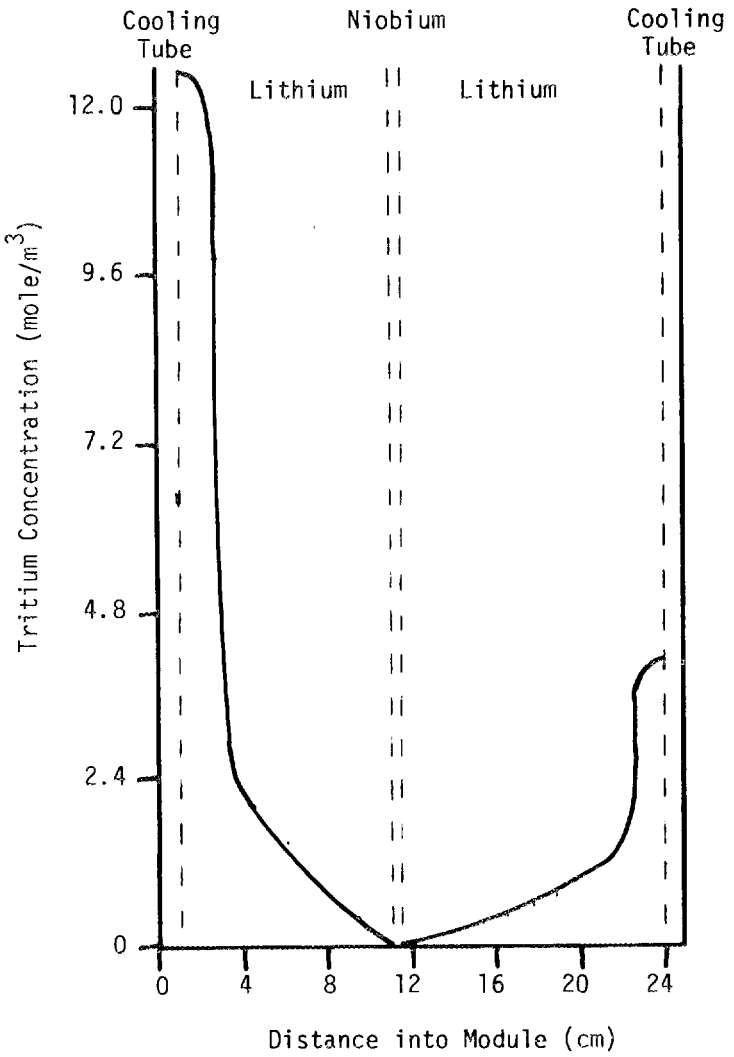
12-19-76	JHL	CEPS-X-246	6



Case

Charged particle loading = 1 MW/m^2

Cooling Tube ID = 1.0 cm

Coolant Temperature Rise = 67°C

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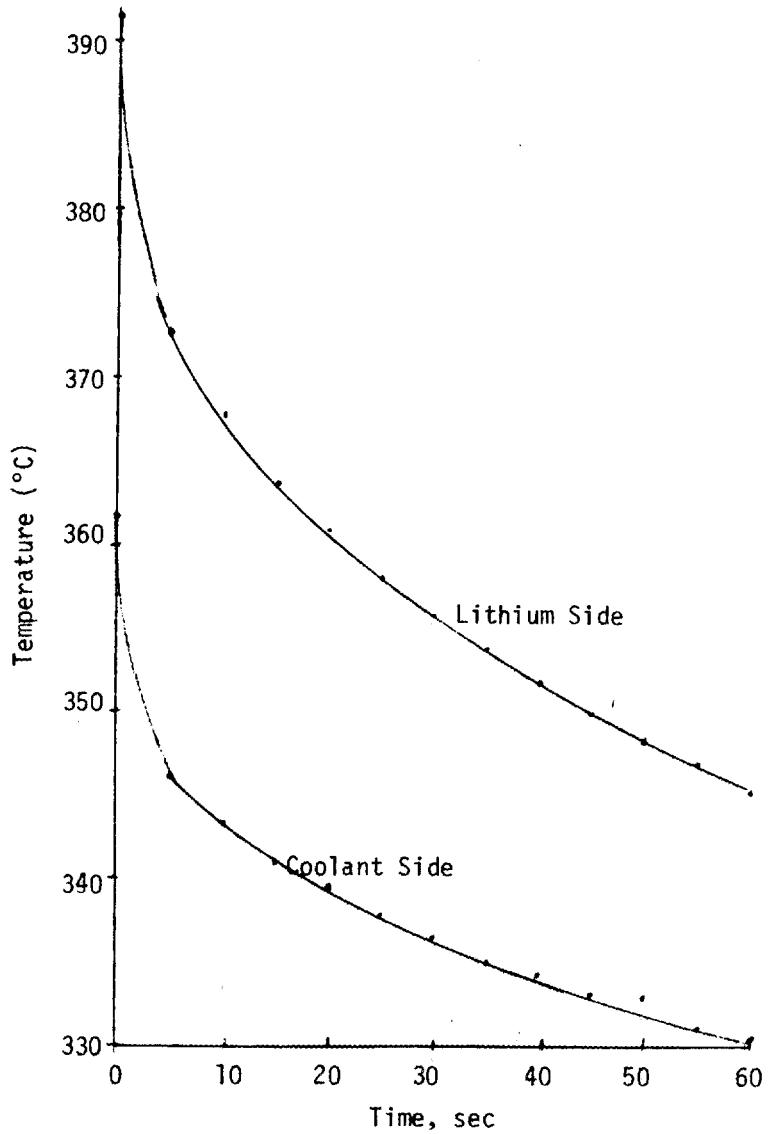
STEADY STATE TRITIUM CONCENTRATION PROFILE

DATE	DRAWN BY	FILE NO.	FIG.
12-19-76	KAK	CEPS-X-246	7



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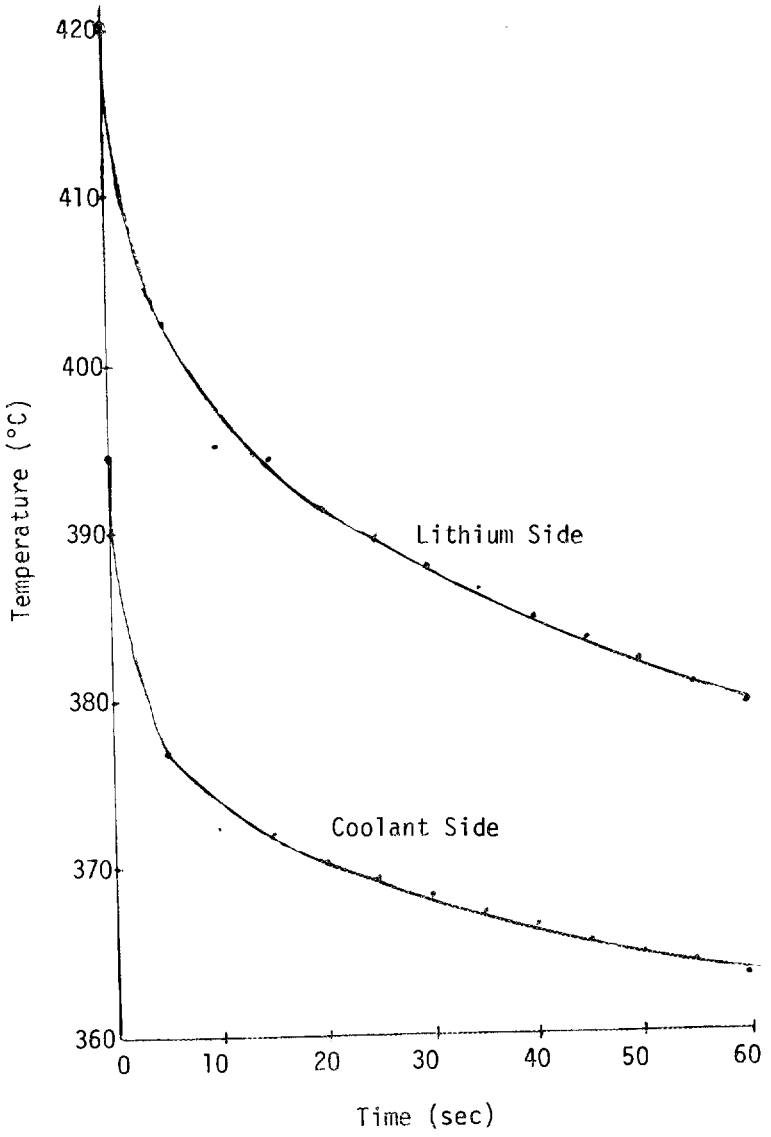
VARIATION OF INNER AND OUTER
LEFT WALL TEMPERATURES WITH TIME

DATE	DRAWN BY	FILE NO.	FIG.
12-19-76	KAK	CEPS-X-246	8



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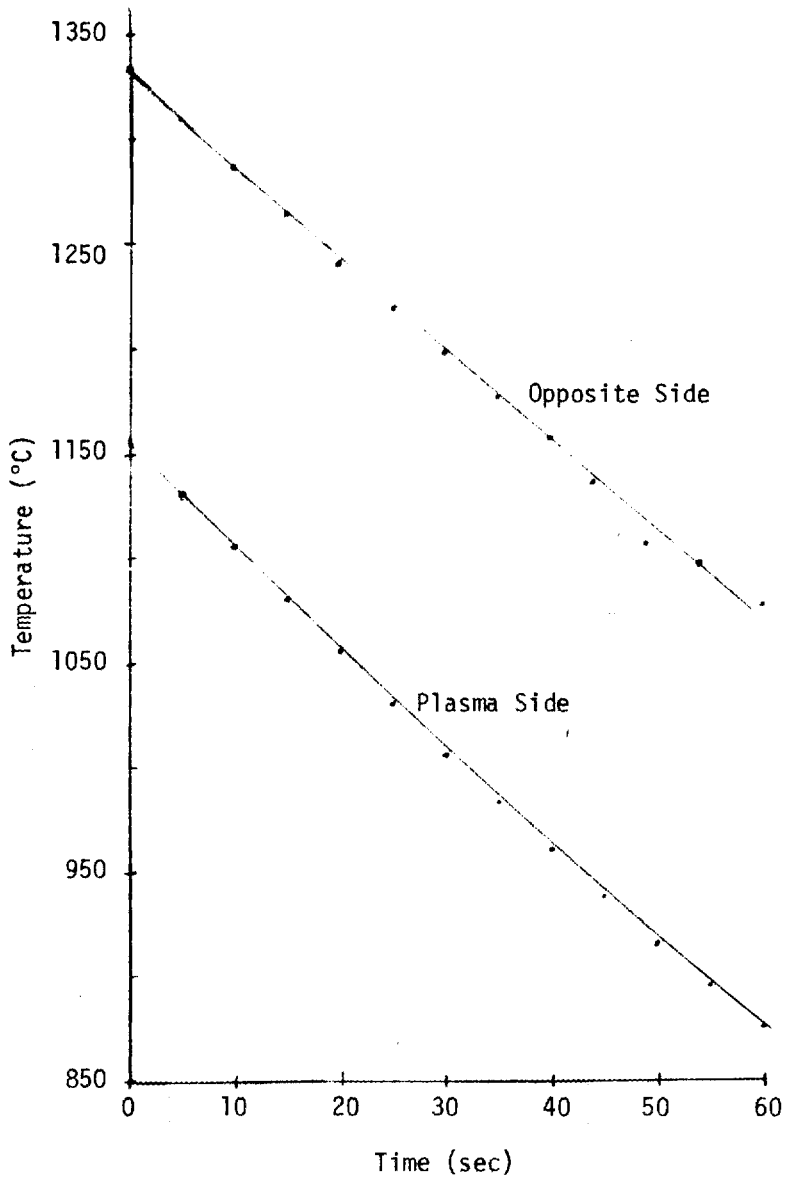
VARIATION OF INNER AND OUTER
RIGHT WALL TEMPERATURES WITH TIME

DATE	DRAWN BY	FILE NO.	FIG.
12-19-76	KAK	CEPS-X-246	9



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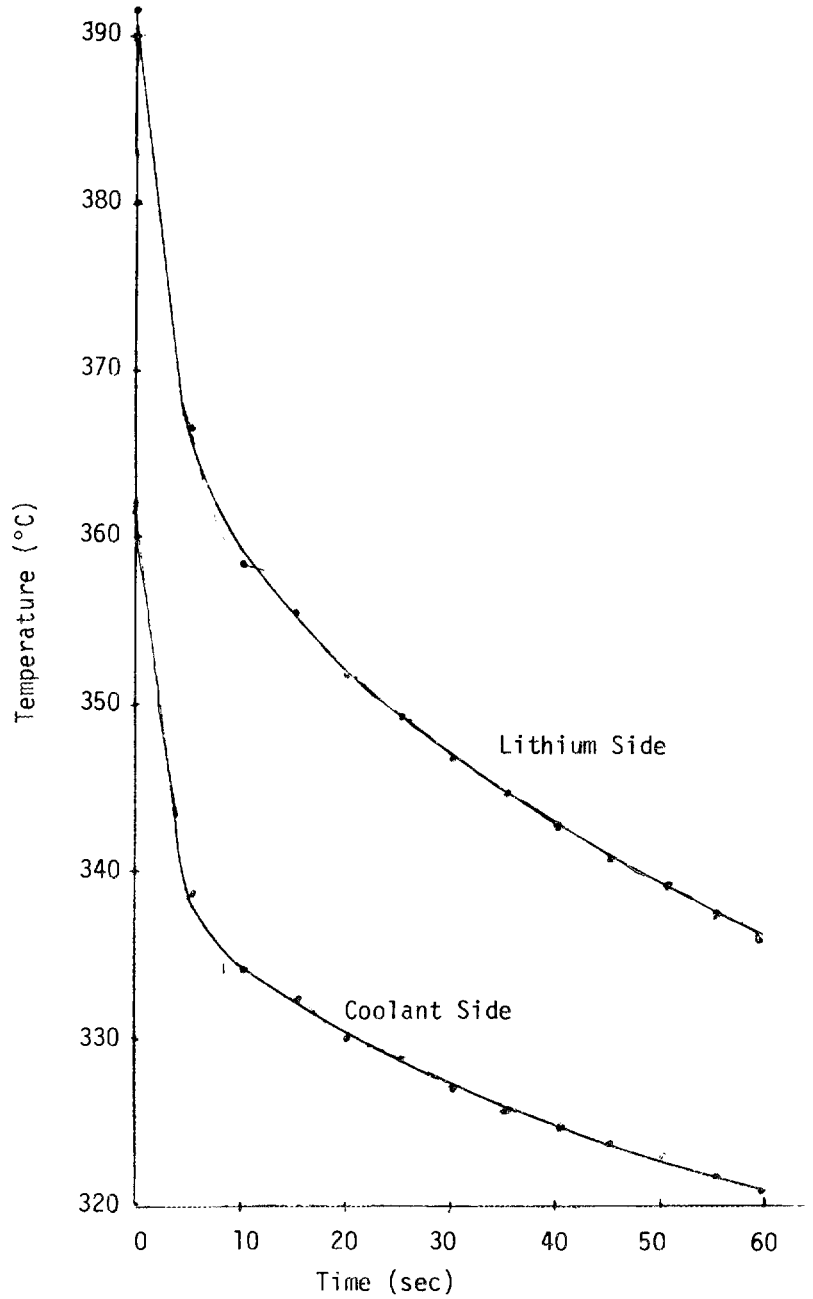
VARIATION OF NIOBIUM WALL TEMPERATURE WITH TIME

DATE	DRAWN BY	FILE NO.	FIG.
12-19-76	JSD	CEPS-X-246	10



y = 2.13 m

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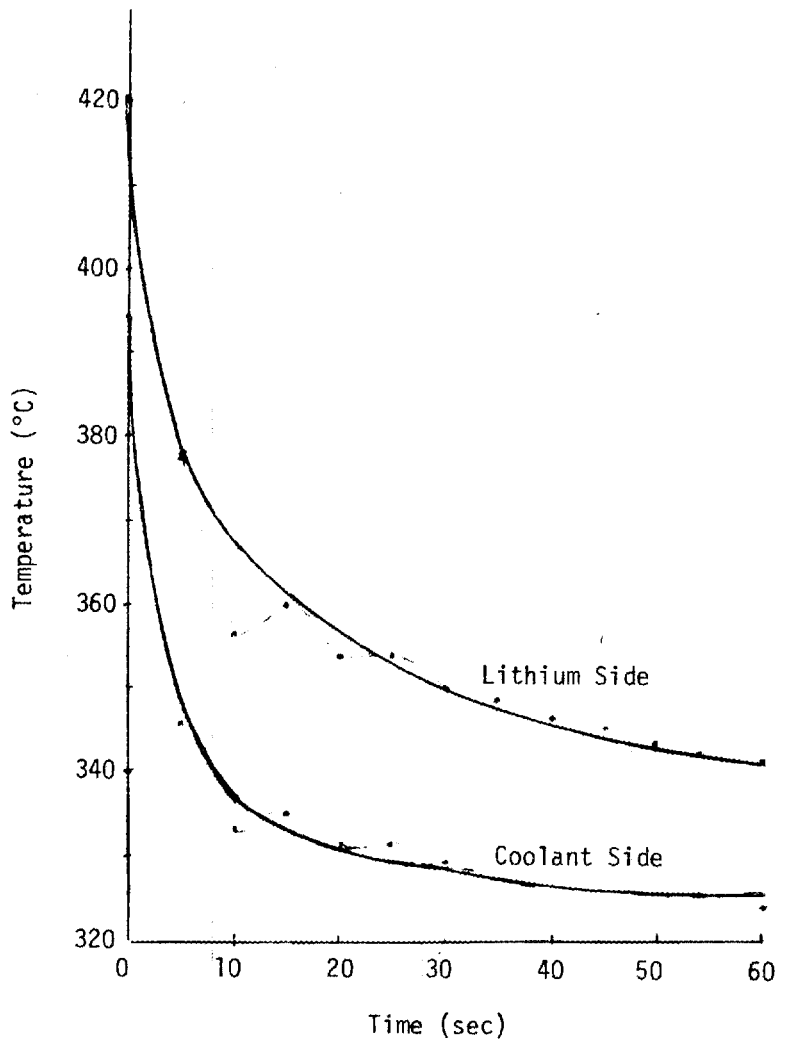
VARIATION OF INNER AND OUTER
LEFT COOLANT WALL TEMPERATURE
WITH TIME

DATE	DRAWN BY	FILE NO.	FIG.
12-19-76	JHL	CEPS-X-246	11



y = 2.13 m

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VARIATION OF INNER AND OUTER RIGHT COOLING WALL TEMPERATURE WITH TIME

DATE	DRAWN BY	FILE NO.	FIG.
12-19-76	KAK	CEPS-X-246	12

Table 6. Results of the Transient Temperature Simulation

	Steady State (°C)	Transient Case Min (°C)	Transient Case Max (°C)	Change from Steady State Temperature Min (°C)	Change from Steady State Temperature Max (°C)	Temperature Across Tube Min (°C)	Temperature Across Tube Max (°C)
Left side tube wall adjacent to the coolant	362	321	330	32	41	27	92
Left side tube wall adjacent to the lithium	391	336	345	46	55		
Right side tube wall adjacent to the coolant	394	324	363	31	70	0.95	120
Right side tube wall adjacent to the lithium	420	341	380	40	79		
Left side of the niobium wall	1168	886	888	280	282	160	189
Right side of the niobium wall	1329	1074	1077	252	255		

5. DISCUSSION OF RESULTS

5.1 Overall Energy Balance

5.1.1 Elimination of Unacceptable Designs

As shown in Tables 3, 4, and 5, all of the designs considered with a coolant temperature rise of 200°C were unacceptable. A large number of these cases produced coolant temperatures on the plasma side of the module in excess of 400°C. Since the exterior surface temperature of the module cannot exceed 400°C, all such cases are immediately discarded. These cases were those with the larger values of charged particle loading. Such large values (forcing an equal amount of energy to be generated in the front lithium zone) deposit a large fraction (>60%) of the total module output in the cooling tube adjacent to the plasma. These large amounts of energy deposition then cause large coolant temperatures and consequently excessive exterior tube wall temperatures.

After application of the 400°C temperature limit criteria, 12 cases remain. To these cases is applied the requirement of a 200°C temperature difference maximum across the niobium wall. Since all cases had values greater than 2400°C, as determined by GRADT, they were all eliminated.

The same criteria were applied to all the cases for a coolant temperature rise of 67°C. By limiting the outside of the cooling tube adjacent to the plasma to a temperature of 400°C, 30 of the 80 cases were eliminated as shown in Table 2. The table also points out a trend in this wall temperature. As the charged particle loading is increased, holding the tube diameter constant, the outside wall temperature increases. However, as one increases cooling tube diameter for a constant charged particle loading, the outside wall temperature also increases. This occurs because, as one increases the cooling tube diameter, holding the system dimensions constant, lithium is effectively being replaced with salt coolant or stainless steel tubing. Since the heat generation rates due to neutron flux for salt coolant and stainless steel tubing are two and four times higher than that for lithium, increasing the cooling tube diameter increases the amount of energy produced within the module. In addition, by keeping the charged particle loading constant, roughly the same thickness of front lithium zone is required to balance this flux. Therefore, the effective result is to reduce only the thickness of the rear lithium zone. Thus, more of the heat deposition occurs in the front cooling tube adjacent to the plasma. This causes higher coolant temperatures and thus higher exterior wall temperatures.

Finally, the limit of a 200°C temperature difference across the niobium wall was applied to all the remaining cases by analyzing the output from the one-dimensional temperature profile. These results appear on Table 4. All cases except one exceed this limit and were thus discarded. The one acceptable case occurred for a charged particle loading of 1 MW/m^2, a

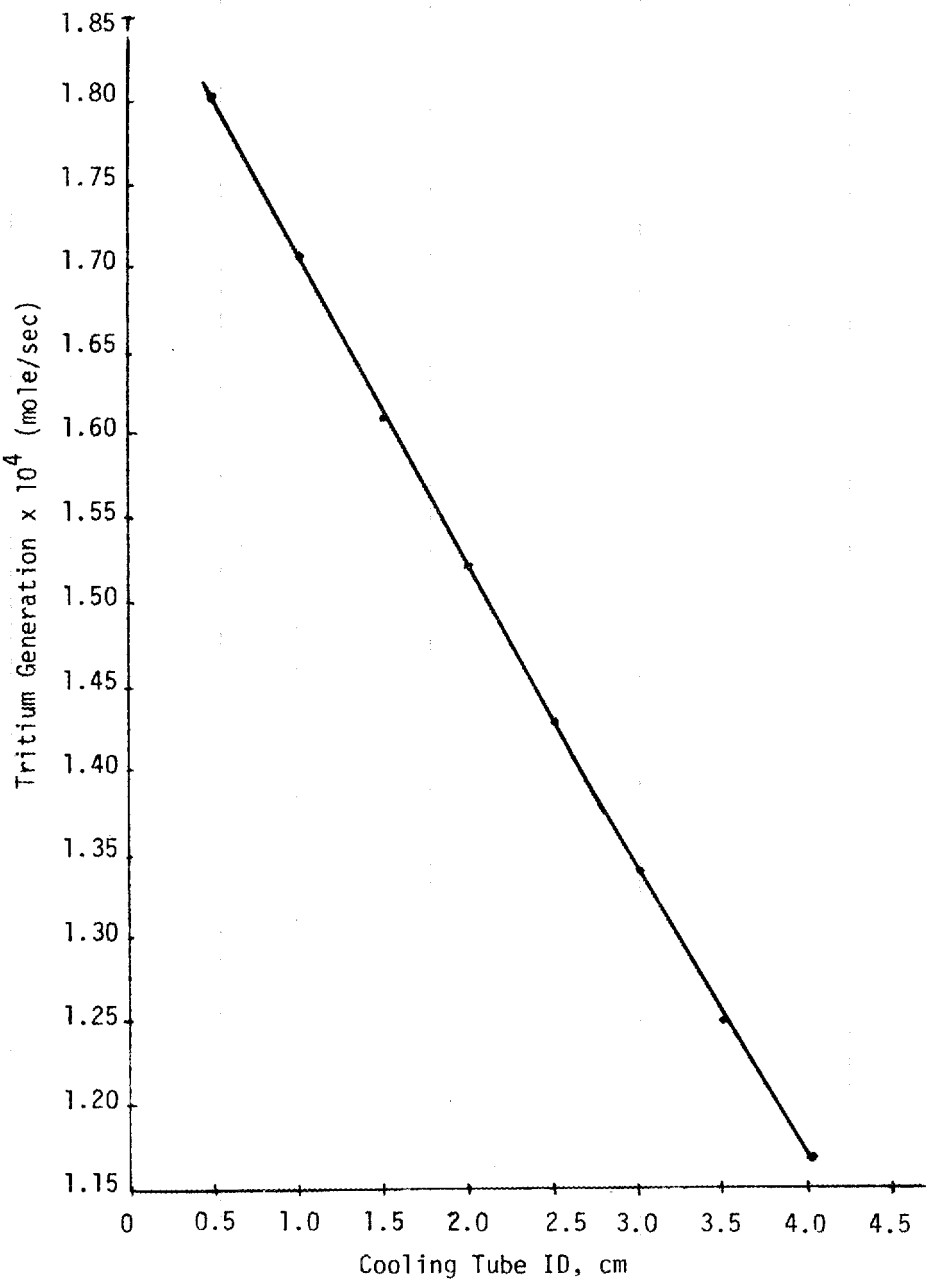
cooling tube inside diameter of 1 cm, and a coolant temperature rise of 67°C.

A trend also appears in these data. As one increases the charged particle loading at a constant value of coolant tube ID, the temperature drop across the niobium wall decreases. Temperature gradients across the niobium wall occur because the rates of heat generation in the front and back lithium sections are not equal. At low charged particle loadings, the flux due to this load can be matched by a very small front lithium section. This leaves a large rear section with its consequently large value of heat generation. These unbalanced rates of heat production then produce large temperature gradients. At larger values of charged particle loading, the size of the front lithium section must be increased to balance this flux. This reduces the size of the rear section. Since at low loadings, the rear section is significantly larger (e.g., 22 of 25 cm), increasing the loading makes the two lithium sections more equal in size. This brings the heat production rates in the two sections closer together, lowering the temperature gradient across the niobium wall.

Another trend is that as coolant tube inside diameter is increased for a fixed value of charged particle loading, the niobium wall temperature gradient is reduced. This occurs for a reason similar to that explained above. By increasing cooling tube ID, one is effectively only reducing the size of the rear lithium section. This reduces the heat generation rate in this section making it approach the generation rate in the front section, reducing the gradient across the niobium walls.

These cases are all for a cassette thickness of 25 cm. The overwhelming trend here is that in many cases, the excessive difference in size between the front and rear lithium sections caused many designs to exceed the temperature criteria. Most of these were caused because the rear section was significantly larger than the front section. Therefore, if modules of a smaller thickness were used (e.g., two modules each 12-cm-thick instead of one module 25-cm-thick), the effect would be to reduce the rear lithium section, because the size of the front lithium zone must remain the same size to balance the heat flux due to the charged particle loading. This would allow the heat generation rates to be much closer in the front and rear zones, making many more cases fit within the established criteria.

Furthermore, it can be observed that by lowering the overall temperature rise of the coolant, the outside tube wall temperature facing the plasma is lowered. Therefore, coolant temperature rises of lower than 67°C would make more cases fit the 400°C maximum and should be investigated. For this case study, the range of cooling tube diameters considered was 0.5 to 4.0 cm. This range of variables is a legitimate choice. Since below a cooling tube ID of 1 cm the pumping power begins to be a significant function of the total module power output, this represents a lower limit. Furthermore, if one plots the tritium production rate in the module as a function of cooling tube ID, the result is shown in Fig. 13. By the time a tube ID of 4 cm is attained, the production rate has dropped



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TRITIUM GENERATION DEPENDENCE
ON COOLING TUBE DIAMETER

DATE	DRAWN BY	FILE NO.	FIG.
12-19-76	JSD	CEPS-X-246	13

to 65% of its value at 0.5 cm. Since this is a significant decrease in tritium production, 4 cm is an approximate upper limit for tube diameter.

5.1.2 Variation of Module Power Output with Variation in Cooling Tube ID and Charged Particle Loading

As can be seen from Fig. 4, increasing the cooling tube inside diameter increases the total module power output. This occurs because as the cooling tube diameter is increased, lithium is being replaced by stainless steel cooling tube and molten salt coolant. Since the rates of heat generation due to neutron flux are four and two times higher than the heat generation in lithium, respectively, replacing lithium with these other materials increases the rate of heat generation within the module, and thus the total module power output.

Furthermore, the module power input increases as the charged particle loading is increased. Since the neutron flux is constant in all these cases, and the heat generation within the module is only a function of neutron flux, then the heat generation within the module will be a constant. Then by increasing the charged particle loading, one is adding additional energy to the module which will increase its total power output, and higher values of charged particle loading will thus produce a larger total module power output.

5.1.3 Ratio of Pumping Power to Total Module Power Output

The effect of variation of the coolant tube ID on the ratio of coolant pumping power to total module power is shown in Fig. 5. Below a tube diameter of 1 cm, the ratio rises rapidly, indicating a much greater fraction of the total power output must be used for pumping power. This is because, as the tube diameter decreases, pumping power increases due to increased pressure drop,and total module power output decreases for the reasons explained above. Both of these effects combine to increase the ratio. Exactly the converse occurs for increasing tube diameter, resulting in the observed low value for the ratio.

5.2 Two-Dimensional Steady State Temperature Profile

The results of the two-dimensional steady state calculation for the one acceptable case of a charged particle loading of 1.0 MW/m^2, a cooling tube ID of 1.0 cm, and a coolant temperature rise of 67°C is shown in Fig. 6. This plot depicts only the temperature at the top and bottom of the cassette, which are the points of occurrence of the extremes in temperature. The temperature increases on both sides of the niobium wall as that wall is approached, ending in a flat profile at the wall. This must be the result since the wall boundary condition is specified as adiabatic.

From the computer output (Appendix 9.3.2) it can be seen that the temperature decreases slightly at the very bottom of the lithium on the left side adjacent to the lower cooling tube. This would be expected since such a point is subject to convective cooling by the coolant and would, therefore, behave much the same as the side walls of the module which exhibit similar behavior. The maximum lithium temperature on this left side occurs at a point roughly 40 cm above the tube bottom.

The right side of the lithium behaves differently. In this case, since temperature increases as one moves away from the bottom of the module, this bottom will exhibit the lowest temperatures. Since the top of the module is assumed to be adiabatic, the module top will exhibit a maximum in temperature.

In addition, since the top and bottom profiles reflect the upper and lower bounds of temperature within the cassette, the plot allows one to see that the temperature changes in the vertical direction is much less than that in the horizontal direction. Therefore the assumption of no vertical temperature gradient in the derivation of the one-dimensional model is valid.

During the course of setting up this problem for HEATING5, an error was made by assigning $x = 0$ to occur at the inside of the right wall of the cooling tube adjacent to the plasma. Since the heat generation rates are functions of distance from the module face adjacent to the plasma, an error would be introduced into all the heat generation terms. This can be corrected by multiplying the heat generation function by a constant.

5.3 Steady State Tritium Concentration Profile

Figure 7 shows the steady concentration profile of tritium through the cassette as generated by HEATING5. The concentration profiles at the tube walls can be seen to level off due to the assumption that the cooling tubes are impermeable to tritium. At the tube walls, the temperature decreases rapidly to approach the coolant temperature. Since the diffusivity of tritium in lithium decreases with temperature, the diffusivity will be much smaller at the tube walls, accounting for the fact that the lithium concentrations rise dramatically about 3 cm from the cooling tubes. In addition, since the interior of the niobium tube is assumed to be a vacuum, the tritium concentration at the niobium must drop to zero as it does. Finally, the cooling tube wall concentration on the right side of the module is much higher than the cooling tube wall on the left side. Since the tritium concentration rate is proportional to the neutron flux at any point, which drops rapidly, a corresponding decrease in tritium concentration will be seen between the two cooling tube boundaries.

5.4 Transient Response

The transient simulations provided several interesting results. The most important is that the maximum temperature difference across the U-tubes is on the order of 100°C. This approximation is crude and could be improved by determining the minimum coolant temperature more realistically. This would involve determining the minimum heat flux into the coolant during the transient period and integrating over the surface of the U-tubes. The minimum flux is that which is present at the end of the transient simulation involving the maximum coolant temperatures.

The difference between the maximum and minimum temperature change is 1% at the niobium wall, 23% at the left side tube wall, and 56% at the right side tube wall. The difference is so small at the niobium wall, because the differences between the minimum and maximum bulk coolant temperatures and the initial niobium wall temperature are very nearly equal. The difference is larger at the tube walls, because the differences between the minimum and maximum bulk coolant temperatures and the initial wall temperatures are not nearly the same. The difference is much higher at the right side wall than the left side wall because the error in assuming the minimum coolant temperature to be the inlet temperature is greater on the outlet side of the tube.

The temperature change is greatest at the niobium wall. This is because during the transient period, the heat flux out of the lithium drops. The reduced heat flux is manifested in the form of a flattening temperature profile. The temperature change caused by a flattening profile increases with increasing distance, so it will reach a maximum value at the niobium wall.

The fact that the two sides of the niobium wall do not cool uniformly could cause stress problems. If the module had been designed so that the temperature difference across the niobium tubes was near the maximum value allowed by stress limitations and the sides of the wall cooled at different rates, the temperature difference could become larger than the maximum value allowed.

As expected, due to the larger initial temperature difference between the tube wall and the coolant, the temperature decreases much more rapidly at the beginning of the maximum cooling simulations (Figs. 11 and 12) than at the beginning of the minimum cooling simulation (Figs. 8 and 9). This rapid temperature decrease causes the oscillations indicated by the dashed lines in Fig. 12. These oscillations are a product of the implicit method of solving finite difference equations. The solution is shown to be stable by the fact that the oscillations are damped instead of increasing with increasing time.

6. CONCLUSIONS

1. A computer program, ENBAL, calculates overall energy balances for the cassette.

2. A computer program, GRADT, calculates the temperature based on a simplified one-dimensional model.

3. An input procedure for using HEATING5 successfully determines temperature profiles, tritium concentration profiles, and transient behavior.

4. For a cassette thickness of 25 cm and for a coolant temperature increase greater than 67°C, unacceptable designs for the cassette result.

7. RECOMMENDATIONS

1. Investigate cassette thicknesses less than 25 cm and coolant temperature rises less than 67°C.

2. Modify the overall energy balance program to include design evaluation criteria and variable coolant properties.

8. ACKNOWLEDGMENT

The group would like to thank R.W. Werner, T.J. Huxford, and T.E. Shannon for all their assistance, advice, and encouragement.

9. APPENDIX

9.1 Overall Energy Balance

9.1.1 Mathematical Model

The overall energy balance is based on the following equations. Thermal energy is generated from interactions of the neutrons with the molecules contained in the blanket and from the exothermic tritium generation reaction. It can be shown that the heat released from the tritium reactions is small compared with the interaction energy released. Neutron flux, and therefore heat generation decreases exponentially with distance into the blanket, and can be represented by (14):

$$P_L(x) = 3.74 \exp(-\frac{x}{0.385}) \tag{15}$$

when the neutron wall loading is 1 MW/m^2. Furthermore, in a molten salt coolant, the heat generation is twice that for lithium, or:

$$P_C(x) = 7.48 \exp(-\frac{x}{0.385}) \tag{16}$$

and in the stainless steel coolant tube walls, the rate of heat generation is:

$$P_{SS}(x) = 14.96 \exp(-\frac{x}{0.385}) \tag{17}$$

To find the heat generation within a region with boundaries at distances x_a and x_b from the module face, the appropriate equation for the material being considered is integrated over the volume of the material to give

$$P^T_{ab} = \int P(x)dV = \int P_o \exp(-\frac{x}{0.385})dV \tag{18}$$

Since dV is equal to $A_m dx$, where A_m is the module surface area facing the plasma,

$$P^T_{ab} = A_m P_o \int_{x_a}^{x_b} \exp(-\frac{x}{0.385})dx = 0.385\ A_m P_o[\exp(-\frac{x_a}{0.385}) - \exp(-\frac{x_b}{0.385})] \tag{19}$$

The total power generation within a module is then the sum of all these effects within all regions of the module.

Correlations for heat transfer coefficients for various values of Prandtl number were obtained from the literature (7).

The niobium wall was placed to minimize the thermal stress on the cooling tube adjacent to the plasma. This is done to maintain the structural integrity of the module. Since thermal stress is caused by a temperature gradient across the tube, this gradient was reduced to zero by balancing the heat fluxes through the opposing tube walls. Quantitatively, this balance can be represented as:

$$Q_{inc} + NP^{T}_{SS1}W_t = NP^{T}_{SS2}W_t + NP^{T}_{Li1}W_{Nb} \tag{20}$$

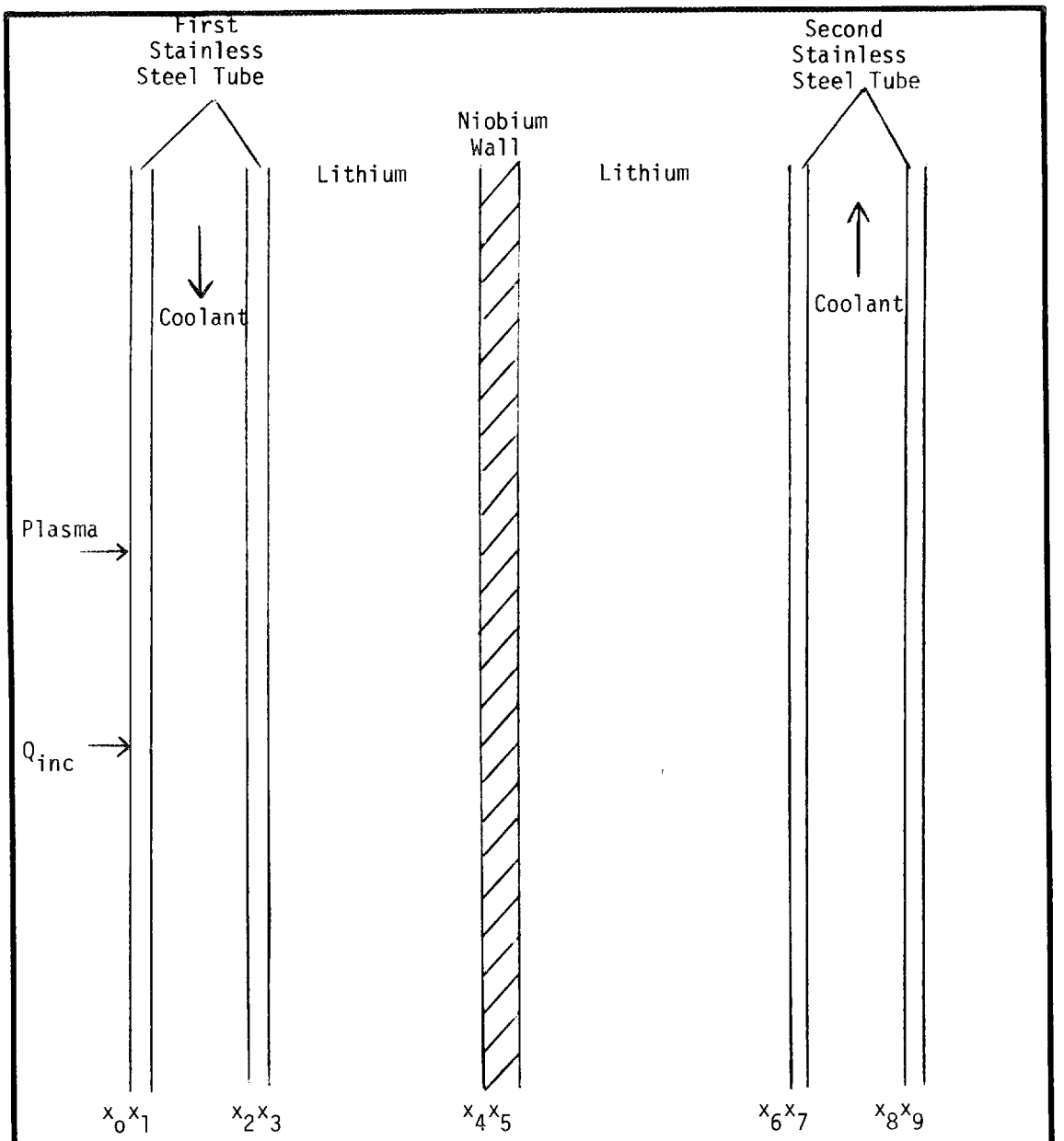
where Q_{inc} is the incident flux due to radiation of charged particles from the plasma ranging from 0.1 to 1.0 MW/m^2 and P_{SS1} and P_{SS2} give the heat generation for the plasma side and lithium side, respectively, within the first stainless steel tube, while P_{Li1} is that generated within the first lithium region.

Defining the positions of the various boundaries as in Fig. 14 and substituting in the appropriate expressions given above gives:

$$\begin{aligned} Q_{inc} &+ (14.96)(0.385)[\exp(-\frac{x_0}{0.385}) - \exp(-\frac{x_1}{0.385})]N \\ &= (14.96)(0.385)[\exp(-\frac{x_2}{0.385}) - \exp(-\frac{x_3}{0.385})]N \\ &+ (3.74)(0.385)[\exp(-\frac{x_3}{0.385}) - \exp(-\frac{x_4}{0.385})]N \end{aligned} \tag{21}$$

Once a tube diameter, tube wall thickness, neutron loading, and incident energy due to charged particle loading are specified, this equation can be solved for x_5, the position of the niobium wall.

The overall energy balance is also used to determine the temperature profile through the coolant. Since this information is input to HEATING5 to determine the two-dimensional lithium temperature profile, the cassette was divided into 44 regions. Since each region must have a uniform boundary condition over each surface, the average coolant temperature in each of regions 1 through 12 and 33 through 44 must be determined. This is done with an energy balance over a section through the cooling tube. An energy balance on the coolant would be:



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BOUNDARY ASSIGNMENTS FOR
OVERALL ENERGY BALANCE

DATE	DRAWN BY	FILE NO.	FIG.
12-19-76	JHL	CEPS-X-246	14

$$\dot{M}\, C_p(T_{out} - T_{in})_i = Q_{inc} + N[P^T_{SS1} + P^T_C + P^T_{SS2} + P^T_{Li1}]V \quad (22)$$

for any region i on the front half of the module. By beginning in region 1 where T_{in} is the inlet coolant temperature and knowing all the heat generation terms, heat capacity, and mass flow rate, one can then determine the temperature profile throughout the coolant.

A similar equation holds on the back side of the niobium tube where

$$\dot{M}\, C_p(T_{out} - T_{in})_i = N[P^T_{SS1} + P^T_C + P^T_{SS1} + P^T_{Li2}]V \quad (23)$$

The heat generation terms in the stainless steel and salt now refer to those in the tubing in the rear of the module. Q_{inc} is eliminated on the rear tube since the rear of the module has no flux of charged particles incident upon it.

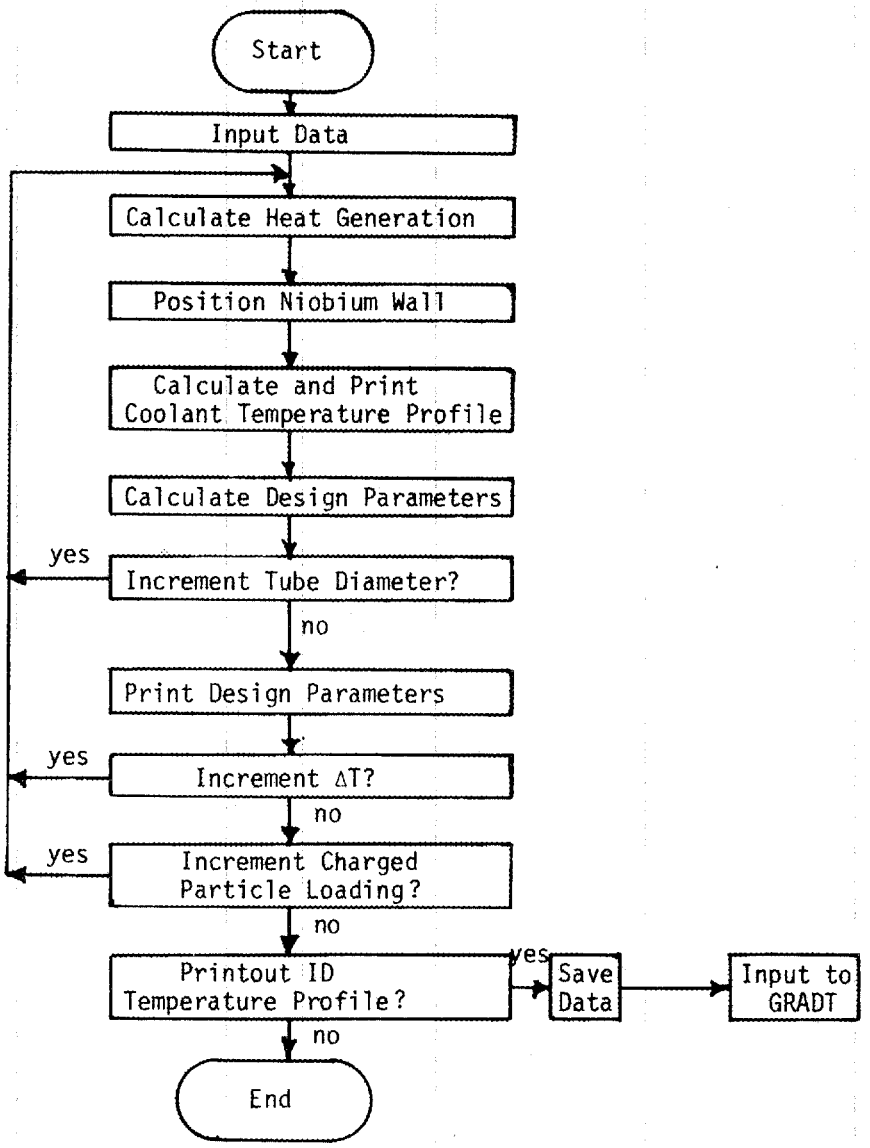
The above model was varied slightly to consider regions 11, 12, 33, and 34. Since regions 11 and 34 have no surface adjacent to the lithium, there will be no heat flux into these sections. Therefore, the bulk temperature in region 11 will be the same as the exit temperature from region 10. Similarly, the bulk temperature in region 34 will be the same as the exit temperature from region 33. To include regions 12 and 33, it was assumed that the flux through a unit length in any of these regions was equal. Since neutron and charged particle loadings are not functions of position, the heat generation in each of regions 13 through 22 will be equal, and the generation in regions 23 through 32 are similarly equal. At steady state, the rate of heat generation in any region (e.g., 15) must equal the rate of heat lost through its surfaces. Since $\partial T/\partial y$ was shown to be much less than $\partial T/\partial x$, flux in the y-direction will be much less than flux in the x-direction. This will apply everywhere except at the bottom of the cassette, where convective cooling will make $\partial T/\partial y$ greater. In central regions, the heat generation in any region (e.g., 17) must equal the flux into the adjacent sections of cooling tube (e.g., 6). If this flux per unit distance is multiplied by the length of surface in a region, the flux into that region and therefore the temperature change can be found.

9.1.2 Use of the Overall Energy Balance Program

The input data requested by the program is outlined in Table 7. A flowsheet of ENBAL is shown in Fig. 15. All units are specified in SI units. The program allows either case studies to be performed over ranges of certain values or temperature profiles to be produced for individual cases.

Table 7. Input Data to ENBAL

Parameter	Units	Notes
Case study or temperature profile		0 = temperature profile 1 = case studies
Neutron wall loading	MW/m^2	
Charged particle loading	MW/m^2	temperature profile only
Upper bound	MW/m^2	case study only
Lower bound	MW/m^2	case study only
Step size	MW/m^2	case study only
Cooling tube ID	cm	temperature profile only
Upper bound	cm	case study only
Lower bound	cm	case study only
Step size	cm	case study only
Coolant temperature change	°C	temperature profile only
Upper bound	°C	case study only
Lower bound	°C	case study only
Step size	°C	case study only
Divertor efficiency	%	
Blanket thickness	cm	
Niobium wall OD	cm	
Height of blanket module	m	
Width of blanket module	m	
Inlet coolant temperature	°K	
Coolant specific heat	J/kg-°K	
Coolant density	kg/m^3	
Coolant viscosity	$N\text{-}sec/m^2$	
Coolant thermal conductivity	W/m-°K	
Cooling tube thermal conductivity	W/m-°K	temperature profile only
Coolant temperature profile output	-	temperature profile only 0 = output printed 1 = no output
Module design parameter output	-	temperature profile only 0 = output printed 1 = no output



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FLOW DIAGRAM FOR ENBAL

DATE	DRAWN BY	FILE NO.	FIG.
12-19-76	REB	CEPS-X-246	15

When performing case studies, the program will automatically vary any of three parameters: the charged particle loading, the cooling tube inside diameter, and the temperature change in the coolant. For all three of these variables, the lower and upper bounds must be supplied for each parameter and a step size. This allows any range of these variables to be examined. If only one of the three values is to be considered, the lower and upper bounds must be typed in as the same value. The step size may then be any non-zero number. Case studies may be performed on other variables, but they must be input each time. The program then determines and prints out the steady state coolant temperature profile and the various module design parameters listed in Table 8. No criteria for evaluation of acceptable designs are considered. Sample outputs are shown in Tables 9 and 10. Table 9 shows a sample of the coolant temperature profile. The first column gives the distance from the bottom of the U-tube (in this case the U-tube was 4-m high) and represents the boundary of a region (Fig. 20). The second column gives the exit coolant temperature from each region. Since this information is intended as input to HEATING5 to determine the two-dimensional temperature profile, column three labels the region number according to the way the HEATING5 regions are set up (Fig. 20). Column four is then the average temperature within this region and is the boundary condition input to HEATING5.

In performing case studies, the variable that is changed most rapidly is cooling tube inner diameter. Therefore, every time the program completes one cycle of the range of tube ID's being considered (with coolant temperature profiles being printed out for each case), a table of module design parameters as in Table 10 is printed out. This table is a summary of the data in Table 8 for each tube ID considered while holding charged particle loading and coolant temperature change constant.

The program also has the capability to predict one-dimensional approximations to two-dimensional temperature profiles through the lithium (Sect. 9.3.2). When determining these one-dimensional profiles, the program will only consider one value of each of charged particle loading,coolant temperature change and cooling tube inner diameter. Outputs of the coolant temperature profile and the module design parameters become optional. All input data are stored in a data file called SDATA. Determination and printout of this one-dimensional lithium temperature profile is performed by a program called GRADT, which is explained in Sect. 9.2. Since this program is called from ENBAL, all data necessary for operating the program must be saved before the program is called. Therefore, the data file SDATA was established. GRADT is called automatically from ENBAL. To facilitate determination of many temperature profiles, an option exists within GRADT to return to ENBAL to consider another case. When this option is flagged, ENBAL is called and all the input data are recovered from file SDATA. This prevents having to enter all the constant parameters again. The values of any of the three variable input parameters can then be modified by flagging any of the outputs from ENBAL for printout. With the modified parameters, the lithium temperature profile is then determined. To vary any other parameter than the three specified variable parameters between successive one-dimensional profiles, the program must be restarted.

Table 8. Module Design Parameters in Output Table from ENBAL

Parameter	Units	Notes
Charged particle loading	MW/m^2	constant for any one table
Coolant temperature change	°K	constant for any one table
Cooling tube ID	cm	several cases considered in any one table
Thickness of front lithium zone	cm	
Thickness of rear lithium zone	cm	
Coolant mass flow rate/module	kg/sec	
Coolant linear velocity	m/sec	
Coolant Reynolds number	-	
Number of cassettes (U-tube)/module	-	
Film heat transfer coefficient	W/m^2-°K	
Total thermal power output/module	MW	
Total coolant pumping power/module	W	power required to move coolant through cooling tubes
Ratio of coolant pumping power to total thermal power	-	

Table 9. Sample of Coolant Temperature Profile

CH PART LOADING= 0.10 MW/M^2
COOLANT DELTA T= 200 K
COOLING TUBE ID= 1.5 CM

DIST(M)	TEMP(K)	REGION	AV T(K)
4	573	INLET	
3.6	577.791	1	575.395
3.2	582.581	2	580.186
2.8	587.372	3	584.977
2.4	592.162	4	589.767
2	596.953	5	594.558
1.6	601.744	6	599.348
1.2	606.534	7	604.139
0.8	611.325	8	608.93
0.4	616.116	9	613.72
0	620.906	10	618.511
0	620.906	11	620.906
0	622.403	12	621.655
0	626.967	33	624.685
0	626.967	34	626.967
0.4	641.57	35	634.268
0.8	656.173	36	648.872
1.2	670.777	37	663.475
1.6	685.38	38	678.078
2	699.983	39	692.682
2.4	714.587	40	707.285
2.8	729.19	41	721.888
3.2	743.793	42	736.492
3.6	758.397	43	751.095
4	773.	44	765.698

Table 10. Sample of Module Design Parameters

CH PART LOADING= 0.50 MW/M^2
COOLANT DELTA T= 67 K

COOLANT TUBE ID (CM)	FRONT LITHIUM (CM)	REAR LITHIUM (CM)	MASS FLOW /MODULE (KG/SEC)	COOLANT VELOCITY (M/SEC)	REYNOLDS NUMBER	CASSETTES /MODULE
0.5	4.60	18.79	105.74	17.82	49888.	180
1.0	4.70	17.58	110.36	9.30	52069.	90
1.5	4.80	16.37	114.97	6.46	54242.	60
2.0	4.90	15.16	119.55	5.04	56406.	45
2.5	5.00	13.94	124.12	4.18	58562.	36
3.0	5.10	12.73	128.67	3.61	60709.	30
3.5	5.20	11.52	133.21	3.30	64646.	25
4.0	5.30	10.31	137.73	2.97	66461.	22

COOLANT TUBE ID (CM)	HT TRANS COEFF (W/M^2-K)	TOTAL MODULE POWER (MW)	MODULE PRESSURE DROP (N/M^2)	MODULE PUMPING POWER (W)	PUMPING /TOTAL POWER
0.5	40935.	10.91	4.542E+06	2.858E+05	2.620E-02
1.0	21208.	11.39	6.122E+05	4.022E+04	3.532E-03
1.5	14626.	11.86	1.950E+05	1.334E+04	1.125E-03
2.0	11332.	12.34	8.814E+04	6.272E+03	5.085E-04
2.5	9352.	12.81	4.822E+04	3.563E+03	2.782E-04
3.0	8030.	13.28	2.974E+04	2.278E+03	1.716E-04
3.5	7251.	13.74	2.093E+04	1.660E+03	1.207E-04
4.0	6492.	14.21	1.473E+04	1.207E+03	8.495E-05

9.1.3 ENBAL Listing

```
10 DIM O(12,30)
20 DIM B(30)
30 PRINT "CASE STUDIES (1) OR TEMPERATURE PROFILES (0)";
40 INPUT V9
50 PRINT "NEUTRON WALL LOADING (MW/M^2)";
60 INPUT N1
65 IF V9=0 THEN 320
70 PRINT "CHARGED PARTICLE LOADING (MW/M^2)"
80 IF V9=1 THEN 130
90 INPUT J1
100 J2=J1
110 J3=1
120 GO TO 150
130 PRINT "   BOUNDS (LOWER,UPPER,STEP)=";
140 INPUT J1,J2,J3
150 PRINT "INSIDE DIAMETER OF COOLING TUBES (CM)"
160 IF V9=1 THEN 210
170 INPUT J7
180 J8=J7
190 J9=1
200 GO TO 230
210 PRINT "   BOUNDS (LOWER,UPPER,STEP)=";
220 INPUT J7,J8,J9
230 PRINT "DELTA T FOR COOLANT (DEG K)"
240 IF V9=1 THEN 290
250 INPUT J4
260 J5=J4
270 J6=1
280 GO TO 310
290 PRINT "   BOUNDS (LOWER,UPPER,STEP)=";
300 INPUT J4,J5,J6
310 IF V8=1 THEN 660
320 PRINT "DIVERTOR EFFICIENCY (%)=";
330 INPUT E1
340 PRINT "BLANKET THICKNESS IN (CM) =";
350 INPUT B1
360 PRINT "NIOBIUM WINDOW THICKNESS (CM) =";
370 INPUT N2
380 PRINT "LENGTH OF BLANKET MODULE (M) =";
390 INPUT L1
400 PRINT "WIDTH OF BLANKET MODULE (M) =";
410 INPUT W1
420 PRINT "INLET COOLANT TEMP (DEG K)=";
430 INPUT T8
440 PRINT "COOLANT SPECIFIC HEAT (J/KG-K)=";
450 INPUT C1
460 PRINT "COOLANT DENSITY (KG/M^3)=";
470 INPUT D2
480 PRINT "COOLANT VISCOSITY (N-S/M^2)=";
490 INPUT V1
```

```
500 PRINT "COOLANT THERMAL CONDUCTIVITY (W/M-K)=";
510 INPUT K2
520 IF V9=1 THEN 600
530 FILES SDATA,GDATA
540 PRINT "COOLING TUBE THERMAL CONDUCTIVITY (W/M-K)=";
550 INPUT K9
555 SCRATCH #1
560 PRINT #1,N1,E1,B1,N2,L1,W1,T8,C1,D2,V1,K2,K9
570 GO TO 600
590 INPUT #1,N1,E1,B1,N2,L1,W1,T8,C1,D2,V1,K2,K9
600 V8=1
610 PRINT "COOLANT TEMPERATURE PROFILE? (0=YES,1=NO)";
620 INPUT V7
630 PRINT "MODULE DESIGN PARAMETERS? (0=YES,1=NO)";
640 INPUT V6
645 V9=0
650 GO TO 70
660 FOR A=J1 TO J2 STEP J3
670 FOR X1=J4 TO J5 STEP J6
680 I3=0
690 FOR D1=J7 TO J8 STEP J9
700 I3=I3+1
710 O(1,I3)=D1
720 Q1=A*(1-E/100)*W1*L1*1.0E6
730 T1=D1/18
740 LET Y0=0
750 LET Y1=T1/100
760 LET Y2=Y1+D1/100
770 LET Y3=Y2+Y1
780 LET Y4=Y3
790 LET Z1=W1*L1
800 LET Q2=5.76E6*N1*(EXP(-Y0/.385)-EXP(-Y1/.385))*Z1
810 LET Q3=2.88E6*N1*(EXP(-Y1/.385)-EXP(-Y2/.385))*Z1
820 LET Q4=5.76E6*N1*(EXP(-Y2/.385)-EXP(-Y3/.385))*Z1
830 LET Y4=Y4+.001
840 LET Y9=B1/100
850 LET Q5=1.44E6*N1*(EXP(-Y3/.385)-EXP(-Y4/.385))*Z1
860 LET S1=(Q1+Q2)-(Q4+Q5)
870 IF S1>0 THEN 830
880 IF S1<=0 THEN 890
890 LET Y5=(N2/100)+Y4
900 LET Y6=(B1/100)-(T1/50)-(D1/100)
910 LET Y7=Y6+T1/100
920 LET Y8=Y7+(D1/100)
930 LET Q6=1.44E6*N1*(EXP(-Y5/.385)-EXP(-Y6/.385))*Z1
940 LET Q7=5.76E6*N1*(EXP(-Y6/.385)-EXP(-Y7/.385))*Z1
950 LET Q8=2.88E6*N1*(EXP(-Y7/.385)-EXP(-Y8/.385))*Z1
960 LET Q9=5.76E6*N1*(EXP(-Y8/.385)-EXP(-Y9/.385))*Z1
970 LET Q0=(Q1+Q2+Q3+Q4+Q5+Q6+Q7+Q8+Q9)*1.0E-6
980 LET T3=(Y4-Y3)*100
990 LET T2=(Y6-Y5)*100
```

```
1000 O(2,I3)=T3
1010 O(3,I3)=T2
1020 O(4,I3)=Q0
1030 T7=T8
1040 LET W2=D1/100
1050 LET M1=(Q0*1.0E6)/(C1*X1)
1060 O(5,I3)=M1
1070 LET N3=INT((W1*100)/((2*T1)+D1))
1080 O(12,I3)=N3
1090 LET M2=M1/N3
1100 LET V2=(4*M2)/(D2*3.14*W2^2)
1110 O(6,I3)=V2
1120 R9=(Q1+Q2+Q3+Q4+Q5)/(M2*C1*N3)
1130 R9=R9/(100*L1+B1/2)
1140 R8=(Q6+Q7+Q8+Q9)/(M2*C1*N3)
1150 R8=R8/(100*L1+B1/2)
1160 R7=R9*10*L1
1170 R6=R8*10*L1
1180 R5=R9*B1/2
1190 R4=R8*B1/2
1200 R1=D2*V2*W2/V1
1210 O(7,I3)=R1
1220 B(0)=T8
1230 IF V7=1 THEN 1330
1235 PRINT
1240 PRINT
1250 PRINT "            COOLANT TEMPERATURE PROFILE"
1260 PRINT
1270 PRINT USING "          CH PART LOADING= ##.## MW/M^2",A
1280 PRINT USING "          COOLANT DELTA T=    ### K",X1
1290 PRINT USING "          COOLING TUBE ID=   ##.# CM",D1
1300 PRINT "DIST(CM)","TEMP(K)","REGION","AV T(K)"
1310 PRINT "---------","-------","------","-------"
1320 PRINT L1,T8,"INLET"
1330 J=1
1340 FOR I=1 TO 10
1350 T6=T7
1360 T7=T7+R7
1370 T5=(T6+T7)/2
1380 S2=L1*(1-I/10)
1390 B(J)=T5
1400 J=J+1
1405 IF V7=1 THEN 1420
1410 PRINT S2,T7,I,T5
1420 NEXT I
1430 IF V7=1 THEN 1450
1440 PRINT " 0",T7," 11",T7
1450 T6=T7
1460 T7=T7+R5
1470 T5=(T6+T7)/2
1480 IF V7=1 THEN 1500
1490 PRINT " 0",T7," 12",T5
1500 T6=T7
```

```
1510 T7=T7+R4
1520 T5=(T6+T7)/2
1530 IF V7=1 THEN 1560
1540 PRINT " 0",T7," 33",T5
1550 PRINT " 0",T7," 34",T7
1560 I0=0
1570 FOR I=35 TO 44
1580 I0=I0+1
1590 T6=T7
1600 T7=T7+R6
1610 T5=(T6+T7)/2
1620 S2=L1*I0/10
1630 B(J)=T5
1640 J=J+1
1650 IF V7=1 THEN 1670
1660 PRINT S2,T7,I,T5
1670 NEXT I
1675 B(21)=T8+X1
1680 LET P1=(V1*C1)/K2
1690 IF R1<10000 THEN 1710
1700 IF R1>10000 THEN 1730
1710 LET H1=(4.364*K2)/(D1/100)
1720 GO TO 1840
1730 IF P1<=0.1 THEN 1770
1740 IF (P1+.5)<=1.5 THEN 1790
1750 IF (P1+1.0)<=21 THEN 1810
1760 IF P1>20 THEN 1830
1770 LET H1=(6.3+(.003*R1*P1))*(K2/(D1/100))
1780 GO TO 1840
1790 LET H1=(.022)*(P1^.6)*(R1^.8)*(K2/(D1/100))
1800 GO TO 1840
1810 LET H1=(.0155)*(P1^.5)*(R1^.83)*(K2/(D1/100))
1820 GO TO 1840
1830 LET H1=(.0118)*(P1^.3)*(R1^.9)*(K2/(D1/100))
1840 O(11,I3)=H1
1850 IF R1<3000 THEN 1870
1860 IF R1>=3000 THEN 1900
1870 PRINT "FLOW IS LAMINAR"
1880 LET F1=64/R1
1890 GO TO 1910
1900 LET F1=.0056+(.5*(R1^-.32))
1910 IF P1<=0.1 THEN 2100
1920 IF (P1+.5)<=1.5 THEN 1950
1930 IF (P1+1.0)<=21 THEN 2100
1940 IF P1>20 THEN 2100
1950 PRINT "GAS, MOLECULAR WEIGHT IS, (GRAM/MOLE)=";
1960 INPUT G1
1970 PRINT "COOLANT TUBE INLET TEMPERATURE (DEGREE KELVIN)=";
1980 INPUT X2
1990 PRINT "AVERAGE COOLANT TEMP IN DEGREES KELVIN=";
2000 INPUT T4
```

```
2010 PRINT "AVERAGE COOLANT PRESSURE (NEWTON/M^2) =";
2020 INPUT P2
2030 PRINT "RATIO OF SPECIFIC HEATS,I.E. (CP/CV) =";
2040 INPUT G2
2050 LET D3=(32*F1*(8.31E3/G1)*T4*(M2^2.0)*L1)/(9.87*P2*(W2^5))
2060 LET P3=M2*C1*X1
2070 LET P4=(1-(1/G2))*(X2/X1)*(D3/P2)
2080 LET P5=P4*P3*N3
2090 GO TO 2630
2100 LET D4=((F1*D2*(V2^2.0))/(2*W2))*L1
2110 O(8,I3)=D4
2120 LET P6=(M2/D2)*D4*N3
2130 P8=P6/(Q0*1.0E6)
2140 O(9,I3)=P8
2150 O(10,I3)=P6
2160 NEXT D1
2165 IF V6=1 THEN 2520
2170 PRINT
2180 PRINT
2190 PRINT
2200 PRINT
2210 PRINT "                    MODULE DESIGN PARAMETERS"
2220 PRINT
2230 PRINT USING "                    CH PART LOADING= ###.## MW/M^2",A
2240 PRINT USING "                    COOLANT DELTA T=     ### K",X1
2250 PRINT
2260 PRINT "COOLANT   FRONT    REAR    MASS FLOW  COOLANT"
2270 PRINT "TUBE ID  LITHIUM  LITHIUM   /MODULE   VELOCITY";
2280 PRINT "  REYNOLDS  CASSETTES"
2290 PRINT "  (CM)     (CM)     (CM)    (KG/SEC)   (M/SEC)";
2300 PRINT "   NUMBER    /MODULE"
2310 PRINT "-------  -------  -------  ---------  --------";
2320 PRINT "  --------  ---------"
2330 FOR K=1 TO I3
2340PRINT USING 2350,O(1,K),O(2,K),O(3,K),O(5,K),O(6,K),O(7,K),O(12,K)
2350: ##.#     ##.##    ##.##     ###.##     ##.##    ######.     ###
2360 NEXT K
2370 PRINT
2380 PRINT
2390 PRINT "                    TOTAL    MODULE     MODULE"
2400 PRINT "COOLANT  HT TRANS   MODULE  PRESSURE    PUMPING    ";
2410 PRINT "PUMPING"
2420 PRINT "TUBE ID    COEFF    POWER     DROP       POWER";
2430 PRINT "      /TOTAL"
2440 PRINT "  (CM)   (W/M^2-K)   (MW)    (N/M^2)      (W)";
2450 PRINT "        POWER"
2460 PRINT "-------  ---------  ------  ---------  ---------";
2470 PRINT "  ---------"
2480 FOR K=1 TO I3
2490 PRINT USING 2500,O(1,K),O(11,K),O(4,K),O(8,K),O(10,K),O(9,K)
2500 : ##.#      #####.    ##.## ##.###^^^^  ##.###^^^^  ##.###^^^^
```

```
2510 NEXT K
2520 NEXT X1
2530 NEXT A
2540 IF V9=1 THEN 2630
2560 SCRATCH #2
2570 PRINT #2,D1,H1,T1,L1,Q4,Q5,Q6,Q7,Y3,Y4,Y5,Y6,T2,T3
2580 FOR I=0 TO 21
2590 PRINT #2,B(I)
2600 NEXT I
2610 PRINT #2,N3,K9
2620 CHAIN GRADT
2630 END

READY
```

9.1.4 ENBAL Nomenclature

Arrays

B(I)	contains bulk temperature profile through coolant	°K
O(I,J)	contains I^{th} variable for the Jth coolant tube ID (to be passed to GRADT)	

Single Variables

A	current value of charged particle loading	MW/m^2
B1	blanket thickness	cm
C1	coolant specific heat	J/kg-°K
D1	current value of coolant tube ID	cm
D2	coolant density	kg/m^2
D3	pressure drop across cooling tube (for gaseous coolant)	N/m^2
D4	pressure drop across cooling tube (for incompressible fluid)	N/m^2
E1	divertor efficiency	%
F1	friction factor for cooling tube	dimensionless
G1	molecular weight (of gaseous coolant)	gm/mole
G2	ratio of specific heats (C_p/C_u)(for gaseous coolant)	dimensionless
H1	heat transfer coefficient (coolant boundary layer)	W/m^2-°K

I	for loop counter	-
I0	region counter	-
I3	total number of coolant tube diameters considered	-
J	total number of regions considered	-
J1	lower limit of charged particle loading	MW/m^2
J2	upper limit of charged particle loading	MW/m^2
J3	step for charged particle loading (for loop)	MW/m^2
J4	lower limit of coolant delta T	°K
J5	upper limit of coolant delta T	°K
J6	step for coolant delta T (for loop)	°K
J7	lower limit of coolant tube ID	cm
J8	upper limit of coolant tube ID	cm
J9	step for coolant tube ID (for loop)	cm
K	for loop counter	-
K2	coolant thermal conductivity	W/m-°K
K9	cooling tube thermal conductivity	W/m-°K
L1	length of blanket module	m
M1	total coolant mass flow through module	kg/sec
M2	coolant mass flow through a single cassette	kg/sec
N1	neutron wall loading	MW/m^2
N2	niobium tube OD	cm
N3	number of cassettes per module	-
P1	coolant Prandtl number	dimensionless
P2	average coolant pressure (for gaseous coolant)	N/m^2
P3	thermal energy absorbed by one cassette coolant (for gaseous coolant)	W

P4	ratio of pumping power to thermal power (for gaseous coolant)	-
P5	total pumping power for module (for gaseous coolant)	W
P6	total pumping power for module (for incompressible coolant)	W
P8	ratio of pumping power to thermal power (for incompressible coolant)	-
Q0	total thermal energy output per module	MW
Q1	thermal load (due to charged particles) on first wall	W
Q2	heat generation in first tubing wall facing plasma	W
Q3	heat generation in salt facing plasma	W
Q4	heat generation in first tubing wall facing lithium	W
Q5	heat generation in first lithium breeding region	W
Q6	heat generation in second lithium breeding region	W
Q7	heat generation in second tubing wall facing lithium	W
Q8	heat generation in salt in second tubing	W
Q9	heat generation in second tubing wall facing back of module	W
R1	coolant Reynolds number	dimensionless
R4	coolant temperature change in region 33	°K
R5	coolant temperature change in region 12	°K
R6	coolant temperature change in regions 35 through 44	°K/region
R7	coolant temperature change in regions 1 through 10	°K/region
R8	coolant temperature change in regions 33 through 44 (small increment)	°K/cm
R9	coolant temperature change in regions 1 through 12 (small increment)	°K/cm
S1	difference in thermal fluxes to sides of first cooling tube	W
S2	distance from bottom of cassette	m

T1	thickness of cooling tube wall	cm
T2	thickness of second (back) lithium breeding region	cm
T3	thickness of first (front) lithium breeding region	cm
T4	average coolant temperature (for gaseous coolant)	°K
T5	average coolant temperature within any region	°K
T6	inlet coolant temperature to any region	°K
T7	outlet coolant temperature from any region	°K
T8	inlet coolant temperature to module	°K
V1	coolant viscosity	N-sec/m^2
V2	average coolant linear velocity	m/sec
V9	flag = 0 for temperature profiles flag = 1 for case studies	- -
W1	width of module	m
W2	cooling tube inside diameter	m
X1	coolant temperature change across module	°K
X2	coolant tube inlet temperature (for gaseous coolant)	°K
Y0	x-coordinate of front of module	m
Y1	x-coordinate of inside first wall, first cooling tube	m
Y2	x-coordinate of inside second wall, first cooling tube	m
Y3	x-coordinate of outside second wall, first cooling tube	m
Y4	x-coordinate of niobium wall facing plasma	m
Y5	x-coordinate of niobium wall facing module rear	m
Y6	x-coordinate of second cooling tube wall facing plasma (outside)	m
Y7	x-coordinate of second cooling tube wall facing plasma (inside)	m

Y8	x-coordinate of second cooling tube wall facing module rear (inside)	m
Y9	x-coordinate of second cooling tube wall facing module rear (outside)	m
Z1	area of module facing plasma	m^2
V8	flag = 0 for performing case study flag = 1 for determining temperature profiles	
V7	flag = 1 - suppresses printout of coolant temperature profile flag = 0 - allows printout of coolant temperature profile	
V6	flag = 1 - suppresses printout of module design parameters flag = 0 - allows printout of module design parameters	

9.2 One-Dimensional Approximation to Two-Dimensional Temperature Profile

9.2.1 Mathematical Model

A one-dimensional approximation to the two-dimensional steady state temperature profile may be determined based on the following assumptions:

1. $(\frac{\partial T}{\partial y}) << (\frac{\partial T}{\partial x})$. The vertical temperature gradient is negligible. Neglecting this gradient would keep the coolant temperature constant along each side of the module, but the temperature would be different on the front and back of the module.

2. Within an incremental volume, lithium thermal conductivity is constant. Since thermal conductivity is not a strong function of temperature, the assumption is valid.

The equation of change of energy in two dimensions at steady state is

$$0 = \frac{\partial}{\partial x}(k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k \frac{\partial T}{\partial y}) + P_L \qquad (3)$$

The first assumption allows one to neglect the second term which yields:

$$0 = \frac{d}{dx}(k \frac{dT}{dx}) + P_L \qquad (24)$$

As was shown in Sect. 9.1.1, the heat generation in the lithium is

$$P_L(x) = 3.74 \exp(-\frac{x}{0.385})N \tag{15}$$

for any neutron wall loading.

There are now two cases to consider, as shown in Fig. 16A, one on each side of the lithium. In zone 1 calculation begins from the left where the coolant temperature is known and moves across the zone by incremental volumes until the adiabatic niobium wall is reached. In zone 2, on the right side, the increments will move from right to left. Each case must be considered separately.

First, consider an incremental region in zone 1 as shown in Fig. 16B. To apply Eq. (24), it must first be integrated to give:

$$k \frac{dT}{dx} = (3.74)(0.385) \exp(-\frac{x}{0.385}) N + a \tag{25}$$

The niobium tube is adiabatic so that $k(dT/dx)$ is 0 at $x = x_4$ which gives

$$a = -(3.74)(0.385) \exp(-\frac{x_4}{0.385})N \tag{26}$$

Substitution into Eq. (25) gives:

$$k \frac{dT}{dx} = (3.74)(0.385) [\exp(-\frac{x}{0.385}) - \exp(-\frac{x_4}{0.385})]N \tag{27}$$

According to the second assumption, k can be considered constant within the region under consideration. Since T_{in} is known, let k be considered constant at $k(T_{in})$. Then integration of Eq. (27) from the left side of the incremental volume to the right side (from X_{in} to X_{out}) will yield:

$$T_{out} = T_{in} + \frac{(3.74)(0.385)N}{k(T_{in})}\left(0.385\left[\exp(-\frac{x_{in}}{0.385}) - \exp(-\frac{x_{out}}{0.385})\right] - \exp(-\frac{x_4}{0.385})(x_{out} - x_{in})\right) \tag{28}$$

where k is estimated from (10):

Fig. 16A

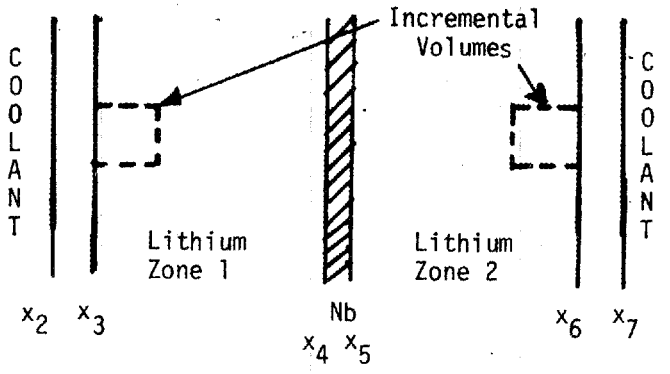


Fig. 16B

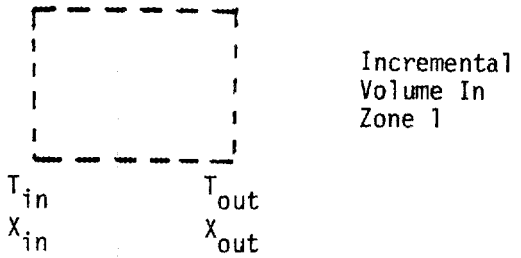
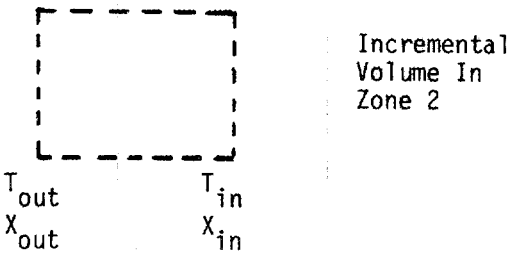


Fig. 16C



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BLANKET CONSIDERATION FOR ONE-DIMENSIONAL LITHIUM TEMPERATURE PROFILE

DATE	DRAWN BY	FILE NO.	FIG.
12-19-76	JHL	CEPS-X-246	16

$$k(T) = 30 + 0.05318\ T - 1.6 \times 10^{-5}\ T^2 \tag{29}$$

To begin the calculations, the wall temperature at the lithium-stainless steel boundary must be determined from

$$Q = UA_{SS}[T(x_3) - T_b] \tag{30}$$

A_{SS} represents the area of the cylindrical stainless steel tube adjacent to the coolant which is half the total surface area of the tube. If the film heat transfer coefficient in the coolant and the thermal conductivity of the stainless steel are known, U can be determined from (1):

$$\frac{1}{U} = \frac{D_1}{100}\left[\frac{100}{D_1 h} + \ln \frac{\left[\dfrac{2(x_3 - x_2) + (D_1/100)}{D_1/100}\right]}{2k_{SS}}\right] \tag{31}$$

With the lithium and stainless steel heat generation equations and the value for T_5 as calculated from the overall energy balance, U as calculated from Eq. (31) and the value calculated for A_{SS}, $T(x_3)$ can be determined from Eq. (30).

In zone 2 the result is slightly different. U and $T(x_6)$ are determined in the same manner as for zone 1. Now the incremental volumes must be evaluated moving from right to left. The region now being considered is shown in Fig. 16C. As before, k is held constant at $k(T_{in})$. In this case the niobium wall position is at x_5. Unlike the previous case, x_{out} is now less than x_{in}. Thus, the final result becomes:

$$T_{out} = T_{in} + \frac{(3.74)(0.385)N}{k(T_{in})}\left[(0.385)\left[\exp(-\frac{x_{in}}{0.385}) - \exp(-\frac{x_{out}}{0.385})\right] - \exp(-\frac{x_5}{0.385})(x_{out} - x_{in})\right] \tag{32}$$

Solution of Eqs. (28) and (32) produces the desired one-dimensional lithium temperature profile.

9.2.2 Use of GRADT - One-Dimensional Temperature Profile

GRADT is used to calculate one-dimensional approximations to two-dimensional temperature profiles within the lithium. The program is only

usable when accessed via ENBAL. Any inputs necessary for determination and printout of the temperature profiles are calculated in ENBAL and saved in data file GDATA. GRADT then recovers these data when it is called. A flow chart of the program is presented in Fig. 17.

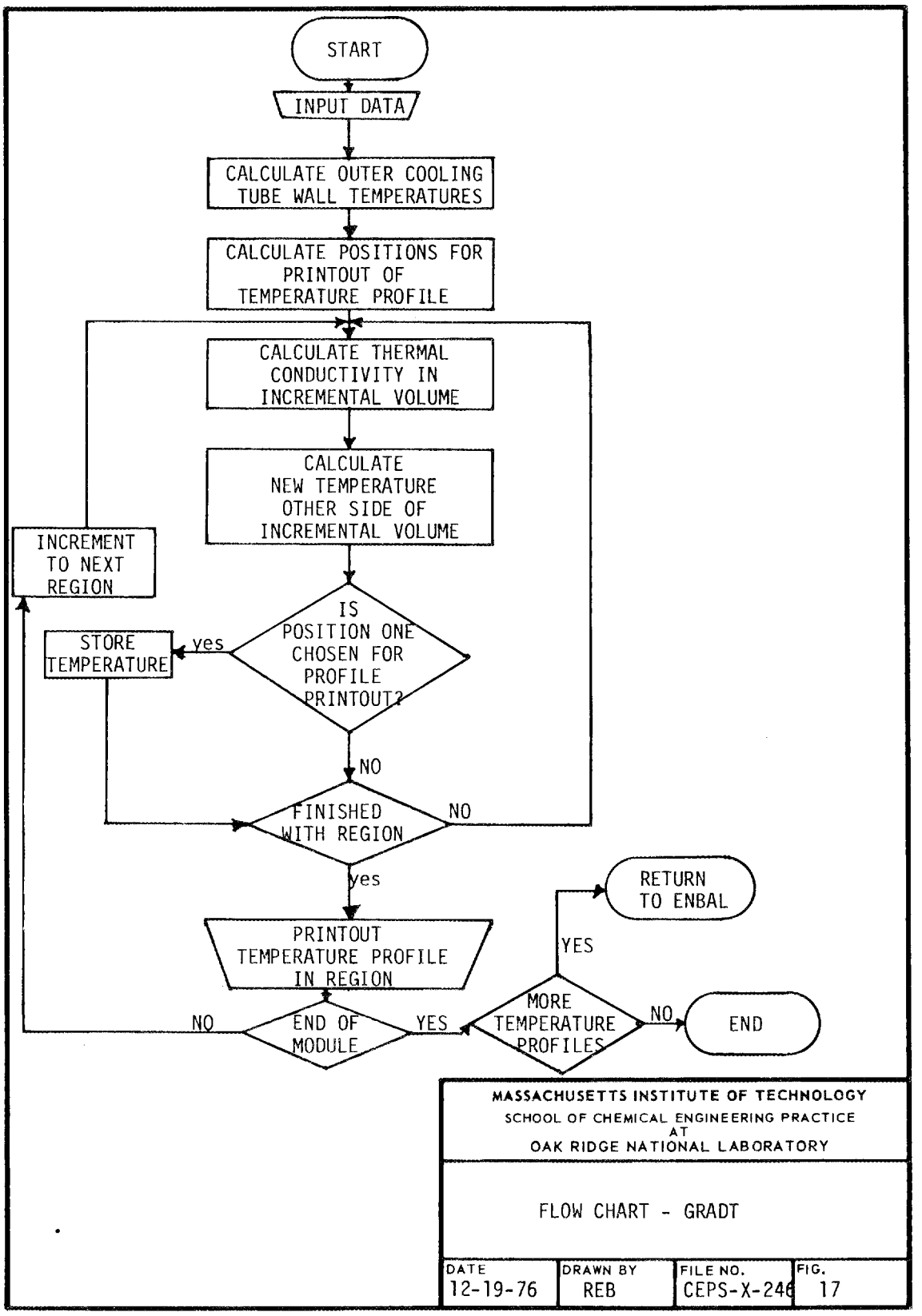
A sample output is shown in Table 11. For each one-dimensional region, ten temperatures are printed out under their respective distances from the module face. The temperatures that always appear are the two wall temperatures at the two lithium-stainless steel interfaces and the wall temperatures on each side of the niobium tube. The distribution of the remaining six temperatures depends on the relative thicknesses of the two lithium sections with the thicker region containing more printed out temperatures. Knowledge of this and the diameter of the niobium tube used allows one to determine the position of the tube on the printed out profile since it is not specifically marked.

9.2.3 GRADT Listing

```
1       REM--THIS PROGRAM, WHEN CALLED FROM ENBAL.BAS,CALCULATES
2       REM--AND PRINTS OUT ONE DIMENSIONAL TEMPERATURE PROFILES.
3       REM--ALL NECESSARY DATA IS PASSED BY ENBAL THROUGH THE
4       REM--DATA FILE GDATA.BAS.
5       REM--
9       REM--RECOVER INPUT DATA
10 FILES GDATA
20 DIM B(21),W(21)
30 INPUT #1,D1,H1,T1,L1,Q4,Q5,Q6,Q7,Y3,Y4,Y5,Y6,T2,T3
40 FOR I=0 TO 21
50 INPUT #1,B(I)
60 NEXT I
70 INPUT #1,N3,K9,N1
78      REM--DEFINING EQUATION FOR THERMAL CONDUCTIVITY AS A
79      REM--FUNCTION OF TEMPERATURE
80 DEF FNB(Z1)=30+0.05318*(Z1-273.16)-1.6E-5*(Z1-273.16)**2
90 A9=0
100 U=1/(D1/100*(1/(D1*H1/100)+(LN((2*T1+D1)/D1)/(2*K9))))
110 A=3.1416*(2*T1+D1)/2*L1/1000*N3
120 E9=(Q4+Q5)/(10*U*A)
130 FOR I=0 TO 10
135     REM--CALCULATE WALL TEMPERATURES AT THE FRONT LITHIUM-
136     REM--COOLING TUBE BOUNDARY
140 W(I)=B(I)+E9
150 NEXT I
160 E8=(Q6+Q7)/(10*U*A)
170 FOR I=11 TO 21
175     REM--CALCULATE WALL TEMPERATURES AT THE REAR LITHIUM-
176     REM--COOLING TUBE BOUNDARY
180 W(I)=B(I)+E8
190 NEXT I
```

```
195       REM--DETERMINE PRINTOUT LOCATIONS FOR TEMP.PROFILE
200 E7=INT(T3/(T3+T2)*7)+1
210 E6=3-E7
220 E5=T3/100/E7
230 E4=T2/100/E6
240 T(1)=Y3
250 FOR I=1 TO E7
260 T(I+1)=T(I)+E5
270 NEXT I
280 T(10)=Y6
290 W=9
300 FOR I=1 TO E6
310 T(J)=T(J+1)-E4
320 J=J-1
330 N  T I
340 FOR I=0 TO 10
350 W9=L1*(1-I/10)
360 W(1)=W(I)
370 Z1=W(I)
380 K=2
385       REM--DETERMINE TEMPERATURE PROFILE AT 1 MM INTERVALS
386       REM--ACROSS THE FRONT SECTION OF LITHIUM
390 FOR J=Y3+0.001 TO Y4 STEP 0.001
400 K9=FNB(Z1)
410 K8=Y4
420 K7=J-0.001
430 GOSUB 900
440 Z2=F8
450 IF J<T(K) THEN 480
455       REM--STORE TEMPERATURE AT PRINTOUT LOCATION
460 U(K)=Z2
470 K=K+1
480 Z1=Z2
490 NEXT J
500 U(K)=Z2
510 W(10)=W(21-I)
520 Z1=W(21-I)
530 K=9
535       REM--DETERMINE TEMPERATURE PROFILE AT 1 MM INTERVALS
536       REM--ACROSS THE REAR SECTION OF LITHIUM
540 FOR J=Y6-0.001 TO Y5 STEP -0.001
550 K9=FNB(Z1)
560 K8=Y5
570 K7=J+0.001
580 GOSUB 900
590 Z2=F8
600 IF J>T(K) THEN 630
605       REM--STORE TEMPERATURE AT PRINTOUT LOCATION
610 U(K)=Z2
620 K=K-1
630 Z1=Z2
```

```
640 NEXT J
650 U(K)=Z2
660 IF A9=1  THEN 790
665       REM--PRINT OUT COMPLETE PROFILE
670 PRINT
680 PRINT
690 PRINT
700 PRINT "                STEADY STATE TEMPERATURE DISTRIBUTION"
710 PRINT
720 PRINT ,"HORIZONTAL DISTANCE (M)"
730 PRINT USING 740,T(1),T(2),T(3),T(4),T(5),T(6),T(7),T(8)
740 :       ##.### ##.### ##.### ##.### ##.### ##.### ##.### ##.###
750 PRINT USING 760,T(9),T(10)
760 : VERT.    ##.### ##.###
770 PRINT "DIST(M)",,"TEMPERATURE (DEG K)"
780 A9=1
790 PRINT
800 PRINT USING 810,V9,U(1),U(2),U(3),U(4),U(5),U(6),U(7),U(8)
810 :##.## ####.# ####.# ####.# ####.# ####.# ####.# ####.# ####.#
820 PRINT USING 830,U(9),U(10)
830 :           ####.# ####.#
840 NEXT I
850 PRINT
860 PRINT
870 PRINT
880 PRINT
890 GO TO 960
895       REM--CALCULATION OF TEMPERATURE AT FAR SIDE OF INCRE-
896       REM--MENTAL VOLUME
900 F9=.385*1.44/K9*(EXP(-J/.385)-EXP(-K7/.385))
910 F9=-F9*1.0E6*N1
920 F8=Z1-1.44/K9*EXP(-K8/.385)*1.0E3*N1+F9
930 IF K7<J THEN 950
940 F8=Z1+1.44/K9*EXP(-K8/.385)*1.0E3*N1+F9
950 RETURN
960 PRINT "MORE TEMPERATURE PROFILES? (0=NO,1=YES)"
970 INPUT V5
980 IF V5=0 THEN 1000
990 CHAIN ENBAL
1000 END
```



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FLOW CHART - GRADT

DATE	DRAWN BY	FILE NO.	FIG.
12-19-76	REB	CEPS-X-246	17

Table 11. Sample of a Steady State Temperature Distribution

```
                    HORIZONTAL DISTANCE (M)
          0.028   0.053   0.078   0.083   0.106   0.129   0.153   0.176
VERT.       0.199   0.222
DIST(M)                            TEMPERATURE (DEG K)

4.00    613.4   803.2   859.2  1956.6  1925.0  1824.1  1664.8  1443.1
          1148.7   720.7

3.60    6[illegible].1   804.7   860.7  1955.5  1924.0  1823.0  1663.7  1442.0
          1147.5   719.2

3.[illegible]0    618.6   807.7   863.6  1953.5  1921.9  1821.0  1661.7  1439.9
          1145.1   716.1

2.80    622.1   810.7   866.4  1951.4  1919.9  1818.9  1659.6  1437.7
          1142.7   713.1

2.40    625.5   813.6   869.3  1949.4  1917.8  1816.9  1657.5  1435.5
          1140.4   710.1

2.00    629.0   816.6   872.2  1947.4  1915.8  1814.8  1655.4  1433.4
          1138.0   707.0

1.60    632.4   819.6   875.1  1945.3  1913.8  1812.8  1653.4  1431.2
          1135.6   704.0

1.20    635.9   822.6   878.0  1943.3  1911.7  1810.8  1651.3  1429.1
          1133.3   701.0

0.80    639.4   825.6   880.9  1941.3  1909.7  1808.7  1649.2  1426.9
          1130.9   697.9

0.40    6[illegible].8   828>6   883.8  1939.3  1907.7  1806.7  1647.2  1424.8
          1128.6   694.9

0.00    646.3   831.6   886.7  1937.2  1905.7  1804.7  1645.1  1422.7
          1126.2   691.8
MORE TEMPERATURE PROFILES? (0=NO, 1=YES)
?0
```

9.2.4 GRADT Nomenclature

B(I)	contains bulk temperature profile through coolant	°K
T(I)	horizontal positions at which temperatures will be printed out	m
U(I)	temperature at p horizontal position I	°K
W(I)	outside wall temperature of cooling tube	°K

Single Variable

A	area for heat transfer out of a region into coolant	m^2
A9	flag = 0 if title and labels have not been printed out flag = 1 if title and labels have been printed out	
D1	cooling tube ID	cm
E6	number of temperatures (besides wall temperature) to be printed out in back lithium region	
E7	number of temperatures (besides wall temperature) to be printed out in front lithium region	
E4	spacing (horizontal) of temperatures to be printed out in back lithium region	m
E5	spacing (horizontal) of temperatures to be printed out in front lithium region	m
E8	temperature change across tube wall in back lithium region	°K
E9	temperature change across tube wall in front lithium region	°K
F8	intermediate value of Z2	°K
F9	intermediate value used to determine the temperature on far side of incremental volume = Z2	°K
H1	coolant boundary layer heat transfer coefficient	W/m^2-°K
I	for loop counter	-
J	for loop counter or current region under consideration	
K	current region under consideration	
K7	horizontal position of one side of incremental volume	m

K8	horizontal position of niobium wall	m
K9	initially, thermal conductivity of cooling tube wall later, thermal conductivity of lithium	W/m-K
L1	length of module	m
N3	number of cassettes per module	
Q4	heat generation in first tube wall facing lithium	W
Q5	heat generation in first lithium breeding region	W
Q6	heat generation in second lithium breeding region	W
Q7	heat generation in second tube wall facing lithium	W
T1	thickness of cooling tube wall	cm
T2	thickness of second lithium breeding region	cm
T3	thickness of first lithium breeding region	cm
U	overall heat transfer coefficient for cooling tube wall	W/m^2-K
V5	flag = 0 no more temperature profiles desired flag = 1 more temperature profiles desired	
V9	vertical position (distance from bottom of cassette) of region currently being considered	m
Y3	x-coordinate of outside second wall, first cooling tube	m
Y4	x-coordinate of niobium wall facing plasma	m
Y5	x-coordinate of niobium wall facing module rear	m
Y6	x-coordinate of outside second cooling tube, wall facing plasma	m
Z1	known temperature on one side of incremental volume	°K
Z2	(= T9) new temperature on opposite side of incremental volume from Z1	°K

9.3 HEATING5

9.3.1 General Description

HEATING5 is a computer program designed to solve steady state and/or transient heat conduction problems in one, two, or three-dimensional Cartesian or cylindrical coordinates or one-dimensional spheroid coordinates. The program has provisions for phase changes and time, temperature, and position-dependent heat generation rates. The boundary conditions, which may be specified at the interface between two regions or on the boundaries of a region, may be fixed temperatures or a combination of prescribed heat flux, forced convection, natural convection, and radiation. Time and/or temperature dependence of the boundary condition parameters is provided for in this program. HEATING5 approximates the partial differential equations involved in the formulation of heat conduction problems by finite difference equations.

To use HEATING5, the configuration of the problem must be approximated by dividing it into regions, depending on the shape, material structure, indentations, and cutouts. A set of lattice lines perpendicular to each axis and extending the entire length of the remaining coordinates is then constructed to produce the mesh required for the solution of the finite difference equations. The material parameters and boundary conditions must then be entered as either constant, tabular functions, or analytical functions. Information regarding the type of simulation, steady state, transient, or an alternating series of steady state and transient problems, and the desired method of solution must be entered to complete the inputs necessary for description of the problem.

HEATING5 automatically lists the input data and prints out the initial temperature distribution for any type of problem. The final temperature distribution for steady state problems and the temperatures as a function of time for transient problems are printed out in the form of two-dimensional maps of the temperatures of the nodes in each plane. The temperatures of specified nodes may be monitored during the calculation as a function of the number of iterations for steady-state problems or the number of time steps for transient problems. Information can be written on a specified output unit and used by a plotting routine to create various types of plots.

9.3.2 Determination of the Steady State Temperature Profile

The steady state temperature profile in the first blanket zone can be determined after the overall energy balance has been performed. The temperature profile within the lithium and the tube walls adjacent to the lithium can be determined by solving the heat conduction equation and imposing the boundary conditions determined by the placement of the adiabatic niobium wall, the coolant temperature profile, and the heat transfer coefficient within the coolant.

The steady state heat conduction equation is given by:

$$0 = \frac{\partial}{\partial x}(k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k \frac{\partial T}{\partial y}) + S_n \tag{3}$$

The boundary conditions at the interfaces between the coolant and tubing are:

$$h(T_b - T_t) = -k_t(\frac{\partial T_t}{\partial x}) \tag{4}$$

$$h(T_b - T_t) = -k_t(\frac{\partial T_t}{\partial y}) \tag{5}$$

Since the top of the U-tube is assumed to be insulated, the boundary condition there is:

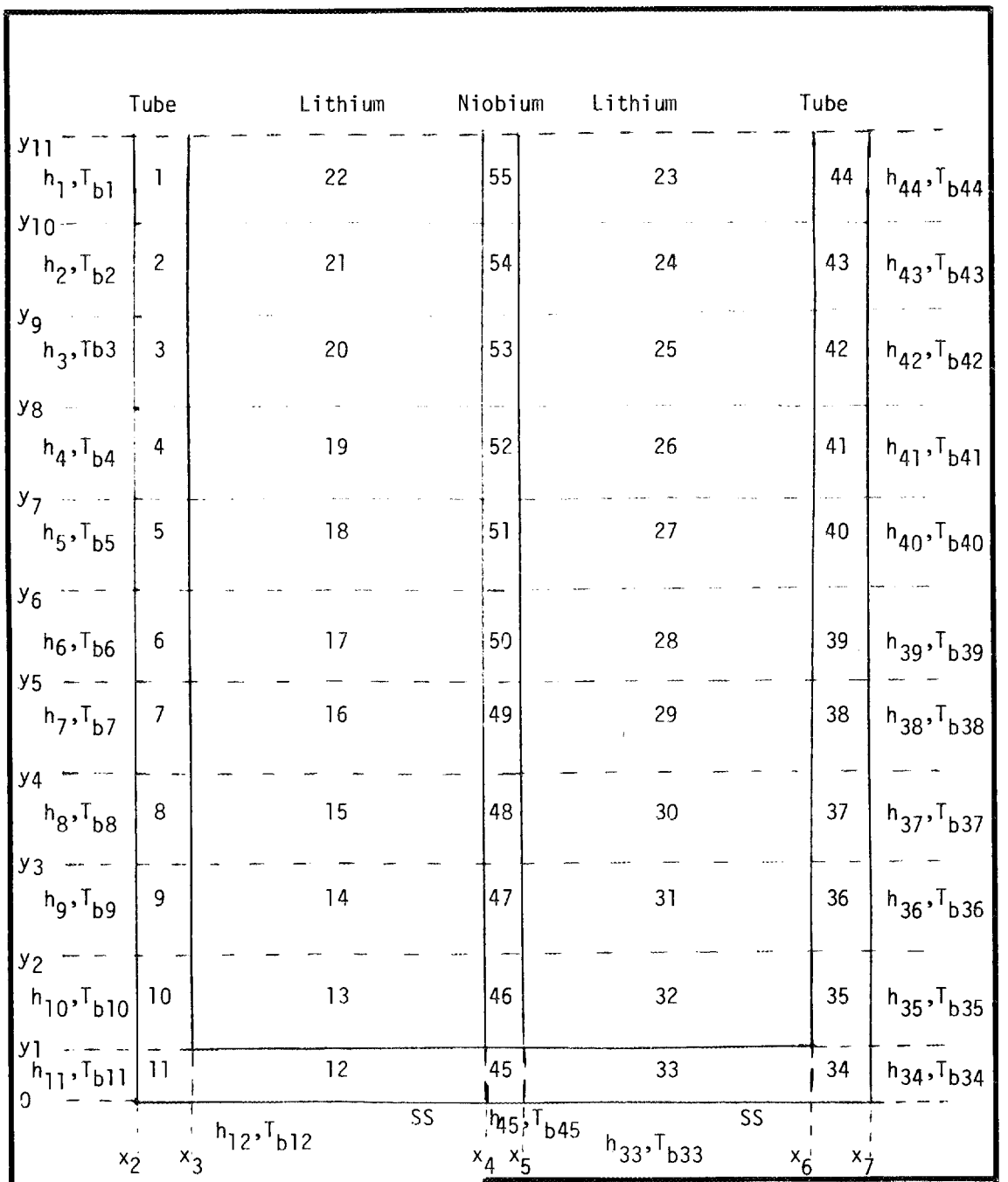
$$(\frac{\partial T_t}{\partial y})_{top} = 0 \tag{6}$$

At the interfaces between the niobium tubes and the lithium and the top of the blanket, the boundary condition is:

$$(\frac{\partial T_L}{\partial x}) = (\frac{\partial T_L}{\partial y})_{top} = 0 \tag{7}$$

Since HEATING5 is not capable of solving problems where the bulk coolant temperature is allowed to vary with position, the configuration of the problem has to be approximated by a series of different regions each with different bulk temperature (Fig. 18). In this way, a continuous temperature distribution in the coolant tubes can be simulated. Allowance for different film heat transfer coefficients in each region has been made even though for this study the coefficient has been assumed to be constant throughout the tube.

A summary of the required inputs for HEATING5 is presented in Table 12. The input 'xxxz' classified the job by the computer by giving maximum CPU time and should be input as 300X for a steady state simulation. The maximum CPU time specified on the data cards, IT MAX, is used as a safety factor to allow for the printout of an interim temperature distribution should the maximum CPU time be exceeded during calculation. For steady state simulations, a value of 300 is sufficient. The geometry of the problem is described by X2-X7 and Y1-Y12. PASS and POLI are necessary to describe the heat generation functions, while T_{bi} and h_i specify the boundary conditions.



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CONFIGURATION USED FOR
HEATING5 SIMULATION

DATE	DRAWN BY	FILE NO.	FIG.
12-20-76	JHL	CEPS-X-246	18

Table 12. Summary of Inputs for HEATING5

Control Cards	
xxxz	maximum CPU time in seconds, minutes, or hours, e.g., 100S = 100 seconds, 100M = 100 minutes, or 001H = 1 hour
Data Cards	
ITMAX	maximum CPU time, sec
X2-X7	defined in the nomenclature
Y1	thickness of the coolant tube wall, m
YN	$(2 \leq N \leq 11)$ - YL + 0.40(N - 1), m
P_{ass}	preexponential factor for the dissipation of neutron energy in the stainless steel, W/m^2 (4.7×10^7 W/m^2 for 3.14 MW/m^2 neutron wall loading)
P_{OLI}	preexponential factor for the dissipation of neutron energy in the lithium, W/m^2 (1.175×10^7 W/m^2 for 3.14 MW/m^2 neutron wall loading)
T_{bi}	bulk temperature of the coolant fluid adjacent to region i during the steady state period, °C
h_i	heat transfer coefficient between the tube wall and the coolant fluid adjacent to region i, W/m^2-°C
T_{ti}	bulk temperature of the coolant fluid adjacent to region i during the transient period, °C

A sample output generated by HEATING5 is presented on the following pages. The beginning of the output represents input return. By examining the input return, the user can check whether the simulation being performed is in fact the desired simulation. The next three pages contain the map of the node numbers which describe the mesh used for solving the finite difference equations. If the user wishes to monitor the temperature at specific positions during the approach to steady state, he needs to merely select the desired node numbers and follow the procedure outlined in the HEATING5 manual (11). The initial temperature distribution is printed out on the next four pages. The point which corresponds to the lower lefthand corner of the U-tube is located at the upper lefthand corner of the temperature distribution map. The numbers in the column headed 'DISTANCE' represent distance in the y-direction, while the numbers to the right of the word 'DISTANCE' represent distance in the x-direction. The dashed lines around the boundary of the map divide the map into areas where the stainless steel tube wall is located and areas which contain lithium. The niobium tube is located between the columns headed 'FINE GRID-14' and 'FINE GRID-15'. The last four pages contain the steady state temperature distribution. The temperature increases from the first coolant tube wall to the niobium wall, then decreases from the niobium wall to the second coolant tube wall as is to be expected when an adiabatic wall is placed in the middle of a heat-generating region which is cooled on both sides. The maximum and minimum temperatures as well as the elapsed CPU time are printed on the last page.

9.3.3 Tritium Concentration Profile

Integration of the steady state concentration profile of tritium in the lithium over the volume of lithium gives the amount of tritium holdup in the blanket. Since tritium costs approximately $\$1 \times 10^6$/kg, it is desirable to have the smallest holdup possible for a fixed production rate.

Tritium generation (at a set neutron wall loading) is a function of distance from the plasma, which is approximately equal to distance from the start of the cooling tube wall. The H^3 generation rate is shown to be (project calculation file):

$$R = \frac{\text{moles } H^3}{m^3\text{-sec}} = \frac{2.19 \times 10^{19}(10^{-0.74x}) + 2.88 \times 10^{19}(10^{-3.9x})}{6.02 \times 10^{23}} \qquad (33)$$

where x is the distance (m) from the cooling tube wall closest to the plasma.

Concentration is a function of diffusivity and diffusivity is a function of temperature. In the cassette, temperature changes in both the horizontal (x) and vertical (y) directions. Therefore the tritium concentration is a function of both these coordinate values. Application of the equation of continuity yields:

SUMMARY OF REGION DATA

NUMBERS AND FCN NUMBER				********** DIMENSIONS **********						-------- BOUNDARY NUMBERS --------					
REG. NO.	MATL NO.	INIT TEMP	HEAT GEN.	LEFT-X-OR INNER-R	RIGHT-X-OR OUTER-R	LOWER-Y-OR LEFT-THETA	UPPER-Y-OR RIGHT-THETA	REAR-Z	FRONT-Z	LF-X IN-R	RT-X OT-R	LO-Y LF-O	UP-Y RT-O	RR-Z	FT-Z
1	1	0	1	0.0	0.0006	3.6006	4.0006	0.0	0.0	1	0	0	22	0	0
2	1	0	1	0.0	0.0006	3.2006	3.6006	0.0	0.0	2	0	0	0	0	0
3	1	0	1	0.0	0.0006	2.8006	3.2006	0.0	0.0	3	0	0	0	0	0
4	1	0	1	0.0	0.0006	2.4006	2.8006	0.0	0.0	4	0	0	0	0	0
5	1	0	1	0.0	0.0006	2.0006	2.4006	0.0	0.0	5	0	0	0	0	0
6	1	0	1	0.0	0.0006	1.6006	2.0006	0.0	0.0	6	0	0	0	0	0
7	1	0	1	0.0	0.0006	1.2006	1.6006	0.0	0.0	7	0	0	0	0	0
8	1	0	1	0.0	0.0006	0.8006	1.2006	0.0	0.0	8	0	0	0	0	0
9	1	0	1	0.0	0.0006	0.4006	0.8006	0.0	0.0	9	0	0	0	0	0
10	1	0	1	0.0	0.0006	0.0006	0.4006	0.0	0.0	10	0	0	0	0	0
11	1	0	1	0.0	0.0006	0.0	0.0006	0.0	0.0	11	0	11	0	0	0
12	1	0	1	0.0006	0.1006	0.0	0.0006	0.0	0.0	0	0	23	0	0	0
13	2	0	2	0.0006	0.1006	0.0006	0.4006	0.0	0.0	0	22	0	0	0	0
14	2	0	2	0.0006	0.1006	0.4006	0.8006	0.0	0.0	0	22	0	0	0	0
15	2	0	2	0.0006	0.1006	0.8006	1.2006	0.0	0.0	0	22	0	0	0	0
16	2	0	2	0.0006	0.1006	1.2006	1.6006	0.0	0.0	0	22	0	0	0	0
17	2	0	2	0.0006	0.1006	1.6006	2.0006	0.0	0.0	0	22	0	0	0	0
18	2	0	2	0.0006	0.1006	2.0006	2.4006	0.0	0.0	0	22	0	0	0	0
19	2	0	2	0.0006	0.1006	2.4006	2.8006	0.0	0.0	0	22	0	0	0	0
20	2	0	2	0.0006	0.1006	2.8006	3.2006	0.0	0.0	0	22	0	0	0	0
21	2	0	2	0.0006	0.1006	3.2006	3.6006	0.0	0.0	0	22	0	0	0	0
22	2	0	2	0.0006	0.1006	3.6006	4.0006	0.0	0.0	0	22	0	22	0	0
23	2	0	2	0.1056	0.2284	3.6006	4.0006	0.0	0.0	22	0	0	22	0	0
24	2	0	2	0.1056	0.2284	3.2006	3.6006	0.0	0.0	22	0	0	0	0	0
25	2	0	2	0.1056	0.2284	2.8006	3.2006	0.0	0.0	22	0	0	0	0	0
26	2	0	2	0.1056	0.2284	2.4006	2.8006	0.0	0.0	22	0	0	0	0	0
27	2	0	2	0.1056	0.2284	2.0006	2.4006	0.0	0.0	22	0	0	0	0	0
28	2	0	2	0.1056	0.2284	1.6006	2.0006	0.0	0.0	22	0	0	0	0	0
29	2	0	2	0.1056	0.2284	1.2006	1.6006	0.0	0.0	22	0	0	0	0	0
30	2	0	2	0.1056	0.2284	0.8006	1.2006	0.0	0.0	22	0	0	0	0	0
31	2	0	2	0.1056	0.2284	0.4006	0.8006	0.0	0.0	22	0	0	0	0	0
32	2	0	2	0.1056	0.2284	0.0006	0.4006	0.0	0.0	22	0	0	0	0	0
33	1	0	1	0.1056	0.2284	0.0	0.0006	0.0	0.0	0	0	23	0	0	0
34	1	0	1	0.2284	0.2289	0.0	0.0006	0.0	0.0	0	23	23	0	0	0
35	1	0	1	0.2284	0.2289	0.0006	0.4006	0.0	0.0	0	12	0	0	0	0
36	1	0	1	0.2284	0.2289	0.4006	0.8006	0.0	0.0	0	13	0	0	0	0
37	1	0	1	0.2284	0.2289	0.8006	1.2006	0.0	0.0	0	14	0	0	0	0
38	1	0	1	0.2284	0.2289	1.2006	1.6006	0.0	0.0	0	15	0	0	0	0
39	1	0	1	0.2284	0.2289	1.6006	2.0006	0.0	0.0	0	16	0	0	0	0
40	1	0	1	0.2284	0.2289	2.0006	2.4006	0.0	0.0	0	17	0	0	0	0
41	1	0	1	0.2284	0.2289	2.4006	2.8006	0.0	0.0	0	18	0	0	0	0
42	1	0	1	0.2284	0.2289	2.8006	3.2006	0.0	0.0	0	19	0	0	0	0
43	1	0	1	0.2284	0.2289	3.2006	3.6006	0.0	0.0	0	20	0	0	0	0
44	1	0	1	0.2284	0.2289	3.6006	4.0006	0.0	0.0	0	21	0	22	0	0
45	1	0	1	0.1006	0.1056	0.0	0.0006	0.0	0.0	0	0	23	22	0	0
46	0	0	0	0.1006	0.1056	0.0006	0.4006	0.0	0.0	22	22	0	0	0	0
47	0	0	0	0.1006	0.1056	0.4006	0.8006	0.0	0.0	22	22	0	0	0	0
48	0	0	0	0.1006	0.1056	0.8006	1.2006	0.0	0.0	22	22	0	0	0	0
49	0	0	0	0.1006	0.1056	1.2006	1.6006	0.0	0.0	22	22	0	0	0	0
50	0	0	0	0.1006	0.1056	1.6006	2.0006	0.0	0.0	22	22	0	0	0	0
51	0	0	0	0.1006	0.1056	2.0006	2.4006	0.0	0.0	22	22	0	0	0	0
52	0	0	0	0.1006	0.1056	2.4006	2.8006	0.0	0.0	22	22	0	0	0	0
53	0	0	0	0.1006	0.1056	2.8006	3.2006	0.0	0.0	22	22	0	0	0	0
54	0	0	0	0.1006	0.1056	3.2006	3.6006	0.0	0.0	22	22	0	0	0	0
55	0	0	0	0.1006	0.1056	3.6006	4.0006	0.0	0.0	22	22	0	22	0	0

```
********** SUMMARY  OF  MATERIAL  DATA **********

MATERIAL    MATERIAL      ------------ THERMAL PARAMETERS ------------
 NUMBER       NAME        -- TEMPERATURE-DEPENDENT FUNCTION NUMBERS --
                          CONDUCTIVITY        DENSITY        SPECIFIC HEAT
    1        STEEL       1.900000D 01     7.800000D 03     5.690000D 02
                               0                0                0
    2        LITHIUM     0.0              0.0              4.000000D 03
                               2                3                0

***************** SUMMARY  OF  HEAT GENERATION  RATE  D ATA *****************

NUMBER       POWER            TIME-, TEMPERATURE-, AND POSITION-DEPENDENT NUMBERS
            DENSITY             TIME     TEMPERATURE  X OR R      Y OR TH        Z
    1     4.70000D 07            -1           0           1           0           0
    2     1.17500D 07            -1           0           1           0           0
```

**********SUMMARY OF BOUNDARY DATA**********

GENERAL			TEMPERATURE INFORMATION	HEAT TRANSFER COEFFICIENTS RELATED FUNCTION NUMBERS				
NO.	TYPE	FCT FLAG	TEMPERATURE & TIME FCT	ASSOC. FCTS	FORCED CONV.	RADIATION	NATURAL CONV	EXPONENT	FLUX
I	1	0	1.000000 00 -2		2.429500 04	0.0	0.0	0.0	0.0
2	I	0	1.000000 00 -3		2.429500 04	0.0	0.0	0.0	0.0
3	I	0	1.000000 00 -4		2.42950D 04	0.0	0.0	0.0	0.0
4	1	0	1.000000 00 -5		2.42950D 04	0.0	0.0	0.0	0.3
5	I	0	1.000000 00 -6		2.42950D 04	0.0	0.0	0.0	0.0
6	1	C	1.000000 00 -7		2.429500 04	0.0	0.0	0.0	0.0
7	1	0	1.000000 00 -8		2.02950D 04	0.0	0.0	0.0	0.0
a	I	0	1.000000 00 -9		2.42950D 04	0.0	0.0	0.0	0.0
9	1	0	1.000000 00 -10		2.429500 04	0.0	0.0	0.0	0.0
10	1	0	1.000000 00 -11		2.42950D 04	0.0	0.0	0.0	0.0
11	1	0	1.000000 00 -12		2.42950D 04	0.0	0.0	0.0	0.0
12	1	0	1.000000 00 -13		2.429500 04	0.0	0.0	0.0	0.0
13	I	0	1.000000 00 -14		2.429500 04	0.0	0.0	0.0	0.0
14	1	0	1.000000 00 -15		2.429500 04	0.0	0.0	0.0	0.0
IS	1	0	1.000000 00 -16		2.429500 04	0.0	0.0	0.0	0.0
16	1	0	1.000000 00 -17		2.42950D 04	0.0	0.0	0.0	0.0
I-?	1	0	1.000000 00 -18		2.429500 04	0.0	0.0	0.0	0.0
18	1	0	1.000000 00 -19		2.42950D 04	0.0	0.0	0.0	0.0

19	1	0	1.00000D 00 -20	2.42950D 04	0.0	0.0	0.0	0.3
20	1	0	1.00000D 00 -21	2.429550 00	0.0	0.0	0.0	0.0
21	1	0	1.00000D 00 -22	2.429500 04	0.0	0.0	0.0	0.0
22	0	0	0.0 0	0.0	0.0	0.0	0.0	0.0
23	1	0	1.00000D 00 -23	2.429500 04	0.0	0.0	0.0	0.3

GROSS LATTICES AND NUMBERS OF INCREMENTS

R OR X

0.0	0.000560	0.100560	0.105560	0.228360	0.2289 10
3	10	1	10	3	

THETA OR Y

0.0	0.000560	0.400560	0.800560	1.200560	1.600560	2.000 560	2.400560
2.800560	3.200560	3.600560	4.000560				
3	3	3	3	3	3	3	3
3	3	3					

LISTING OF ANALYTIC FUNCTIONS

F(V)= A(1) + A(2)*V + A(3)*V**2 + A(4)*COS(A(5)*V) + A(6)*EXP(A(7)*V) + A(8)*SIN(A(9)*V) + A(10)*LOG(A(11)*V)

NO.	A(1)	A(2)	A(3)	A(4)	A(5)	A(6)	A(7)	A(8)	A(9)	A(10)	A(11)
1	0.0	0.0	0.0	0.0	0.0	9.7100-01	-2.790D 00	0.0	0.0	0.0	0.0
2	3.000D 01	5.318D-02	-1.600D-05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	5.171D 02	-1.490D-04	0.0	0.0	0.0	0.0

FINE LATTICE, X OR R, Y OR THETA, AND Z

1	0.0	2	0.000187	3	0.000373	4	0.000560	5	0.010560
6	0.020560	7	0.030560	8	0.040560	9	0.050560	10	0.060560
11	0.070560	12	0.080560	13	0.090560	14	0.100560	15	0.105560
16	0.117840	17	0.130120	18	0.142400	19	0.154680	20	0.166960
21	0.179240	22	0.191520	23	0.203800	24	0.216080	25	0.228360
26	0.228543	27	0.228727	28	0.228910				

1	0.0	2	0.000187	3	0.000373	4	0.000560	5	0.133893
6	0.267227	7	0.400560	8	0.533893	9	0.667227	10	0.800560
11	0.933893	12	1.067227	13	1.200560	14	1.333893	15	1.467227
16	1.600560	17	1.733893	18	1.867227	19	2.000560	20	2.133893
21	2.267227	22	2.400560	23	2.533893	24	2.667227	25	2.800560
26	2.933893	27	3.067227	28	3.200560	29	3.333893	30	3.467227
31	3.600560	32	3.733893	33.	3.867227	34	4.000560		

THIS PROBLEM CONTAINS 952 NODES.

THE INITIAL TIME INCREMENT = 5.000000D 00

MAP OF THE NODE NUMBERS

GROSS GRID			1			2								
FINE GRID			1	2	3	4	5	6	7	8	9	10	11	12	13
		DISTANCE	0.0	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
1	1	0.0	1	2	3	4	5	6	7	8	9	10	11	12	13
	2	0.00	29	30	31	32	33	34	35	36	37	38	39	40	41
	3	0.00	57	58	59	60	61	62	63	64	65	66	67	68	69
2	4	0.00	85	86	87	88	89	90	91	92	93	94	95	96	97
	5	0.13	113	114	115	116	117	118	119	120	121	122	123	124	125
	6	0.27	141	142	143	144	145	146	147	148	149	150	151	152	153
3	7	0.40	169	170	171	172	173	174	175	176	177	178	179	180	181
	8	0.53	197	198	199	200	201	202	203	204	205	206	207	208	209
	9	0.67	225	226	227	228	229	230	231	232	233	234	235	236	237
4	10	0.80	253	254	255	256	257	258	259	260	261	262	263	264	265
	11	0.93	281	282	283	284	285	286	287	288	289	290	291	292	293
	12	1.07	309	310	311	312	313	314	315	316	317	318	319	320	321
5	13	1.20	337	338	339	340	341	342	343	344	345	346	347	348	349
	14	1.33	365	366	367	368	369	370	371	372	373	374	375	376	377
	15	1.47	393	394	395	396	397	398	399	400	401	402	403	404	405
6	16	1.60	421	422	423	424	425	426	427	428	429	430	431	432	433
	17	1.73	449	450	451	452	453	454	455	456	457	458	459	460	461
	18	1.87	477	478	479	480	481	482	483	484	485	486	487	488	489
7	19	2.00	505	506	507	508	509	510	511	512	513	514	515	516	517
	20	2.13	533	534	535	536	537	538	539	540	541	542	543	544	545
	21	2.27	561	562	563	564	565	566	567	568	569	570	571	572	573
8	22	2.40	589	590	591	592	593	594	595	596	597	598	599	600	601
	23	2.53	617	618	619	620	621	622	623	624	625	626	627	628	629
	24	2.67	645	646	647	648	649	650	651	652	653	654	655	656	657
9	25	2.80	673	674	675	676	677	678	679	680	681	682	683	684	685
	26	2.93	701	702	703	704	705	706	707	708	709	710	711	712	713
	27	3.07	729	730	731	732	733	734	735	736	737	738	739	740	741
10	28	3.20	757	758	759	760	761	762	763	764	765	766	767	768	769
	29	3.33	785	786	787	788	789	790	791	792	793	794	795	796	797
	30	3.47	813	814	815	816	817	818	819	820	821	822	823	824	825
11	31	3.60	841	842	843	844	845	846	847	848	849	850	851	852	853
	32	3.73	869	870	871	872	873	874	875	876	877	878	879	880	881
	33	3.87	897	898	899	900	901	902	903	904	905	906	907	908	909
12	34	4.00	925	926	927	928	929	930	931	932	933	934	935	936	937

GROSS GRID			3	4										5	
FINE GRID			14	15	16	17	18	19	20	21	22	23	24	25	26
		DISTANCE	0.10	0.11	0.12	0.13	0.14	0.15	0.17	0.18	0.19	0.20	0.22	0.23	0.23
1	1	0.0	14	15	16	17	18	19	20	21	22	23	24	25	26
	2	0.00	42	43	44	45	46	47	48	49	50	51	52	53	54
	3	0.00	70	71	72	73	74	75	76	77	78	79	80	81	82
2	4	0.00	98	99	100	101	102	103	104	105	106	107	108	109	110
	5	0.13	126	127	128	129	130	131	132	133	134	135	136	137	138
	6	0.27	154	155	156	157	158	159	160	161	162	163	164	165	166
3	7	0.40	182	183	184	185	186	187	188	189	190	191	192	193	194
	8	0.53	210	211	212	213	214	215	216	217	218	219	220	221	222
	9	0.67	238	239	240	241	242	243	244	245	246	247	248	249	250
4	10	0.80	266	267	268	269	270	271	272	273	274	275	276	277	278
	11	0.93	294	295	296	297	298	299	300	301	302	303	304	305	306
	12	1.07	322	323	324	325	326	327	328	329	330	331	332	333	334
5	13	1.20	350	351	352	353	354	355	356	357	358	359	360	361	362
	14	1.33	378	379	380	381	382	383	384	385	386	387	388	389	390
	15	1.47	406	407	408	409	410	411	412	413	414	415	416	417	418
6	16	1.60	434	435	436	437	438	439	440	441	442	443	444	445	446
	17	1.73	462	463	464	465	466	467	468	469	470	471	472	473	474
	18	1.87	490	491	492	493	494	495	496	497	498	499	500	501	502
7	19	2.00	518	519	520	521	522	523	524	525	526	527	528	529	530
	20	2.13	546	547	548	549	550	551	552	553	554	555	556	557	558
	21	2.27	574	575	576	577	578	579	580	581	582	583	584	585	586
8	22	2.40	602	603	604	605	606	607	608	609	610	611	612	613	614
	23	2.53	630	631	632	633	634	635	636	637	638	639	640	641	642
	24	2.67	658	659	660	661	662	663	664	665	666	667	668	669	670
9	25	2.80	686	687	688	689	690	691	692	693	694	695	696	697	698
	26	2.93	714	715	716	717	718	719	720	721	722	723	724	725	726
	27	3.07	742	743	744	745	746	747	748	749	750	751	752	753	754
10	28	3.20	770	771	772	773	774	775	776	777	778	779	780	781	782
	29	3.33	798	799	800	801	802	803	804	805	806	807	808	809	810
	30	3.47	826	827	828	829	830	831	832	833	834	835	836	837	838
11	31	3.60	854	855	856	857	858	859	860	861	862	863	864	865	866
	32	3.73	882	883	884	885	886	887	888	889	890	891	892	893	894
	33	3.87	910	911	912	913	914	915	916	917	918	919	920	921	922
12	34	4.00	938	939	940	941	942	943	944	945	946	947	948	949	950

```
GROSS GRID                          6
                                    I
   FINE GRID          27          28
       DISTANCE      0.23        0.23
 1   1      0.0   ---27--------28I
     2      0.00    55         56I
     3      0.00    83         84I
 2   4      0.00   111        112I
     5      0.13   139        140I
     6      0.27   167        168I
 3   7      0.40   195        196I
     8      0.53   223        224I
     9      0.67   251        252I
 4  10      0.80   279        280I
    11      0.93   307        308I
    12      1.07   335        336I
 5  13      1.20   363        364I
    14      1.33   391        392I
    15      1.47   419        420I
 6  16      1.60   447        448I
    17      1.73   475        476I
    18      1.87   503        504I
 7  19      2.00   531        532I
    20      2.13   559        560I
    21      2.27   587        588I
 8  22      2.40   615        616I
    23      2.53   643        644I
    24      2.67   671        672I
 9  25      2.80   699        700I
    26      2.93   727        728I
    27      3.07   755        756I
10  28      3.20   783        784I
    29      3.33   811        812I
    30      3.47   839        840I
11  31      3.60   867        868I
    32      3.73   895        896I
    33      3.87   923        924I
12  34      4.00  --951-------952I
```

STEADY STATE TEMPERATURE DISTRIBUTION AFTER 0 ITERATIONS. TIME = 0.0

GROSS GRID			1			2								
FINE GRID			1	2	3	4	5	6	7	8	9	10	11	12	13
		DISTANCE	0.0	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
1	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	4	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	5	0.13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	6	0.27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	7	0.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	8	0.53	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	9	0.67	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	10	0.80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	11	0.93	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	12	1.07	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	13	1.20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	14	1.33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	15	1.47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	16	1.60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	17	1.73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	18	1.87	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	19	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	20	2.13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	21	2.27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	22	2.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	23	2.53	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	24	2.67	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	25	2.80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	26	2.93	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	27	3.07	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	28	3.20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	29	3.33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	30	3.47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	31	3.60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	32	3.73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	33	3.87	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	34	4.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

GROSS GRID			3	4										5	
	FINE GRID		14	15	16	17	18	19	20	21	22	23	24	25	26
		DISTANCE	0.10	0.11	0.12	0.13	0.14	0.15	0.17	0.18	0.19	0.20	0.22	0.23	0.23
1	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	4	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	5	0.13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	6	0.27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	7	0.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	8	0.53	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	9	0.67	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	10	0.80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	11	0.93	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	12	1.07	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	13	1.20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	14	1.33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	15	1.47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	16	1.60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	17	1.73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	18	1.87	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	19	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	20	2.13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	21	2.27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	22	2.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	23	2.53	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	24	2.67	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	25	2.80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	26	2.93	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	27	3.07	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	28	3.20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	29	3.33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	30	3.47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	31	3.60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	32	3.73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	33	3.87	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	34	4.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

```
GROSS GRID                                  6
                                            I
   FINE GRID                27            28
        DISTANCE            0.23          0.23
 1    1        0.0    ----0.0------0I0
      2        0.00      0.0         0I0
      3        0.00      0.0         0I0
 2    4        0.00      0.0         0I0
      5        0.13      0.0         0I0
      6        0.27      0.0         0I0
 3    7        0.40      0.0         0I0
      8        0.53      0.0         0I0
      9        0.67      0.0         0I0
 4   10        0.80      0.0         0I0
     11        0.93      0.0         0I0
     12        1.07      0.0         0I0
 5   13        1.20      0.0         0I0
     14        1.33      0.0         0I0
     15        1.47      0.0         0I0
 6   16        1.60      0.0         0I0
     17        1.73      0.0         0I0
     18        1.87      0.0         0I0
 7   19        2.00      0.0         0I0
     20        2.13      0.0         0I0
     21        2.27      0.0         0I0
 8   22        2.40      0.0         0I0
     23        2.53      0.0         0I0
     24        2.67      0.0         0I0
 9   25        2.80      0.0         0I0
     26        2.93      0.0         0I0
     27        3.07      0.0         0I0
10   28        3.20      0.0         0I0
     29        3.33      0.0         0I0
     30        3.47      0.0         0I0
11   31        3.60      0.0         0I0
     32        3.73      0.0         0I0
     33        3.87      0.0         0I0
12   34        4.00    ----0.0------0I0
```

TEMPERATURES ON NUMBERED BOUNDARIES

BOUNDARY NUMBER	TEMPERATURE
1	302.070000
2	306.500000
3	310.930000
4	315.370000
5	319.800000
6	324.230000
7	328.660000
8	333.100000
9	337.530000
10	341.960000
11	344.870000
12	347.240000
13	349.310000
14	351.370000
15	353.430000
16	355.500000
17	357.560000
18	359.630000
19	361.690000
20	363.750000
21	365.820000

```
22                    0.0
23                  345.890000

                ELAPSED CPU TIME IS    19.56 SECJHDS

THE  MAXIMUM  TEMPERATURE  IS -  c.0                  (+-0.1)

MAX.  TEMP.  APPEARS AT NODES   -          1          2          3          4          5
                                           6          7          8          Y         10
                                          11         12         13         14         15
                                          16         17         18         19         20
                                          21         22         23         24         25
                                          26         27         28         29         30
                                          31         32         33         34         35
                                          36         37         38         39         40
                                          41         42         43         44         45
                                          46         47         48         49         50

THE  MINIMUM  TEMPERATURE  IS -  0.0                  (+-0.1)

MIN. TEMP. APPEARS AT NODES   -           1          2          3          4          5
                                           6          7          8          9         10
                                          11         12         13         14         15
                                          16         17         18         19         20
                                          21         22         23         24         25
                                          26         27         28         29         30
                                          31         32         33         34         35
                                          3d         37         38         39         40
                                          41         42         43         44         45
                                          46         47         48         49         50
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STEADY STATE TEMPERATURE DISTRIBUTION AFTER 164 ITERATIONS. TIME = 0.0

GROSS GRID			1			2								
	FINE GRID		1	2	3	4	5	6	7	8	9	10	11	12	13
		DISTANCE	0.0	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
1	1	0.0	348.40	349.28	350.25	351.37	365.79	373.58	377.92	380.38	381.72	382.34	382.38	381.85	380.67
	2	0.00	349.16	350.25	351.43	352.66	370.51	380.14	385.53	388.57	390.24	391.01	391.06	390.39	388.81
	3	0.00	349.71	351.04	352.46	353.89	375.14	386.64	393.06	396.69	398.69	399.60	399.66	398.88	396.99
2	4	0.00	349.82	351.66	353.41	355.08	379.69	393.05	400.51	404.74	407.06	408.12	408.20	407.29	405.11
	5	0.13	378.67	387.39	396.02	404.58	560.52	684.17	784.03	864.81	929.48	980.01	1017.83	1043.97	1059.21
	6	0.27	383.03	392.79	402.47	412.07	586.25	725.14	838.25	930.59	1005.19	1064.00	1108.36	1139.25	1157.38
3	7	0.40	381.57	391.51	401.36	411.14	588.66	730.27	845.70	940.08	1016.42	1076.69	1122.21	1153.95	1172.59
	8	0.53	379.49	389.46	399.35	409.16	587.52	729.74	845.67	940.46	1017.15	1077.70	1123.45	1155.34	1174.08
	9	0.67	379.48	389.45	399.34	409.14	587.46	729.67	845.59	940.38	1017.08	1077.63	1123.39	1155.29	1174.03
4	10	0.80	377.28	387.26	397.15	406.96	585.62	728.03	844.09	938.98	1015.74	1076.35	1122.15	1154.07	1172.83
	11	0.93	375.08	385.06	394.95	404.77	583.77	726.37	842.56	937.53	1014.36	1075.02	1120.84	1152.79	1171.56
	12	1.07	375.05	385.02	394.91	404.72	583.59	726.10	842.22	937.14	1013.93	1074.55	1120.35	1152.28	1171.04
5	13	1.20	372.85	382.82	392.72	402.53	581.72	724.43	840.68	935.69	1012.54	1073.21	1119.04	1150.99	1169.76
	14	1.33	370.65	380.62	390.52	400.33	579.86	722.76	839.14	934.24	1011.15	1071.86	1117.73	1149.69	1168.48
	15	1.47	370.61	380.58	390.47	400.28	579.68	722.50	838.81	933.85	1010.72	1071.40	1117.23	1149.19	1167.96
6	16	1.60	368.41	378.39	388.28	398.09	577.83	720.83	837.27	932.40	1009.33	1070.06	1115.93	1147.90	1166.68
	17	1.73	366.21	376.19	386.09	395.90	575.97	719.17	835.73	930.95	1007.95	1068.72	1114.62	1146.61	1165.41
	18	1.87	366.18	376.15	386.04	395.85	575.79	718.91	835.40	930.57	1007.52	1068.26	1114.13	1146.11	1164.89
7	19	2.00	363.98	373.96	383.85	393.66	573.94	717.25	833.87	929.12	1006.14	1066.92	1112.83	1144.82	1163.62
	20	2.13	361.78	371.76	381.66	391.47	572.08	715.59	832.34	927.68	1004.76	1065.58	1111.52	1143.54	1162.35
	21	2.27	361.75	371.72	381.61	391.42	571.91	715.32	832.00	927.29	1004.33	1065.12	1111.03	1143.03	1161.83
8	22	2.40	359.55	369.53	379.42	389.23	570.05	713.66	830.48	925.85	1002.95	1063.79	1109.73	1141.75	1160.57
	23	2.53	357.35	367.33	377.23	387.04	568.20	712.01	828.95	924.41	1001.57	1062.46	1108.43	1140.48	1159.30
	24	2.67	357.32	367.29	377.18	386.99	568.03	711.74	828.62	924.03	1001.15	1062.00	1107.95	1139.97	1158.78
9	25	2.80	355.12	365.09	374.99	384.80	566.17	710.09	827.09	922.59	999.77	1060.66	1106.65	1138.69	1157.52
	26	2.93	352.91	362.89	372.79	382.60	564.32	708.43	825.56	921.15	998.39	1059.33	1105.35	1137.42	1156.25
	27	3.07	352.88	362.86	372.74	382.55	564.14	708.17	825.23	920.76	997.97	1058.87	1104.86	1136.91	1155.74
10	28	3.20	350.68	360.66	370.55	380.36	562.29	706.51	823.70	919.33	996.60	1057.55	1103.57	1135.64	1154.48
	29	3.33	348.48	358.46	368.36	378.17	560.44	704.86	822.18	917.90	995.23	1056.23	1102.28	1134.37	1153.22
	30	3.47	348.45	358.43	368.31	378.12	560.27	704.60	821.85	917.52	994.80	1055.77	1101.80	1133.87	1152.71
11	31	3.60	346.25	356.23	366.12	375.93	558.43	702.96	820.34	916.09	993.44	1054.45	1100.52	1132.61	1151.46
	32	3.73	344.06	354.04	363.93	373.75	556.59	701.33	818.85	914.69	992.11	1053.17	1099.27	1131.39	1150.25
	33	3.87	344.04	354.02	363.91	373.72	556.51	701.20	818.68	914.50	991.90	1052.95	1099.03	1131.14	1150.00
12	34	4.00	344.04	354.02	363.91	373.72	556.50	701.18	818.66	914.48	991.88	1052.92	1099.00	1131.10	1149.96

	GROSS GRID		3	4										5	
			I	I										I	
	FINE GRID		14	15	14	17	18	19	20	21	22	23	24	25	26
	DISTANCE		0.10	0.11	0.12	0.13	0.14	0.15	0.17	0.18	0.19	0.20	0.22	0.23	0.23
1	1	0.0	378.14	377.06	379.99	389.17	379.32	377.85	376.92	373.54	370.57	366.83	360.80	350.94	350.33
	2	0.00	385.81	385.46	388.10	388.32	387.27	385.45	383.06	380.11	376.43	371.55	364.33	352.13	391.39
	3	0.00	393.41	393.00	396.15	396.41	395.16	392.99	390.15	386.f13	302.25	376.43	367.82	353.29	352.45
7	4	0.00	400194	400147	404.14	404.45	403.00	400.49	397.18	393.11	388.02	381.26	371.27	354.43	353.51
	5	0.13	1064114	1139124	1132.20	1111.56	1077.56	1030.18	969.10	893.56	802.17	692.57	560.63	398150	391.53
	6	0.27	1163129	1282108	1273.63	1248.77	1207.85	1150.94	1077.84	987.89	879.74	750.88	596.62	407145	399.24
3	7	0.40	1178167	1313169	1304.92	1279.12	1236.65	1177.64	1101.91	1008.83	897.08	764.14	605.22	410142	401.95
	8	0.53	1180620	1321108	1312.24	1286.24	1243.44	1183.97	1107.67	1013.93	901.43	767.64	607.77	411187	403.34
	9	0.67	1180115	1322189	1314.03	1287.98	1245.09	1185.50	1109.06	1015.14	902.43	769.20	608.25	411199	403.44
4	10	0.80	1178195	1323177	1314.91	1288.86	1245.96	1186.37	1109.92	1016.00	903.29		609.18	413103	404.48
	11	0.93	1177168	1324140	1315.54	1289.49	1246.60	1187.02	1110.58	1016.69	904.02	779.07	610.05	414105	405.50
	12	1.07	1177116	1324171	1315.85	1289.79	1246.89	1187.30	1110.84	1016.92	904.22	770.22	610.15	414108	405.53
5	13	1.20	1175488	1325177	1316.41	4290.36	1247.47	1187.89	1111.45	1017.56	904.91	770.98	611.00	415109	406.55
	14	1.33	1174161	1325183	1316.97	1290.92	1248.04	1188.48	1112.06	1018.20	905.59	771.73	611.85	416111	407.56
	15	1.47	1174108	1326112	1317.26	1291.21	1248.32	1186.74	1112.31	1018.43	905.78	771.88	611.95	416114	407.59
6	16	1.60	1172181	1326168	1317.82	1291.78	1248.90	1199.33	1112.92	1019.07	906.47	772.63	612.80	417116	408.61
	17	1.73	1171154	1327124	1318.38	1292.34	1249.48	1189.92	1193.54	1019.72	907.16	773.39	613.66	418118	409.63
	18	1.87	1171802	1327853	1318.68	1292.63	1249.75	1190.19	1113.78	1019.94	907.36	773.54	613.76	418121	409.66
7	19	2.00	1169175	1328109	1329.24	1293.20	1250.33	1190.78	114.40	1020.58	908.04	774.29	614.61	419122	410.68
	23	2.13	1168149	1328165	1319.80	1293.76	1250.90	1191.37	115.01	1021.23	908.74	775.05	615.46	420123	411.69
	21	2.27	1167197	1328194	1320.09	1294.35	1251.18	1191.63	1115.25	1021.45	908.92	775.20	615.56	420127	411.72
8	22	2.40	1166170	1329151	1375.65	1294.62	1251.76	1192.23	1115.87	1022.10	909.61	775.95	616.41	421129	412.74
	23	2.53	1165144	1330107	1321.21	1295.19	1252.34	1192.82	1116.49	1022.74	910.32	776.71	617.27	422131	413.76
	24	2.67	1164192	1330136	1321.51	1295.47	1252.62	1193.09	1116.73	1022.97	910.50	776.86	617.37	422334	413.79
9	25	2.80	1163166	11330192	1322.01	1296.04	1253.19	1193.68	1117.35	1023.61	911.19	777.62	618.22	423135	414.81
	26	2.93	1162140	1331148	1322.63	1296.61	1253.77	1199.27	1117.96	1024.26	911.88	778.37	619.07	424137	415.82
	27	3.07	1161188	1331177	1322.92	1296.89	1254.05	1194.53	1118.21	1024.48	912.07	778.52	619.17	424140	415.85
10	28	3.20	1160162	1332133	1323.48	1297.46	1254.62	1195.13	1118.82	1025.12	912.76	779.28	620.02	425141	416.87
	29	3.33	1159137	1332189	1324.05	1298.03	1255.20	1195.72	1119.44	1025.77	913.45	780.03	620.87	426143	417.88
	30	3.47	1158186	1333119	1324.34	1298.31	1755.48	1195.98	1119.68	1025.99	913.64	780.18	620.98	426346	417.91
11	31	3.60	1157161	1333174	1324.95	1298.88	1256.05	1196.57	1120.29	1026.04	914.33	780.94	621.83	427148	418.93
	32	3.73	1156141	1334127	1325.43	1299.42	1256.60	1197.14	1120.89	1027.26	915.00	781.68	622.68	428150	419.95
	33	3.87	1156115	1334142	1325.57	1299.56	1256.94	1197.27	1121.01	1027.37	915.10	781.76	622.73	428151	419.96
12	34	4.00	1156141	1334145	1325.60	1299.58	1256.77	1197.29	1121.03	1027.39	915.12	781.77	622.73	428151	419.96

GROSS GRID

	FINE GRID	DISTANCE	27	28
			0.23	0.23
1	1	0.0	349.69	349.00
	2	0.00	350.61	349.75
	3	0.00	351.56	350.57
2	4	0.00	352.56	351.56
	5	0.13	384.51	377.45
	6	0.27	390.99	382.70
3	7	0.40	393.43	384.87
	8	0.53	394.77	386.15
	9	0.67	394.86	386.22
4	10	0.80	395.89	387.26
	11	0.93	396.91	388.28
	12	1.07	396.93	388.30
5	13	1.20	397.95	389.32
	14	1.33	398.97	390.34
	15	1.47	398.99	390.36
6	16	1.60	400.02	391.39
	17	1.73	401.04	392.41
	18	1.87	401.06	392.43
7	19	2.00	402.08	393.45
	20	2.13	403.10	394.47
	21	2.27	403.12	394.49
8	22	2.40	404.15	395.52
	23	2.53	405.17	396.54
	24	2.67	405.19	396.56
9	25	2.80	406.21	397.58
	26	2.93	407.23	398.60
	27	3.07	407.25	398.62
10	28	3.20	408.27	399.64
	29	3.33	409.29	400.66
	30	3.47	409.31	400.68
11	31	3.60	410.34	401.71
	32	3.73	411.36	402.73
	33	3.87	411.37	402.74
12	34	4.00	411.37	402.74

TEMPERATURES ON NUMBERED BOUNDARIES

BOUNDARY NUMBER	TEMPERATURE
1	302.070000
2	306.500000
3	310.930000
4	315.370000
5	319.800000
6	324.230000
7	328.660000
8	333.100000
9	337.530000
10	341.960000
11	344.870000
12	347.240000
13	349.310000
14	351.370000
15	353.430000
16	355.500000
17	357.560000
18	359.630000
19	361.690000
20	363.750000
21	365.820000

```
22                    0.0
23                  345.890000

          ELAPSED CPU TIME IS   50.16 SECONDS
THE  MAXIMUM  TEMPERATURE  IS -  1.33442D 03       (+-0.1)
MAX. TEMP. APPEARS AT NODES   -        911        939
THE  MINIMUM  TEMPERATURE  IS -  3.44057D 02       (+-0.1)
MIN. TEMP. APPEARS AT NODES   -        869        897        925
     THE STEADY STATE CALCULATIONS HAVE BEEN COMPLETED.
     NUMBER OF ITERATIONS COMPLETED =   164
```

$$\frac{\partial C}{\partial t} + \frac{\partial N}{\partial x}T + \frac{\partial N}{\partial y}T = R \tag{34}$$

Setting $(\partial C/\partial t) = 0$ for steady state and applying Ficks' Law to Eq. (34) gives

$$0 = \frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial C}{\partial y}\right) + R \tag{35}$$

This equation is analogous in form to the steady state energy equation. Therefore, Eq. (35) may be solved by adaptation of the HEATING5 program. In such an adaption, concentration (C), diffusivity (D), and mass generation (R) are substituted for temperature (T), thermal conductivity (k), and heat generation (S), respectively.

One difficulty in the use of HEATING5 to solve the equation of continuity is the dependence of diffusivity on temperature. HEATING5 allows thermal conductivity to be a function of temperature, but substitution of the mass equation results in diffusivity only being allowed to be a function of concentration which is not the case. This problem is overcome by approximating the lithium and the niobium as a number of regions with a different material in each region. Each material is given a constant diffusivity which is calculated from the average temperature in that region according to the equations:

$$D_L = 2.4 \times 10^{-6} \left(10^{-3.406 \times 10^3/T}\right) \tag{36}$$

$$D_{Nb} = 1.8 \times 10^{-6} \left(e^{-5000/T}\right) \tag{37}$$

where D_L and D_{Nb} are the tritium diffusivity in the lithium and niobium, respectively. Therefore, the temperature profile must be obtained before the concentration profile can be calculated.

For the tritium concentration problem as it was interpreted for use in HEATING5, the gross lattice lines were the boundaries between the different materials. There were 15 material regions, 5 in the y-direction and 3 in the x-direction, in the lithium before the niobium tube, and 25 in the lithium after the tube (5 in the y-direction and 5 in the x). Each wall of the niobium tube was divided into five regions in the y-direction, and the hollow space is divided into five gap regions in the y-direction. Each material region was further divided into four subdivisions by fine lattice lines. The intersection of two lattice lines constitutes a node. The HEATING5 program prints out concentration values at each node. Details on data input format are on file at the Practice School.

The program output includes a printout of input data, a node map in which the increasing x-direction is given from left to right and the increasing y-direction is from top to bottom, a table for specially monitored nodes and the corresponding concentrations, and the concentration profile map, a sample of which is shown in Table 13. The concentration profile is printed under the title steady state temperature distribution (since the program is meant for temperature and not concentration). The outermost row and column correspond to gross lattice lines, the middle row and column to fine lattice lines, and the innermost to actual distances. Once again the increasing x-direction is from left to right and the increasing y-direction is from top to bottom. The concentrations are given in moles/m^3.

9.3.4 Determination of the Transient Temperature Profile

As described in Sect. 3.6, the transient temperature profile in the first blanket zone during a 1-min plasma shutdown must be calculated to determine the thermal stress on the coolant tubes. HEATING5, however, is not written to solve transient problems involving a coolant flow. Even though the transient problem cannot be solved, two limiting cases which bracket the actual transient response can be solved.

When the plasma is shut down, all heat generation ceases. If the coolant mass flow rate remains constant, the bulk coolant temperature will immediately drop due to the lack of incident heat from the plasma. The new coolant temperature change across the U-tube can be determined by assuming that the heat flux from the lithium slab remains for a short time at the steady state value. The minimum value for the initial coolant temperature change will then be given from an overall energy balance by:

$$\Delta T_{CT1} = \frac{T_{CSS}(P_{NT_1} + P_{NT_2} + P_{Li_1} + P_{Li_2})}{\text{total module power}} \tag{38}$$

The new temperature profile in the coolant can be approximated by the manner described in Appendix 9.1.

Since the tube wall is now in contact with a lower coolant temperature, there will be an immediate increase in the heat flux out of the tube wall. The flux reached is the maximum possible heat flux that can occur during the transient period, since the wall temperature will drop due to cooling of the lithium slab, and the bulk coolant temperature will rise, initially, due to the increased heat flux creating a progressively smaller temperature difference between the tube wall and the coolant during the plasma shutdown. Although the coolant temperature will eventually begin to drop, the temperature difference between the coolant and the wall will never be as great as the initial value. The value of the maximum heat flux can be calculated at each point along the surface by application of the following equation:

Table 13. Sample Tritium Concentration Profile

STEADY STATE TEMPERATURE DISTRIBUTION AFTER 126 ITERATIONS, TIME = 0.0

GROSS GRID			1		2		3		4		5	6		7	
FINE GRID		DISTANCE	0.01	0.03	0.04	0.06	0.08	0.09	0.11	0.11	0.11	0.12	0.12	0.12	0.13
1	1	0.0	1034149	617.82	205178	153.32	82195	44.88	0111	0.06	010	010	0.03	0106	16.40
	2	0.40	1034124	617.61	205168	153.24	82191	44.86	0111	0.06	010	010	0.03	0106	16.37
2	3	0.80	986146	776.97	193104	143.67	77145	41.91	0111	0.06	010	010	0.03	0106	14.22
	4	1.20	943108	744.07	181191	135.27	72169	39.34	0111	0.05	010	010	0.03	0106	12.59
3	5	1.60	987157	776.86	185110	137.70	74111	40.10	0111	0.05	010	010	0.03	0106	12.48
	6	2.00	1036124	616.06	188152	140.31	75164	40.93	0111	0.05	010	010	0.03	0106	12.40
4	7	2.40	1081123	648.42	190181	141.31	76109	41.17	0111	0.06	010	010	0.03	0106	12.37
	8	2.80	1126134	683.83	193115	143.35	76154	41.42	0111	0.06	010	010	0.03	0106	12.34
5	9	3.20	1175182	815.67	196188	145.30	77137	41.87	0111	0.06	010	010	0.03	0106	12.30
	10	3.60	1225191	657.45	199108	147.46	78121	42.32	0111	0.06	010	010	0.03	0106	12.27
6	11	4.00	1226116	957.59	199111	147.48	78122	42.32	0111	0.06	010	010	0.03	0106	12.27

GROSS GRID			8		9		10		11		12
FINE GRID		DISTANCE	14	15	16	17	18	19	20	21	22
			0.14	0.15	0.17	0.18	0.19	0.20	0.21	0.23	0.24
1	1	0.0	36163	47.98	62167	84.78	102147	146.82	177161	209.24	219145
		0.40	30156	47.87	62152	84.36	102122	146.49	177144	208.85	219106
2	3	0.80	26156	41.17	53154	63.59	71164	109.35	135171	191.62	209180
	4	1.20	23150	36.16	46191	53.44	58165	91.40	114126	363.17	444102
3	5	1.60	22136	35.89	46154	55.80	63120	95.62	118127	366.91	435175
	6	2.00	23114	35.67	46127	62.27	75108	107.16	129159	365.97	442178
4	7	2.40	23105	35.58	46114	62.36	74180	106.52	128169	368.15	435136
	8	2.80	23103	35.46	45199	61.30	74146	105.81	127172	354.44	428110
5	9	3.20	22156	35.35	45183	61.35	74112	105.19	126189	348.17	420107
	10	3.60	22185	35.23	45168	61.29	73179	104.57	126108	342.18	412140
6	11	4.00	22165	35.22	45168	61.29	73179	104.57	126108	342.16	412136

TEMPERATURES ON NUMBERED BOUNDARIES

BOUNDARY NUMBER	TEMPERATURE
1	0.0
2	0.0

ELAPSED CPU TIME IS 5.31 SECONDS

THE MAXIMUM TEMPERATURE 15 - 1.22610D 03 (+-0.1)

MAX. TEMP. APPEARS AT NODES - 221

THE MINIMUM TEMPERATURE IS - 0.0 (+-0.1)

MIN. TEMP. APPEARS AT NODES -

9	10	11	12	30
31	32	33	34	52
53	54	55	56	74
75	76	77	78	96
97	98	99	100	118
119	120	121	122	140
141	142	143	144	162
163	164	165	166	184
185	186	187	188	206
207	208	209	210	228

THE STEADY STATE CALCULATIONS HAVE BEEN COMPLETED.

NUMBER OF ITERATIONS COMPLETED = 126

$$q_{T_{max(N)}} = h(T_{TL} - T_{w_{SS}}) \tag{39}$$

By integrating this maximum heat flux over the surface of the tube, the maximum coolant temperature during the transient period can be determined. The following equation applies over each section of the coolant tube:

$$\dot{M}_c \, C_{p_c} \, \Delta T_{max_L} = q_{I_{Ni}} (A_i) \tag{40}$$

where:

$$q_{I_{Ni}} = \text{average of } q_{max(N)} \text{ in region i} \tag{41}$$

Once the maximum coolant temperatures during the transient period have been determined, the maximum wall temperatures during the transient period can be determined by using HEATING5. The transient temperature profile can be determined by first performing a steady state simulation with the original coolant temperatures and heat generation rates, then setting the heat generation rates to zero and the coolant temperatures to their maximum transient value and performing a transient simulation.

The minimum wall temperatures during the transient period can be determined by assuming that the coolant temperature throughout the entire U-tube drops immediately to the inlet temperature at the outset of the transient period. Since no matter how low the heat flux from the lithium becomes, the coolant temperature can never drop below the inlet value, the wall temperatures will never become lower than the values obtained by performing a transient simulation with coolant temperatures equal to the inlet temperature.

The maximum stress will occur when the difference between the temperatures of the wall face adjacent to the lithium and the wall face adjacent to the plasma is a maximum. Similarly, the minimum stress will occur when the difference between these temperatures is a minimum. Since order of magnitude calculations showed that the temperature of the wall face adjacent to the plasma drops to the bulk temperature of the coolant in under one second, the temperature of this wall face can be taken to be equal to the bulk coolant temperature throughout the transient period. Therefore, the maximum stress could be determined by using the maximum wall temperatures (which are the steady state values) and the minimum coolant temperature (which is the inlet temperature). Analogously, the minimum stress could be obtained by using the minimum wall temperatures (which occur at the end of the transient simulation where the coolant temperature equals the inlet temperature) and the maximum coolant temperatures (which are calculated at the end of the steady state simulation).

The only new inputs to HEATING5 for the transient simulations are the T_{T_i}, the coolant temperatures during the transient period. The first transient simulation (minimum cooling) can be performed by inputting the maximum T_{T_i}'s while the second transient simulation (maximum cooling) can be performed by using the inlet coolant temperature for the T_{T_i}'s. The maximum CPU time (xxx and ITMAX) may have to be increased to 500 sec for the transient simulations.

The output generated by HEATING5 for a transient simulation begins with a steady state simulation at time equals zero (see data file). Following the steady state simulation, transient temperature maps are printed out at 5-sec intervals. Maximum and minimum temperatures and elapsed CPU times are also output.

9.4 Location of Original Data

All original data are in the form of computer output. The data from the case study run on the overall energy balance program are bound into a file called "Computer Output from Case Study on Overall Energy Balance Program." The computer ouput from HEATING5 for the steady state simulation of the temperature and tritium concentration profile and the steady state solution for the maximum and minimum stress analysis is bound into a book called"HEATING5 Data Book." These are on file at the MIT School of Chemical Engineering Practice, Bldg. 3001, ORNL.

9.5 Nomenclature

A	surface area, m^2
a	integration constant
C	concentration of tritium, mole/m^3
C_p	heat capacity of coolant, J/kg-°K
D	inside diameter of coolant tube, cm
D	diffusivity of tritium through lithium (or niobium), m^2/sec
G	inner diameter of niobium tube, m
h	heat transfer coefficient (film) for coolant, W/m^2-°K
k	thermal conductivity, W/m-°K
$\dot{M}$	mass flow rate of coolant, kg/sec
n	neutron
N	neutron loading, MW/m^2

N_T	molar flux of tritium, moles/m^2-sec
P^T	total power generation within region per MW/m^2 neutron loading, W/m^3
P	power generation (density), (MW/m^3)/(MW neutron loading/m^2)
P_o	surface (x = 0) power density, (MW/m^3)/(MW neutron loading/m^2)
Q	energy deposition in coolant, W
Q_{inc}	charged particle loading, MW/m^2
$q_{T_{max}}$	maximum possible heat flux during the transient period at a point N on the surface
R	rate of tritium generation, mole/m^3-sec
S_n	rate of heat generation due to neutronic collisions, MW/m^3
T	temperature, °K or °C
t	time, sec
t_1	front distance between cooling tube wall and niobium wall, m
t_2	back distance from niobium wall to cooling tube, m
T_{bT1}	minimum possible bulk coolant temperature during transient period
T_{wSS}	steady state temperature on the inside of the tube wall which faces the lithium
U	overall heat transfer coefficient between the coolant and lithium through stainless steel tube, W/m^2-°K
V	volume, m^3
W	width of wall
x	horizontal coordinate
X0	plasma side outer wall x-coordinate
X1	plasma side inner wall x-coordinate
X2	lithium side inner wall x-coordinate
X3	lithium side outer wall x-coordinate
X4	front outer wall niobium coordinate
X4B	front inner wall niobium coordinate

X4C back inner wall niobium coordinate

X5 back outer niobium coordinate

X6 back lithium side outer wall x-coordinate

X7 back lithium side inner wall x-coordinate

X8 back side inner wall x-coordinate

X9 back side outer wall x-coordinate

y vertical coordinate

$\Delta T_{c_{SS}}$ coolant temperature change across the U-tube during steady state

$\Delta T_{c_{TL}}$ coolant temperature change across the U-tube immediately after plasma shutdown

ΔT_{max_i} maximum temperature

Subscripts

a position a

ab between a and b

b bulk coolant, position b

c coolant

i region i

in into a region being considered

L lithium

$Li_{1,2}$ lithium in region 1 (front) or in region 2 (back)

m module

max maximum

min minimum

Nb niobium

out out of a region being considered

SS stainless steel

SS1 plasma side of tube

SS2 lithium side of tube

t tubing

w niobium wall

9.6 Literature References

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