Natural Circulation in the Blanket Heat Removal System During a Loss-of-Pumping Accident (LOFA) Based on Initial Conceptual Design

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Table of Contents

1	Summary	1
2	Background	1
3	Description of the Model	2
4	Vertical Mixed Convection Friction Factors	4
5	Discussion and Results	4
6	Conclusions	12
7	References	12

Appendix A: Derivation of the Governing Equations

Appendix B: Buoyancy-Assisted and Buoyancy-Opposed Friction Factor Multipliers

Appendix C: Sample Input Deck

Appendix D: Code Listing

List of Figures

Figure 1	Schematic of the blanket primary HR system with three lumped modules and one lumped heat exchanger loop.....	3
Figure 2	Natural circulation flowrates during a T/B LOFA.....	6
Figure 3	Expanded view of the flowrates during the flow reversal process.....	6
Figure 4	Transient fluid temperatures of the two headers and the shell side of the heat exchanger during a T/B LOFA.....	7
Figure 5	Transient temperatures in the headers and Leg 1 during a T/B LOFA.	8
Figure 6	Transient temperatures in the headers and Leg 2 during a T/B LOFA.	8
Figure 7	Transient temperatures in the headers and Leg 3 during a T/B LOFA.	9
Figure 8	Transient temperatures in the headers and the tube side of the heat exchanger during a T/B LOFA.....	9
Figure 9	Outlet header pressure during a T/B LOFA.....	10
Figure 10	Natural circulation flowrates during a blanket only LOFA.	11
Figure 11	Transient fluid temperatures in the two headers and the shell side of the heat exchanger during a blanket only LOFA.	11
Figure A-1	Schematic of the blanket primary HR system with three lumped modules and one lumped heat exchanger loop.....	A1
Figure A-2	Schematic of one of the module legs of the natural convection network showing the control volumes used to derive the momentum equation.	A2
Figure A-3	Schematic of the heat exchanger leg of the natural convection network.	A3
Figure A-4	Schematic of the outlet header showing the mass flowrates.....	A4
Figure A-5	Schematic of the heat exchanger showing the heat transfer to the secondary side.....	A6
Figure B-1	Friction factor multipliers for buoyancy-assisted and buoyancy-opposed mixed convection in vertical channels.....	B2

List of Tables

Table 1	Cruciform-type module descriptions showing NC model relationship.	2
Table 2	Normal operation deposited power levels.....	5

1 Summary

A transient natural convection model of the APT blanket primary heat removal (HR) system was developed to demonstrate that the blanket could be cooled for a sufficient period of time for long term cooling to be established following a loss-of-flow accident (LOFA). The particular case of interest in this report is a complete loss-of-pumping accident. For the accident scenario in which pumps are lost in both the target and blanket HR systems, natural convection provides effective cooling of the blanket for approximately 68 hours, and, if only the blanket HR systems are involved, natural convection is effective for approximately 210 hours. The heat sink for both of these accident scenarios is the assumed stagnant fluid and metal on the secondary sides of the heat exchangers.

2 Background

Loss of power could leave the APT Target/Blanket (T/B) Facility without running pumps resulting in no forced circulation in the primary and secondary heat removal systems for an extended period of time. Natural circulation (NC) would occur in the primary HR system; however, without circulation through the secondary sides of the heat exchangers there would not be an ultimate heat sink for the decay power in the blanket modules. To prevent some or all of the blanket modules from eventually overheating and losing structural integrity, either power would have to be restored or the cavity flood system would have to be activated. There would be a period of time following the loss of forced convection in the HR systems when the modules would be cooled by natural convection. The stagnant water in the secondary sides of the heat exchangers could serve as a temporary heat sink, diminishing in effectiveness as it heats up. A transient single-phase natural convection model of the primary HR system was developed to determine the duration of time of effective passive cooling of the modules. A special purpose fortran program was written, called NCLOFA, and a listing of the code is provide in Appendix D.

The accident under consideration is a facility loss-of-power that results in the simultaneous loss of both the T/B primary and secondary coolant pumps. This accident is unmitigated except for a beam shutdown. The primary HR systems would ultimately dry out by boiling off the coolant inventories, if corrective action is not taken. This would occur much sooner in the target system than the blanket because of the differences in both metal and coolant masses. The target can survive high temperatures where thermal radiation to the blanket is an acceptable heat removal mechanism; whereas, without cavity flooding, the blanket cannot maintain its structural integrity very long after dryout. Based on results presented in Ref. [1], the target is assumed to dry out twenty-four hours after the onset of the accident and the target decay power is then deposited in the Module 1 decouplers. The model is run until the HR system coolant reaches its saturation temperature. Beyond this point two-phase flow is established; however, the NC model chosen for this set of analyses is limited to single-phase conditions. Even though it is anticipated that significant cooling capability further exists once boiling begins. No formal credit for boiling capability is taken at this time, since a significant increase in modeling complexity would only extend the existing acceptable period of time available prior to taking corrective action.. The consequences of this accident

scenario envelop those of the scenario where only the blanket primary and secondary coolant pumps are lost.

3 Description of the Model

The transient single-phase NC model of the primary HR system is based on a flow network with three lumped modules and one lumped heat exchanger, as shown in Fig. 1. The three lumped modules constitute three parallel legs between the fixed inlet and outlet headers, and the heat exchanger is in a fourth leg that forms the network into a closed loop. The various legs of the flow network that make up the NC model represent lumped flow paths. Table 1 provides a brief description of the 16 module cruciform-type units in the current blanket design (see Ref. [2] for further details). These modules are combined into lumped flow paths (referred to as legs) as listed below:

- "Leg 1" – the lateral Row-1/decoupler modules listed as Modules 1 and 4 in Table 1;
- "Leg 2" – the remaining vertical modules listed as Modules 2, 3, 5, 6, 7, 8, and 9 in Table 1;
- "Leg 3" – all horizontal modules listed as Modules 10, 11, 12, 13, 14, 15, and 16 in Table 1;
- "Hx leg" – blanket primary HR loop containing the two heat exchangers, two pumps, and piping from the outlet header back around to the inlet header closing the flow network.

Table 1 Cruciform-type module descriptions showing NC model relationship.

16 Module Number (Location)	Module Types (downflow / upflow)	NC Model ID
Module 1: (Front 1 st Lateral)	Decoupler / Row 1	Leg 1
Module 4: (Back 1 st Lateral)	Decoupler / Row 1	
Module 2: (Front 2 nd Lateral)	Row 3 / Row 2	Leg 2
Module 3: (Front 2 nd Lateral)	Row 3 / Row 2	
Module 5: (Back 2 nd Lateral)	Row 3 / Row 2	
Module 6: (Back 2 nd Lateral)	Row 3 / Row 2	
Module 7: (1 st Downstream)	Decoupler / Row 1	
Module 8: (2 nd Downstream)	Row 2 / Row 1	
Module 9: (3 rd Downstream)	Row 2 / Row 2	
Module 10: (Blanket Upstream)	Decoupler / Row 2	Leg 3
Module 11: (Lower Front Upper)	Decoupler / Row 2	
Module 12: (Lower Front Lower)	Row 2 / Row 2	
Module 13: (Lower Back Upper)	Decoupler / Row 2	
Module 14: (Lower Back Lower)	Row 2 / Row 2	
Module 15: (Upper Front)	Row 2 / Row 2	
Module 16: (Upper Lower)	Row 2 / Row 2	
Primary HR Loop	Piping, Heat Exchangers, Pumps	HX Leg

The labels above are also provided in Fig. 1. The pressurizer is not modeled explicitly but does establish the network reference pressure at the inlet header. The heated upflow and downflow sections of a module are treated separately in the momentum equations, and the impact of buoyancy-assisted/opposed mixed convection flow is accounted for through a Rayleigh number dependent modification of the Darcy friction factor. The heated solid sections of the modules are lumped together with the coolant flowing through them in the thermal energy equations. The aluminum clad lead plates and the fluid in the adjacent channels are assumed to be isothermal. This is reasonable at the low metal power densities encountered under post beam shutdown conditions and with the high heated surface area to fluid volume ratios for the flow channels. This simplification avoids the necessity of solving conjugate heat transfer problems within the modules. There are four momentum equations, one for each leg in the loop and a continuity equation for the outlet header. These five equations are solved simultaneously for the four leg mass flowrates and the outlet header pressure each time step using a standard Newton-Raphson method. The inlet header pressure is a boundary condition that specifies the system reference pressure.

Figure 1 Schematic of the blanket primary HR system with three lumped modules and one lumped heat exchanger loop.

For determining the transient temperature distribution within the network, each of the module legs of the network is divided into five cells, while the heat exchanger leg is divided into three. Under low flow conditions for which this model is intended, this spatial resolution is adequate. A thermal energy equation is derived for each leg cell, each of the headers, and for the shell (or secondary) side of the heat exchanger. The energy equations are differenced in time allowing a varying degree of implicitness

specified by the user. The energy equations are solved iteratively each time step in a two-step process. The two header temperatures and the temperature on the secondary side of the heat exchanger are updated. With these updated values, the network leg temperatures are updated by marching in the flow direction from the upstream to the downstream header for each leg. This process is repeated until convergence occurs. The momentum and thermal energy equations are derived in Appendix A.

The natural circulation is driven by the time dependent decay power in the heated sections of the module legs. After 24 hours have elapsed, the total target decay power is deposited in the decoupler section of Leg 1. This is the heated section in Leg 1 closest to the inlet header. This additional power is ramped in over a period of one hour. The NC simulation commences one hour after the onset of the accident and continues until the primary coolant reaches its saturation temperature. The model predicts the transient mass flowrates in the network legs, the outlet header pressure, the transient temperature distribution in the primary coolant, and the shell side heat exchanger temperature. Appendix C contains a sample-input file and Appendix D contains a code listing of the NCLOFA program.

4 Vertical Mixed Convection Friction Factors

The Darcy friction factors for mixed forced/free laminar convection through vertical passages can differ significantly from the forced convection values defined as sixty-four over the Reynolds number. In upflow through a heated vertical channel, buoyancy flattens the parabolic radial velocity profile and increases the wall velocity gradient, thereby, increasing the wall shear. In downflow, buoyancy decreases the radial velocity gradient at the wall and therefore the wall shear. The friction factor for heated upflow is increased, and for downflow it is decreased. No effect exists for horizontal flow paths.

Based on a plot of Fanning friction factors for buoyancy assisted and retarded flows between vertical flat plates in Ref. [3], correlations were developed for friction factor multipliers as functions of a modified Rayleigh number. These correlations are developed in Appendix B. They are used in the NC model to modify the friction factors in the heated sections of the two network vertical module legs.

5 Discussion and Results

Two facility loss-of-power accident scenarios were simulated with the NC model: a simultaneous loss of both the T/B primary and secondary coolant pumps, and a loss of only the blanket primary and secondary coolant pumps. The first scenario is the more interesting of the two because flow reversals occur. It is also the more limiting case because, with the addition of the target decay power, more power (approximately double) is transferred to the coolant. The results of this accident simulation are described first and in detail. The results for the latter scenario are described primarily by comparison and contrast with the results of the former.

Figure 2 shows, for the first accident scenario, the network mass flowrates for the three modules and the heat exchanger leg as functions of elapsed time. By definition, positive flow through the three module legs travels from the inlet header to the outlet header and return flow occurs through the heat exchanger leg. During normal operation (NO) and prior to the depositing of the target power in the decoupler, the flow is positive throughout the network. The target is assumed to dry out within twenty-four hours of the

onset of the accident, and thereafter, the target decay power is dissipated by thermal radiation to the cooler adjacent blanket system decouplers. The blanket decouplers virtually surround the ladder assemblies, neutronically decoupling the target from the lead blanket. It is assumed that all thermal radiation emanating from the target ladders is deposited into the decouplers. This power is assumed to be ramped in over a period of one hour. With the addition of the target power, significantly more power is dissipated in the decoupler than in the Row-1 section of Leg 1, and buoyancy causes a flow reversal to occur. Deposited power levels under NO conditions are given in Table 2. Figure 3 shows an expanded view of the network mass flowrates during the period in which the flow reversals occur. Shortly after the flow reversal occurs in Leg 1 of the network, the flows reverse in Leg 3 and the Hx leg. The flow does not reverse in Leg 2. There are no preferred flow directions, due to buoyancy, in Leg 3 and the Hx leg of the network, so the flows in these legs readily reverse as consequences of the flow reversal in Leg 1. Buoyancy dictates the flow direction in Leg 2, and since the relative power distribution in this module doesn't change, neither does its flow direction.

Table 2 Normal operation deposited power levels.

NC Model ID	Deposited Power (MW) [NO downflow section]	Deposited Power (MW) [NO upflow section]
Leg 1	8.222	15.768
Leg 2	9.083	17.695
Leg 3	0.0	5.712
HX Leg	0.0	0.0
Totals	56.48 (blanket) 68.01 (targets)	- -

Figure 4 shows the temperatures of the two headers and the shell side of the heat exchanger. Prior to the flow reversals, the inlet header is colder than the outlet header, which is to be expected since the flows in all three modules are positive. After the flow reversals, the outlet header is colder than the inlet header. The shell side of the heat exchanger has the lowest of the three temperatures. This is the system heat sink. The increased heating rate of the fluid after the target power is deposited in the decoupler is evident from the slopes of the transient temperature plots.

Figure 2 Natural circulation flowrates during a T/B LOFA.

Figure 3 Expanded view of the flowrates during the flow reversal process.

Figures 5 through 7 show the two header temperatures and the temperatures in the two heated sections of each of the three legs, respectively. Figure 8 shows the two header temperatures and the heat exchanger temperature. The effects of the flow reversals on the relative magnitudes of the temperatures in the heated sections of legs one and three are evident. The flow does not reverse in Leg 2, and therefore, the downstream heated section remains hotter than the upstream heated section throughout the accident scenario. These two temperatures exceed the inlet header temperature after the flow reversals because the flow in this leg occurs from the inlet header to the outlet header. The highest system temperature occurs in this module. The heat exchanger primary (or tube side) temperature is equal to the inlet header temperature prior to the flow reversals, and it is slightly lower than the outlet header temperature after the flow reversals. After the flow reversals, the outlet header temperature is slightly greater than the heat exchanger temperature because Leg 2 continues to discharge into the outlet header.

Figure 4 Transient fluid temperatures of the two headers and the shell side of the heat exchanger during a T/B LOFA.

Figure 5 Transient temperatures in the headers and Leg 1 during a T/B LOFA.

Figure 6 Transient temperatures in the headers and Leg 2 during a T/B LOFA.

Figure 7 Transient temperatures in the headers and Leg 3 during a T/B LOFA.

Figure 8 Transient temperatures in the headers and the tube side of the heat exchanger during a T/B LOFA.

Figure 9 shows the transient outlet header pressure. It is constant at 107.3 psia, given a specified inlet header pressure of 106.24 psia. The difference between the two pressures is hydrostatic. In each leg of the network, the net buoyant force balances the dynamic pressure drop force. At the inlet header pressure the saturation temperature is 166.8°C and the inlet header reaches this temperature 67.9 hours after the onset of the accident. Once the mean fluid temperature reaches saturation, bulk boiling will commence and the system will start to pressurize. The primary and secondary coolants will continue to heat up as the saturation temperatures increase due to system pressurization. Since pressurizing the primary blanket HR system would threaten its integrity, bulk boiling should be avoided. The point at which the primary coolant temperature reaches saturation is defined as the limit of effective natural convection cooling by the blanket HR system.

Figure 9 Outlet header pressure during a T/B LOFA.

If the LOFA is confined only to the blanket HR system, the period of adequate natural convection cooling under single-phase flow is significantly longer than for the scenario just considered, in which both the target and blanket systems are involved. As Table 2 shows, the blanket only constitutes ~45% of the total deposited power being generated in the T/B facility. Figure 10 shows the mass flowrates in the three legs and the Hx leg of the NC network. The flowrates decrease monotonically due to the decay of the internal heat generation in the blanket modules. There is no flow reversal because the relative power distribution within the blanket modules remains constant. Figure 11 shows the transient fluid temperatures in the inlet header, outlet header, and on the shell side of the heat exchanger. Approximately 210 hours are required for the fluid in the outlet header to reach its saturation temperature of 167.2°C. This is considerably longer than 68 hours of effective natural convection cooling in the accident scenario that involves the target.

Figure 10 Natural circulation flowrates during a blanket only LOFA.

Figure 11 Transient fluid temperatures in the two headers and the shell side of the heat exchanger during a blanket only LOFA.

6 Conclusions

The period of effective single-phase natural convection cooling of the APT blanket, following a facility loss-of-power accident that results in the simultaneous loss of both the T/B primary and secondary pumps, is approximately 68 hours. This is the time required for the coolant to reach its saturation temperature. The transient heat sink for this accident scenario is the stagnant fluid in the shell side of the heat exchanger. If the target HR system is not involved in this accident scenario, the period of effective natural convection cooling is extended to approximately 210 hours. These are the allowable time periods available for restoring electrical power to the pumps or establishing an alternate means for cooling the blanket assemblies.

The volume of assumed stagnant water on the shell sides of the heat exchangers and the masses of metal in the heat exchangers are the heat sinks for the NC model. Other than sensible heating, no other phenomena with respect to the shell side of the heat exchanger were considered in this accident analysis. If the pressure in the blanket secondary HR system is less than that in the primary system, the secondary side fluid would boil before the primary fluid reached saturation. This probably will not be the case since maintaining the secondary side heat exchanger pressure at a higher value than the primary side is desirable for radionuclide containment. This aspect of the accident analysis does warrant further consideration. Boiling on the secondary side could provide effective cooling for a while, but the heat sink would completely lose its effectiveness after dryout. The fluid in the secondary HR system could also circulate by natural convection, thereby, extending the period of time that the system is an effective heat sink for the primary HR system.

7 References

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Appendix A: Derivation of the Governing Equations

The primary HR system flow network consisting of three lumped legs, as shown in Fig. A-1, is divided up into several interconnected discrete control volumes. To derive the governing equations for transient single-phase natural convection for this simplified model, the incompressible continuity, momentum, and thermal energy equations were applied to the control volumes. A Boussinesq fluid was assumed to handle the buoyancy terms in the momentum equations. Four momentum equations, one for each leg, and the continuity equation for the outlet header are solved simultaneously for the mass flowrates in each leg and the outlet header pressure. The thermal energy equations for the header temperatures, the heat exchanger shell side temperature, and the temperature distributions within each network leg are solved separately from the momentum equations.

Figure A-1 Schematic of the blanket primary HR system with three lumped modules and one lumped heat exchanger loop.

Figure A-2 shows one of the lumped module legs of the network and a close up of a representative control volume of one of the sections of the leg. The external forces acting on the fluid in the control volume are shown. They are the normal facing pressure forces, the body force, and the wall shear (or frictional force). The linear momentum equation (Eq. a1) is applied to each of the five control volumes within a leg. Equation a2 is the body force term and Eq. a3 is the frictional force term. The "n" in the subscript refers to the leg number, and the second number refers to the cell number, one through five. Equation a4 is the momentum equation for the first cell of the leg.

There are four additional equations, one for each of the other cells. If the area changes between cells are neglected, the five momentum equations can be added together to yield a single leg momentum equation (Eq. a5) with the header pressures and the leg mass flowrate as unknowns. At the low flowrates expected under natural convection conditions, the pressure distributions in the network legs will be close to hydrostatic. The flow area expansions/contractions occur in pairs with the same elevation, points 2 and 5 and points 3 and 4 in Fig. A-2. For these reasons the area changes can be neglected. The alternative would be to calculate intermediate pressures at the cell faces, and this would significantly increase the number of simultaneous non-linear equations to be solved and from an accuracy perspective is not warranted.

Figure A-2 Schematic of one of the module legs of the natural convection network showing the control volumes used to derive the momentum equation.

$$\frac{d}{dt}(m\bar{v}) + \dot{m}(\bar{v}_{out} - \bar{v}_{in}) = \sum \bar{F} \quad (a1)$$

$$F_B = \rho_o [1 - \beta(T_{n1} - T_o)] A_{n1} g \Delta z_{n1} \quad (a2)$$

$$F_f = \frac{f_{n1} L_{n1} \dot{m}_n^2}{2 \rho_o D_{n1} A_{n1}} \quad (a3)$$

$$L_{n1} \frac{d\dot{m}_n}{dt} = F_B + F_f + P_1 A_{n1} - P_2 A_{n2} \quad (a4)$$

$$\sum_i L_{ni} \frac{d\dot{m}_n}{dt} = \sum_i (F_{Bni} + F_{fni}) + P_{in} A_{n1} - P_{out} A_{n5} \quad (a5)$$

where

- F - force
- ρ - fluid density
- f - Darcy friction factor
- $\dot{m}$ - mass flowrate
- β - coefficient of thermal expansion
- P - pressure
- A - flow area
- T - temperature
- L - cell length
- g - gravitational constant
- D - hydraulic diameter
- Δz - elevation difference

Figure A-3 shows a schematic of the network leg that contains the heat exchanger. This leg is divided into three sections. The overall momentum equation for the mass flowrate in this leg is derived in the same manner as the equations for the module legs.

Figure A-3 Schematic of the heat exchanger leg of the natural convection network.

Figure A-4 is a schematic of the outlet header that shows the mass flowrates entering and exiting the header. Positive flowrates are shown. The continuity equation is applied to the control volume to yield Eq. a6. This equation and the four network leg momentum equations are solved simultaneously each time step for the leg mass flowrates and the outlet header pressure. The inlet header pressure is a boundary condition.

A mixed implicit/explicit scheme is used to derive the thermal energy equations. A separate equation is derived for each cell of the network legs and for each header. There is also an energy equation for the secondary side of the heat exchanger. Equation a7 is the thermal energy equation for the second cell of the module leg shown

in Fig. A-2. This cell is the downflow section of the heated module. Upwind differencing is used, and Eq. a7 applies to the case with positive flow. With negative flow the convective terms would be appropriately modified. The value of the coefficient " α " determines the degree of implicitness of the equation. The equation is fully implicit with " α " set equal to one and fully explicit with " α " set equal to zero. A value of one-half results in the Crank-Nicholson scheme. The superscript "n" denotes the new time level. Equation a8 is the expression for the updated nodal temperature. Note that only upstream temperatures at the new time level appear on the right-hand-side of the equation. Therefore, the temperatures in a specified leg of the network can be updated in a marching scheme starting at its upstream header.

Figure A-4 Schematic of the outlet header showing the mass flowrates.

$$\dot{m}_1 + \dot{m}_2 + \dot{m}_3 - \dot{m}_{HX} = 0 \quad (a6)$$

$$(m_s + m)\bar{C}_p \frac{T_{n2}^n - T_{n2}}{\Delta t} = \dot{m}_n C_p [\alpha T_{n1}^n + (1 - \alpha)T_{n1}] - \dot{m}_n C_p [\alpha T_{n2}^n + (1 - \alpha)T_{n2}] + \dot{Q}_{n2}(t) \quad (a7)$$

$$T_{n2}^n = \frac{\frac{(m_s + m)\bar{C}_p}{\Delta t} T_{n2} + \dot{m}_n C_p [\alpha T_{n1}^n + (1 - \alpha)T_{n1}] - \dot{m}_n C_p (1 - \alpha)T_{n2} + \dot{Q}_{n2}(t)}{\frac{(m_s + m)\bar{C}_p}{\Delta t} + \alpha \dot{m}_n C_p} \quad (a8)$$

where

- m - fluid mass
- m_s - solid (metal) mass
- C_p - fluid specific heat

- $\bar{C}_p$ - mass weighted liquid/solid composite specific heat
 $\dot{Q}_{n2}(t)$ - deposited decay power for cell n2
 α - implicitness parameter
 Δt - time step size

Similar equations can be derived for the remaining cells of the module leg shown in Fig. A-2. The storage terms for the two heated cells represent both the masses of the lead/aluminum metal and the fluid in the channels. Their specific heats are composite values. There is also a time dependent internal heat generation source term in each of the two equations representing heated sections.

There are also thermal energy equations for the two headers and the secondary side of the heat exchanger. Equation a9 is the energy equation for the outlet header. The flows are assumed to be positive, as shown in Fig. A-4. If any of the leg flows are negative, the equation would have to be appropriately modified to use the upstream value of temperature. Equation a10 is the expression for the updated outlet header temperature. The inlet header thermal energy equation is derived in a similar fashion.

$$mC_p \frac{T_{out}^n - T_{out}}{\Delta t} = \sum_{i=1,3} \dot{m}_i C_p [\alpha T_{i,5}^n + (1-\alpha)T_{i,5}] - \dot{m}_{Hx} C_p [\alpha T_{out}^n + (1-\alpha)T_{out}] \quad (a9)$$

$$T_{out}^n = \frac{\left[\frac{mC_p}{\Delta t} - \dot{m}_{Hx} C_p (1-\alpha) \right] T_{out} + \sum_{i=1,3} \dot{m}_i C_p [\alpha T_{i,5}^n + (1-\alpha)T_{i,5}]}{\frac{mC_p}{\Delta t} + \dot{m}_{Hx} C_p \alpha} \quad (a10)$$

Figure A-5 is a schematic of the heat transfer between the primary and secondary sides of the heat exchanger. Equation a11 is the thermal energy equation for the tube side of the heat exchanger, and Eq. a12 is the energy equation for the shell side. The shell side of the heat exchanger is assumed to exchange energy only with the tube side. The outer surface of the shell is assumed to be an adiabatic boundary. Equation a13 is the expression for the heat transfer rate between the two sides of the heat exchanger. The heat transfer coefficient accounts for single-phase convective heat transfer on both sides of the heat exchanger and conduction through the tube walls. The mass and specific heat for the secondary side of the heat exchanger are composites of both the metal and the liquid.

$$mC_p \frac{T_{Hx,2}^n - T_{Hx,2}}{\Delta t} = \dot{m}_{Hx} C_p [\alpha (T_{Hx,1}^n - T_{Hx,2}^n) + (1-\alpha)(T_{Hx,1} - T_{Hx,2})] - \dot{Q}_{conv} \quad (a11)$$

$$(mC_p)_{sh} \frac{T_{sh}^n - T_{sh}}{\Delta t} = \dot{Q}_{conv} \quad (a12)$$

$$\dot{Q}_{conv} = h_{conv} A_{Hx} [\alpha T_{Hx,2}^n + (1-\alpha)T_{Hx,2} - \alpha T_{sh}^n - (1-\alpha)T_{sh}] \quad (a13)$$

Figure A-5 Schematic of the heat exchanger showing the heat transfer to the secondary side.

Appendix B: Buoyancy-Assisted and Buoyancy-Opposed Friction Factor Multipliers

To account for the influence of wall heating on the friction factors for flow through the vertical modules, results of an analytical study of fully developed laminar flow between vertical parallel plates were used (see Ref. [3]). A plot of the product of the friction factor and the Reynolds number versus the one-fourth power of a modified Rayleigh number was used to develop functional relations for mixed convection multipliers to friction factors. The modified Rayleigh number used is defined as

$$Ra = \frac{g\beta \left(\frac{dT_w}{dx} \right) D_{HP}^4 \rho^2 \text{Pr}}{\mu^2} \quad (b1)$$

For fully developed flow with a constant wall heat flux, the wall and fluid axial temperature gradients are equal. The wall axial temperature gradient can, therefore, be expressed as a function of the wall power and the fluid mass flowrate (Eq. b2).

$$\frac{\Delta T}{L} = \frac{\dot{Q}_w}{L \dot{m} C_p} \quad (b2)$$

Substituting Eq. b2 and the definition of the Prandtl number into the expression for the modified Rayleigh number results in Eq. b3, the form of the modified Rayleigh number that is used in the NC model of the primary HR system. The Rayleigh number is directly proportional to the deposited power in the fluid and inversely proportional to the mass flowrate. It expresses the relative importance of buoyancy in vertical mixed convection.

$$Ra = \frac{g\beta \dot{Q}_w D_{HP}^4 \rho^2}{\dot{m} \mu L k} \quad (b3)$$

Reference 3 presents results for the range of Rayleigh numbers to the one-fourth power from zero to twelve. Results are presented for both buoyancy-assisted and buoyancy-opposed flows. For buoyancy-opposed flow, results are presented for the Rayleigh number to the one-fourth-power range up to four. Beyond this point the buoyancy-opposed mixed convection friction behavior is not defined. From the results in Ref. [3], Darcy friction factor multiplier relations were developed. These relations are Eqs. b-4 through b-8, and they are shown graphically by the solid lines in Fig. B-1. The curves are first-order continuous over the entire Rayleigh number to the one-fourth-power range shown. The curve for buoyancy-opposed flow at Rayleigh numbers to the one-fourth power greater than four is simply conjecture, and it is included in the model to insure that a reasonable value of the friction factor multiplier is returned in all cases. Having first-order continuous constitutive relations in the model is desirable from a numerical perspective.

$$\phi \equiv \frac{f_{Mixed}}{f_{Laminar}} = 1.0 \quad \text{for} \quad Ra^{1/4} \leq 1.5 \quad (b4)$$

Buoyancy-Assisted Flow:

$$\phi = \begin{cases} e^{\left[C_1 \left(Ra^{1/4} - 1.5 \right)^2 + C_2 \left(Ra^{1/4} - 1.5 \right)^3 \right]} & \text{for } 1.5 < Ra^{1/4} \leq 8.0 \\ e^{\left[C_3 + C_4 \left(Ra^{1/4} - 1.5 \right) \right]} & \text{for } Ra^{1/4} > 8.0 \end{cases} \quad (\text{b5 \& b6})$$

Buoyancy-Opposed Flow:

$$\phi = \begin{cases} e^{\left[C_5 \left(Ra^{1/4} - 1.5 \right)^2 + C_6 \left(Ra^{1/4} - 1.5 \right)^3 + C_7 \left(Ra^{1/4} - 1.5 \right)^4 \right]} & \text{for } 1.5 < Ra^{1/4} \leq 8.0 \\ 0.041\bar{6} & \text{for } Ra^{1/4} \leq 8.0 \end{cases} \quad (\text{b7 \& b8})$$

where:

$$C_1 = 0.11815501$$

$$C_2 = -0.29378955 \times 10^{-2}$$

$$C_3 = -0.33784101 \times 10^1$$

$$C_4 = 0.11636369 \times 10^1$$

$$C_5 = -0.38259936$$

$$C_6 = 0.71433520 \times 10^{-1}$$

$$C_7 = -0.37145261 \times 10^{-2}$$

Figure B-1 Friction factor multipliers for buoyancy-assisted and buoyancy-opposed mixed convection in vertical channels.

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION)

The Rayleigh number is inversely proportional to the mass flowrate. If the Rayleigh number to the one-fourth power were not limited to a maximum value of twelve in the NC model, it could grow without bound during flow reversals. Even with this restriction on the value of the parameter, there will be a large discontinuity in the values of the friction factor multipliers as the flow direction reverses in a heated vertical passage. To prevent this discontinuity, Eq. b-9 modifies the friction factor multiplier when the Reynolds number is less than twenty-five. This equation interpolates non-linearly between the buoyancy-assisted and buoyancy-opposed values of the friction factor multiplier at a Reynolds number of twenty-five and a value of unity when the Reynolds number is zero. It can easily be seen that, with Eq. b9, at a Reynolds number of twenty-five the friction factor multiplier is unaltered, and at zero the friction factor multiplier is unity. This equation insures that the friction factor and its first derivative are continuous as the flow reverses. The dotted lines in Fig. B-1 show the values of the friction factor multiplier at a Reynolds number of one.

$$\phi_{(Re \leq 25)} = 1 - \left[3 - 2 \left(\frac{Re}{25} \right) \right] \left(\frac{Re}{25} \right)^2 + \left[3 - 2 \left(\frac{Re}{25} \right) \right] \left(\frac{Re}{25} \right)^2 \phi \quad (b9)$$

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION)

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Appendix C: Sample Input Deck

A sample-input file for the NCLOFA code (see Appendix D) is provided below. The input file applies to the LOFA in which both the target and blanket HR system pumps are lost and the target power is deposited into the Module 1 Decoupler 24 hours after beam shutdown. The input is structured such that data unique to a specific leg is grouped together and comment lines are provided describing the input variables.

Input file data.in

NCLOFA input file:

This is the input deck for a natural convection model of the APT target/blanket HR cooling system. Three module loops are modelled and the outer loop with a heat exchanger. The secondary side of the heat exchanger is a heat sink. Units are SI.

calibration data:

tstart	start time in hours
tend	end time in hours
dt	time step in seconds
nplot	frequency for plotting
nsolve	frequency for updating mass/momentum calculations
itrans	transient mass/momentum eqns (1=yes;0=no)
tgstrt	start time for target power to blanket in hours
tgramp	ramp time to full target power deposition in hours
target	initial deposited power for entire target ladders
alpha	implicitness parameter for time differencing (1-fully implicit,0-fully explicit,1/2-crank nichelson)
dfdtmx	multiplier to reduce the size of the timestep during the flow reversal: $\text{delt}(t)=\text{dfdtmx}*\text{dt}$
eps_t	convergence tolerance for energy eqn solver
maxit_t	maxiumu number of iterations for energy eqn solver
eps_m	convergence tolerance for mass/momentum eqn solver
maxit_m	maxiumu # of iterations for mass/momentum eqn solver

tstart	tend	dt
1.0	70.0	10.0
nplot	nsolve	itrans
100	1	1
tgstrt	tgramp	target
24.0	1.0	68.01e6
alpha	dfdtmx	
.5	0.005	
eps_t	maxit_t	eps_m
0.001	100	0.001
		maxit_m
		500

module #1 loop from the inlet header to the outlet header (5 sections):

aml(1-5)	the 5 flow areas
dzl(1-5)	the 5 delta elevations
zll(1-5)	the 5 lengths
dh1(1-5)	the 5 hydraulic diameters
frmka1	form loss term (K/area)
sm12,sm14	metal masses in heat structures
cp12,cp14	specific heats of heat structures
rough	pipe roughness

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION)

Page: 2 of 4

```

-----
am11    am12    am13    am14    am15
0.0609  0.199    1.64    0.199    0.0609
dz11    dz12    dz13    dz14    dz15
6.1506  2.7582    0.0     -2.7582  -5.3886
zl11    zl12    zl13    zl14    zl15
10.77   2.7582    0.3048  2.7582    10.77
dh11    dh12    dh13    dh14    dh15    frmka1
0.1905  0.00861  0.289   0.005063 0.1905    0.0
sm12    cp12    sm14    cp14    rough
177.01  925.0    2748.48 188.02    1.0e-5

```

module #2 loop from the inlet header to the outlet header (5 sections):

```

am2(1-5) the 5 flow areas
dz2(1-5) the 5 delta elevations
zl2(1-5) the 5 lengths
dh2(1-5) the 5 hydraulic diameters
frmka2   form loss term (K/area)
sm22-sm24 metal masses in heat structures
cp22-cp24 specific heats of heat structures

```

```

-----
am21    am22    am23    am24    am25
0.08574 0.34647 6.5617  0.34647 0.08574
dz21    dz22    dz23    dz24    dz25
6.1506  3.5     0.0     -3.5     -5.3886
zl21    zl22    zl23    zl24    zl25
10.777  3.5     0.3048  3.5     10.0152
dh21    dh22    dh23    dh24    dh25    frmka2
0.1524  0.00311 0.289   0.00311 0.1524    0.0
sm22    cp22    sm24    cp24
34007.86 171.23 28539.52 173.29

```

module #3 loop from the inlet header to the outlet header (5 sections):

```

am3(1-5) the 5 flow areas
dz3(1-5) the 5 delta elevations
zl3(1-5) the 5 lengths
dh3(1-5) the 5 hydraulic diameters
frmka3   form loss term (K/area)
sm32-sm34 metal masses in heat structures
cp32-cp34 specific heats of heat structures

```

```

-----
am31    am32    am33    am34    am35
0.06236 0.16017 1.64    0.16017 0.06236
dz31    dz32    dz33    dz34    dz35
9.07    0.0     0.0     0.0     -8.308
zl31    zl32    zl33    zl34    zl35
13.73   2.479   0.3048  2.479   13.05
dh31    dh32    dh33    dh34    dh35    frmka3
0.09843 0.09526 0.289   0.09526 0.09843 143.4
sm32    cp32    sm34    cp34
0.0     925.0    2751.65 167.58

```

heat exchanger loop (inlet to outlet headers 3 sections):

```

ahx(1-5) the 3 flow areas
dzhx(1-5) the 3 delta elevations
zlhx(1-5) the 3 lengths
dhhx(1-5) the 3 hydraulic diameters

```


BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION)

Page: 3 of 4

frmkax	form loss term (K/area)
wmssh1	mass of HX secondary shell side
arsh1	heat transfer area of HX secondary shell side
convh	convection hT coef. of HX secondary shell side
cpsh1	specific heat of HX secondary shell side

ahx1	ahx2	ahx3	
0.17936	1.13116	0.17936	
dzhx1	dzhx2	dzhx3	
-3.7859	0.0	3.0239	
zlhx1	zlhx2	zlhx3	
52.885	7.92	36.122	
dhhx1	dhhx2	dhhx3	frmkax
0.47788	0.01021	0.47788	40.2
wmsh1	arsh1	convh	cpsh1
50852.0	3510.0	5.0	4009.0

inlet and outlet headers:

volin	volume of inlet header
volout	volume of outlet header
pin	inlet header pressure

volin	volout	pin
0.31727	0.31727	7.325e5

fluid properties:

rho	density
cp	specific heat

rho	cp
987.0	4184.3

initial guess at temperatures and flowrates:

tin,tout	inlet and outlet header temperatures
tm1(1-5)	temperatures in module #1
tm2(1-5)	temperatures in module #2
tm3(1-5)	temperatures in module #3
thx(1-3)	temperatures in the HX loop
tsh1	HX secondary shell side temperature
flw1-flw3	mass flowrates through the three modules
flwhx	mass flowrate through the HX loop
q12,q14	initial deposited powers in module #1
q22,q24	initial deposited powers in module #2
q32,q34	initial deposited powers in module #3

tin	tout			
322.0	325.5			
tm11	tm12	tm13	tm14	tm15
322.0	322.5	323.0	325.0	325.0
tm21	tm22	tm23	tm24	tm25
322.0	323.5	324.0	325.5	325.5
tmh1	tmh2	tmh3	tm34	tm35
322.0	323.5	324.0	325.5	325.5
thx1	thx2	thx3	tsh1	
325.5	324.0	322.0	317.0	
flw1	flw2	flw3	flwhx	
5.440	4.926	1.965	12.331	

BLANKET SAFETY ANALYSIS FOR LOFA

Section: Appendix C

(NATURAL CIRCULATION)

Date: 08/06/98

Page: 4 of 4

q12	q14	q22	q24	q32	q34
8.222e6	15.768e6	9.083e6	17.695e6	0.0e6	5.712e6

calibration data:

icalib	calibration flag (1=yes;0=no)
pincal,poutcal	inlet and outlet header calibration pressures (Pa)
pmpcal	pump pressure drop (Pa)
flwcal(1-4)	initial guess (kg/s)

icalib	pincal	poutcal	pmpcal	
0	7.325e5	4.5671e5	7.6048e5	(40 and 110 psid pres drop)
flw1	flw2	flw3	flwhx	
544.0	615.0	410.0	1569.0	

flw1	flw2	flw3	flwhx
5.440	4.926	1.965	12.331
0.0	0.0	0.0	0.0

q12	q14	q22	q24	q32	q34
8.222e6	15.768e6	9.083e6	17.695e6	0.0e6	5.712e6

Appendix D: Code Listing

A code listing of the fortran program **NCLOFA** and its associated fortran subroutines is presented below. A algorithm description is provided at the front of each routine. The following is a listing of the routines:

- nclofa.f – main program that reads in the input and writes out the output.
- momtm.f – performs Newton iterations for momentum equations.
- momloop.f – generates each leg's momentum equation and Jacobian.
- rayleigh.f – computes Rayleigh number and heating orientation.
- frict.f – computes multiplier and friction factor.
- outhdr.f – generates header Jacobian terms.
- tmean.f – computes mean fluid temperatures.
- condlq.f – computes fluid thermal conductivity.
- dpower.f – computes deposited decay power levels.
- ludcmp.f – generates LUD decomposition of linearized equation set.
- lubksb.f – performs forward/backward passes of LUD process.

Main program nclofa.f

```

program nclofa
c
c *****
c *
c * PROGRAM nclofa
c *
c * THIS PROGRAM COMPUTES NATURAL CIRCULATION DURING A LOFA WHERE
c * 3 COMPOSITE MODULES ARE EMPLOYED ALONG WITH A HEAT EXCHANGER
c * LOOP.
c *
c *****
c
c      implicit real*8 (a-h,o-z), integer (i-n)
c      include 'param.inc'
c      parameter (g=9.8066d0)
c
c      character*80 line1
c      character esc
c
c      dimension flw(mxloop), flwcal(mxnode), flwpred(mxnode)
c      dimension flwn(mxloop)
c      dimension ncell(mxloop), ntype(mxloop)
c
c      dimension zlt(mxloop)
c      dimension tm1(mxnode), am1(mxnode), dh1(mxnode), dz1(mxnode),
c      & z11(mxnode), tm1n(mxnode), wms1(mxnode), q1(mxnode),
c      & sm1(mxnode), cp1(mxnode)
c      dimension tm2(mxnode), am2(mxnode), dh2(mxnode), dz2(mxnode),
c      & z12(mxnode), tm2n(mxnode), wms2(mxnode), q2(mxnode),
c      & sm2(mxnode), cp2(mxnode)
c      dimension tm3(mxnode), am3(mxnode), dh3(mxnode), dz3(mxnode),
c      & z13(mxnode), tm3n(mxnode), wms3(mxnode), q3(mxnode),

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION)

```

&          sm3(mxnode), cp3(mxnode)
dimension thx(mxnode), ahx(mxnode), dhhx(mxnode), dzhx(mxnode),
&          zlhx(mxnode), thxn(mxnode), wshx(mxnode)
dimension qd1(mxnode), qd2(mxnode), qd3(mxnode), qd4(mxnode),
&          fold1(mxnode), fold2(mxnode), fold3(mxnode), fold4(mxnode),
&          fnew1(mxnode), fnew2(mxnode), fnew3(mxnode), fnew4(mxnode)

C
data ncell/5,5,5,3/
data ntype/1,1,1,2/

C
C === SET I/O UNITS AND OPEN FILES =====
C
iin1 = 5
iout1 = 7
iout2 = 8
iout3 = 17
iout4 = 19
iout5 = 22
iout6 = 23
iout7 = 26
itec = 12
itec1 = 13
itec2 = 14
itec3 = 15
itec4 = 16
convt = 273.15d0
convp = 14.696d0/101325.0d0
conv_tim = 3600.0d0

C
C INITIALIZE TIME COUNTERS
C
esc = char(27)
write (*,10) esc

C
C open files:
C
open (unit=iin1, file='data.in', status='old')
open (unit=iout1, file='results.out', status='unknown')
open (unit=iout2, file='cal.out', status='unknown')
open (unit=iout3, file='rayl.out', status='unknown')
open (unit=iout4, file='rayfrct.out', status='unknown')
open (unit=iout5, file='jacob.out', status='unknown')
open (unit=iout6, file='convg.out', status='unknown')
open (unit=iout7, file='restrt.out', status='unknown')
open (unit=itec, file='tec.dat', status='unknown')
open (unit=itec1, file='tec1.dat', status='unknown')
open (unit=itec2, file='tec2.dat', status='unknown')
open (unit=itec3, file='tec3.dat', status='unknown')
open (unit=itec4, file='tec4.dat', status='unknown')

C
C === START OF INPUT PROCESSING =====
C
C Read in the input:
C Print input data for 1-D 3-module model.
write (iout1,1000)
write (iout1,901)
write (iout1,1000)

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```
c
c --- CONTROL PARAMETER INPUT: -----
c
  do i=1,26
    read (iin1,900) line1
    write (iout1,900) line1
  enddo

c
c TIME STEP AND RUN TIME:
  read (iin1,900) line1
  write (iout1,900) line1
  read (iin1,*) tstart, tend, dt
  write (iout1,*) tstart, tend, dt

c
c FREQUENCIES FOR PLOTTING AND MASS/MOM SOLVING:
  read (iin1,900) line1
  write (iout1,900) line1
  read (iin1,*) nplot, nsolve, itrans
  write (iout1,*) nplot, nsolve, itrans

c
c TARGET POWER TIMING:
  read (iin1,900) line1
  write (iout1,900) line1
  read (iin1,*) tgstrt, tgramp, target
  write (iout1,*) tgstrt, tgramp, target

c
c IMPLICITNESS PARAMETER FOR TIME DIFFERENCING & FF RATE CHANGE:
  read (iin1,900) line1
  write (iout1,900) line1
  read (iin1,*) alpha, dfdtmx
  write (iout1,*) alpha, dfdtmx

c
c CHECK (AND LIMIT) RANGE OF ALPHA
  alpha = dmax1(alpha,zero)
  alpha = dmin1(alpha,one)

c
c ENERGY AND MASS/MOMENTUM SOLVERS CONVERGENCE TOLERANCES AND
c MAXIMUM NUMBER OF ITERATIONS ALLOWED:
  read (iin1,900) line1
  write (iout1,900) line1
  read (iin1,*) eps_t,maxit_t,eps_m,maxit_m
  write (iout1,*) eps_t,maxit_t,eps_m,maxit_m

c
c --- MODULE #1 INPUT (VERTICAL LATERAL MODULES): -----
c
  do i=1,11
    read (iin1,900) line1
    write (iout1,900) line1
  enddo

c
  read (iin1,900) line1
  write (iout1,900) line1
  read (iin1,*) (aml(i), i=1,ncell(1))
  write (iout1,*) (aml(i), i=1,ncell(1))
  read (iin1,900) line1
  write (iout1,900) line1
  read (iin1,*) (dz1(i), i=1,ncell(1))
```

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION))

Page: 4 of 40

```

      write (iout1,*) (dz1(i), i=1,ncell(1))
      read  (iin1,900) line1
      write (iout1,900) line1
      read  (iin1,*) (z11(i), i=1,ncell(1))
      write (iout1,*) (z11(i), i=1,ncell(1))
      read  (iin1,900) line1
      write (iout1,900) line1
      read  (iin1,*) (dh1(i), i=1,ncell(1)), frmka1
      write (iout1,*) (dh1(i), i=1,ncell(1)), frmka1
      read  (iin1,900) line1
      write (iout1,900) line1
      read  (iin1,*) sm12,cp12,sm14,cp14,rough
      write (iout1,*) sm12,cp12,sm14,cp14,rough
c
c --- MODULE #2 INPUT (ALL REMAINING VERTICAL MODULES): -----
c
      do i=1,10
        read  (iin1,900) line1
        write (iout1,900) line1
      enddo
c
      read  (iin1,900) line1
      write (iout1,900) line1
      read  (iin1,*) (am2(i), i=1,ncell(2))
      write (iout1,*) (am2(i), i=1,ncell(2))
      read  (iin1,900) line1
      write (iout1,900) line1
      read  (iin1,*) (dz2(i), i=1,ncell(2))
      write (iout1,*) (dz2(i), i=1,ncell(2))
      read  (iin1,900) line1
      write (iout1,900) line1
      read  (iin1,*) (z12(i), i=1,ncell(2))
      write (iout1,*) (z12(i), i=1,ncell(2))
      read  (iin1,900) line1
      write (iout1,900) line1
      read  (iin1,*) (dh2(i), i=1,ncell(2)), frmka2
      write (iout1,*) (dh2(i), i=1,ncell(2)), frmka2
      read  (iin1,900) line1
      write (iout1,900) line1
      read  (iin1,*) sm22,cp22,sm24,cp24
      write (iout1,*) sm22,cp22,sm24,cp24
c
c --- MODULE #3 INPUT (ALL HORIZONTAL MODULES): -----
c
      do i=1,10
        read  (iin1,900) line1
        write (iout1,900) line1
      enddo
c
      read  (iin1,900) line1
      write (iout1,900) line1
      read  (iin1,*) (am3(i), i=1,ncell(3))
      write (iout1,*) (am3(i), i=1,ncell(3))
      read  (iin1,900) line1
      write (iout1,900) line1
      read  (iin1,*) (dz3(i), i=1,ncell(3))
      write (iout1,*) (dz3(i), i=1,ncell(3))

```

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION))

Page: 5 of 40

```

      read (iin1,900) line1
      write (iout1,900) line1
      read (iin1,*) (zl3(i), i=1,ncell(3))
      write (iout1,*) (zl3(i), i=1,ncell(3))
      read (iin1,900) line1
      write (iout1,900) line1
      read (iin1,*) (dh3(i), i=1,ncell(3)), frmka3
      write (iout1,*) (dh3(i), i=1,ncell(3)), frmka3
      read (iin1,900) line1
      write (iout1,900) line1
      read (iin1,*) sm32,cp32,sm34,cp34
      write (iout1,*) sm32,cp32,sm34,cp34
c
c --- HEAT EXCHANGER LOOP INPUT #4: -----
c
      do i=1,12
        read (iin1,900) line1
        write (iout1,900) line1
      enddo
c
      read (iin1,900) line1
      write (iout1,900) line1
      read (iin1,*) (ahx(i), i=1,ncell(4))
      write (iout1,*) (ahx(i), i=1,ncell(4))
      read (iin1,900) line1
      write (iout1,900) line1
      read (iin1,*) (dzhx(i), i=1,ncell(4))
      write (iout1,*) (dzhx(i), i=1,ncell(4))
      read (iin1,900) line1
      write (iout1,900) line1
      read (iin1,*) (zlhx(i), i=1,ncell(4))
      write (iout1,*) (zlhx(i), i=1,ncell(4))
      read (iin1,900) line1
      write (iout1,900) line1
      read (iin1,*) (dhhx(i), i=1,ncell(4)), frmkak
      write (iout1,*) (dhhx(i), i=1,ncell(4)), frmkak
      read (iin1,900) line1
      write (iout1,900) line1
      read (iin1,*) wmsshl,arshl,convh,cpshl
      write (iout1,*) wmsshl,arshl,convh,cpshl
c
c --- FIXED HEADER INPUT: -----
c
      do i=1,6
        read (iin1,900) line1
        write (iout1,900) line1
      enddo
c
      read (iin1,900) line1
      write (iout1,900) line1
      read (iin1,*) volin,volout,pin
      write (iout1,*) volin,volout,pin
c
c --- FLUID PROPERTIES INPUT: -----
c
      do i=1,5
        read (iin1,900) line1

```

BLANKET SAFETY ANALYSIS FOR LOFA
(NATURAL CIRCULATION))

```
        write (iout1,900) line1
    enddo

c
    read  (iin1,900) line1
    write (iout1,900) line1
    read  (iin1,*) rho,cp
    write (iout1,*) rho,cp

c
c --- INITIAL CONDITIONS (TEMPERATURES AND FLOWRATES) INPUT: -----
c
    do i=1,14
        read  (iin1,900) line1
        write (iout1,900) line1
    enddo

c
c FLUID TEMPERATURES:
    read  (iin1,900) line1
    write (iout1,900) line1
    read  (iin1,*) tin,tout
    write (iout1,*) tin,tout
    read  (iin1,900) line1
    write (iout1,900) line1
    read  (iin1,*) (tm1(i), i=1,ncell(1))
    write (iout1,*) (tm1(i), i=1,ncell(1))
    read  (iin1,900) line1
    write (iout1,900) line1
    read  (iin1,*) (tm2(i), i=1,ncell(2))
    write (iout1,*) (tm2(i), i=1,ncell(2))
    read  (iin1,900) line1
    write (iout1,900) line1
    read  (iin1,*) (tm3(i), i=1,ncell(3))
    write (iout1,*) (tm3(i), i=1,ncell(3))
    read  (iin1,900) line1
    write (iout1,900) line1
    read  (iin1,*) (thx(i), i=1,ncell(4)),tshl
    write (iout1,*) (thx(i), i=1,ncell(4)),tshl

c
c MASS FLOWTRANS:
    read  (iin1,900) line1
    write (iout1,900) line1
    read  (iin1,*) (flw(i), i=1,mxloop)
    write (iout1,*) (flw(i), i=1,mxloop)

c
c DEPOSITED POWERS:
    read  (iin1,900) line1
    write (iout1,900) line1
    read  (iin1,*) q12,q14,q22,q24,q32,q34
    write (iout1,*) q12,q14,q22,q24,q32,q34

c
c --- CALIBRATION DATA INPUT: -----
c
    do i=1,7
        read  (iin1,900) line1
        write (iout1,900) line1
    enddo

c
c HEADER PRESSURES:
```


BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

      read (iin1,900) line1
      write (iout1,900) line1
      read (iin1,*) icalib,pincal,poutcal,pmpcal
      write (iout1,*) icalib,pincal,poutcal,pmpcal
c
c INITIAL GUESS FOR MASS FLOWRATES:
      read (iin1,900) line1
      write (iout1,900) line1
      read (iin1,*) (flwcal(i), i=1,mxloop)
      write (iout1,*) (flwcal(i), i=1,mxloop)
c
c === END OF INPUT PROCESSING =====
c
c
c === PERFORM INITIAL CALCULATIONS =====
c
c print the header for output file.
      write (iout1,1000)
      write (iout1,902)
      write (iout1,1000)
c
c COMPUTE FLUID CELL MASSES FOR EACH LOOP, HEADERS, AND SHELL.
c ALSO COMPUTE TOTAL LENGTH OF EACH LOOP.
c
      do j=1,mxloop
          zlt(j) = zero
      enddo
c
      do i=1,ncell(1)
          wms1(i) = rho*am1(i)*z11(i)
          zlt(1) = zlt(1) + z11(i)
      enddo
c
      do i=1,ncell(2)
          wms2(i) = rho*am2(i)*z12(i)
          zlt(2) = zlt(2) + z12(i)
      enddo
c
      do i=1,ncell(3)
          wms3(i) = rho*am3(i)*z13(i)
          zlt(3) = zlt(3) + z13(i)
      enddo
c
      do i=1,ncell(4)
          wms4(i) = rho*am4(i)*z14(i)
          zlt(4) = zlt(4) + z14(i)
      enddo
c
      wmsin = rho*volin
      wmsout = rho*volout
      pout = pin + 7360.5d0
c
c SET SOLID CELL MASSES AND SPECIFIC HEATS FOR EACH MODULE LOOP:
c
      do i=1,ncell(1)
          sm1(i) = zero
          cp1(i) = zero

```

BLANKET SAFETY ANALYSIS FOR LOFA
(NATURAL CIRCULATION))

```

        enddo
        sm1(2) = sm12
        sm1(4) = sm14
        cp1(2) = cp12
        cp1(4) = cp14
c
        do i=1,ncell(2)
            sm2(i) = zero
            cp2(i) = zero
        enddo
        sm2(2) = sm22
        sm2(4) = sm24
        cp2(2) = cp22
        cp2(4) = cp24
c
        do i=1,ncell(3)
            sm3(i) = zero
            cp3(i) = zero
        enddo
        sm3(2) = sm32
        sm3(4) = sm34
        cp3(2) = cp32
        cp3(4) = cp34
c
c
c COMPUTE INITIAL AVERAGE FLUID TEMPERATURE, BETA, AND VISCOSITY:
c
        iskip = 0
        call tmean (wmsin,wmsout,wms1,wms2,wms3,wmslx,
&                  tin,tout,tm1,tm2,tm3,thx,tnot,beta,vis,
&                  iskip,ncell)
c
c COMPUTE FLUID THERMAL CONDUCTIVITY:
c
        ifld = 1
        call cond1q (tnot,ifld,cond1,dummy)
c
c INITIAL TARGET POWER PARAMETER SETTINGS AND TIMING POINTS:
c
        tstart = conv_tim*tstart
        tendhr = tend
        tend = conv_tim*tend
ccc        nstep = int((tend-tstart)/dt) + 1
        tgstrt = conv_tim*tgstrt
        tgramp = conv_tim*tgramp
        tgdry = tgstrt + tgramp
        nstep = int(((tend-tstart-2.5*tgramp)/dt)+
&                  (2.5*tgramp)/(dfdtmx*dt))+1
        eps_p = 1.0d-3
c
        do i=1,ncell(1)
            q1(i) = zero
        enddo
        q1(2) = q12
        q1(4) = q14
c
        do i=1,ncell(2)

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

      q2(i) = zero
    enddo
    q2(2) = q22
    q2(4) = q24
  c
    do i=1,ncell(3)
      q3(i) = zero
    enddo
    q3(2) = q32
    q3(4) = q34
  c
  c INITIAL DECAY POWER LEVELS:
  c
    eltim_p = tstart + eps_p
    call dpower (eltim_p,tgstrt,tgdry,
      &          target,q1,q2,q3,qd1,qd2,qd3,qdhx,
      &          ncell)
  c
  c Stuff the old friction factor arrays for the loops:
  c
    do i=1,ncell(1)
      fold1(i) = 64.0/100.0
    enddo
    do i=1,ncell(2)
      fold2(i) = 64.0/100.0
    enddo
    do i=1,ncell(3)
      fold3(i) = 64.0/100.0
    enddo
    do i=1,ncell(4)
      foldhx(i) = 64.0/100.0
    enddo
  c
  c COMPUTE INITIAL FLOW STATE (IF TRANSIENT TERMS NOT USED):
  c
    tmhr = tstart/conv_tim
  c    write (*,1015) tmhr
    write (*,20) esc, tmhr, tendhr
  cc    if (itrans.eq.0) then
      eltim = 3600.0
      call momtm (rho,vis,g,beta,rough,zlt,dt,cond1,eltim,
        &          qd1,qd2,qd3,qdhx,
        &          fold1,fold2,fold3,foldhx,dfdtmx,
        &          fnew1,fnew2,fnew3,fnewhx,
        &          am1,dz1 ,z11 ,dh1 ,frmka1,tm1,
        &          am2,dz2 ,z12 ,dh2 ,frmka2,tm2,
        &          am3,dz3 ,z13 ,dh3 ,frmka3,tm3,
        &          ahx,dzhx,zlhx,dhhx,frmka3,thx,
        &          pin,pout,flw,flwn,tnot,ncell,ntype,
        &          eps_m,maxit_m,itrans,icnv)
  c
  c SET OLD TIME MASS FLOWRATES TO NEW TIME VALUES
    do j=1,mxloop
      flw(j) = flwn(j)
    enddo
  cc  endif
  c

```

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION)

Page: 10 of 40

```

c === WRITE INITIAL CONDITIONS TO TECPLOT FILES =====

```

```

c

```

```

c COMPOSITE FILE:

```

```

    write (itec,210)
    write (itec,'(17d12.4)') tstart/conv_tim,flw(1),flw(2),flw(3),
&      flw(4),tin-convt,tout-convt,thx(2)-convt,
&      tshl-convt,tml(2)-convt,tml(4)-convt,tml(2)-convt,
&      tm2(4)-convt,tm3(2)-convt,tm3(4)-convt,tnot-convt,
&      pout*convp

```

```

c

```

```

c MODULE #1 FILE:

```

```

    write (itec1,211)
    write (itec1,'(8d12.4)') tstart/conv_tim,tin-convt,
&      tml(1)-convt,tml(2)-convt,tml(3)-convt,
&      tml(4)-convt,tml(5)-convt,tout-convt

```

```

c

```

```

c MODULE #2 FILE:

```

```

    write (itec2,212)
    write (itec2,'(8d12.4)') tstart/conv_tim,tin-convt,
&      tm2(1)-convt,tm2(2)-convt,tm2(3)-convt,
&      tm2(4)-convt,tm2(5)-convt,tout-convt

```

```

c

```

```

c MODULE #3 FILE:

```

```

    write (itec3,213)
    write (itec3,'(8d12.4)') tstart/conv_tim,tin-convt,
&      tm3(1)-convt,tm3(2)-convt,tm3(3)-convt,
&      tm3(4)-convt,tm3(5)-convt,tout-convt

```

```

c

```

```

c HEAT EXCHANGER #4 FILE:

```

```

    write (itec4,214)
    write (itec4,'(7d12.4)') tstart/conv_tim,tout-convt,
&      thx(1)-convt,thx(2)-convt,thx(3)-convt,
&      tin-convt,tshl-convt

```

```

c

```

```

c === PERFORM CALIBRATION CHECKING =====

```

```

c

```

```

c COMPUTE LOOP FLOWRATES BASED ON INPUTTED HEADER PRESSURE DROP
c AND WRITE RESULTS TO OUTPUT FILE.

```

```

c

```

```

c      if (icalib.eq.1) then
c        do i=1,mxloop
c          flwpred(i) = flwcal(i)
c        enddo
c        call flwloop (rho,vis,g,beta,rough,zlt,dt,
c      &      am1,dz1 ,z11 ,dh1 ,frmka1,
c      &      am2,dz2 ,z12 ,dh2 ,frmka2,
c      &      am3,dz3 ,z13 ,dh3 ,frmka3,
c      &      ahx,dzhx,zlhx,dhxx,frmka3,
c      &      pincal,poutcal,pmpcal,flwpred,tnot,
c      &      ncell,ntype,eps_m,maxit_m)
c        dp = pincal - poutcal
c        dp = dp*convp
c        dpmp = pmpcal*convp
c
c        write (iout2,2000) dp, dpmp
c        do i=1,mxloop
c          write (iout2,'(i5,10x,2f14.5)') i,flwcal(i),flwpred(i)

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

c      enddo
c      endif
c
c === PERFORM TRANSIENT CALCULATIONS =====
c
      dtshrt = dfdtmx*dt
      dtreg = dt
      tshst = tgstrt+.75*tgramp
      tshstp = tshst+2.5*tgramp
      eltim = tstart
      do it=1,nstep
        if ((eltim .ge. tshst) .and. (eltim .lt. tshstp))then
          dt = dtshrt
        else
          dt = dtreg
        end if
        eltim_p = eltim + half*dt
        eltim = eltim + dt
      do
c
c COMPUTE BLANKET/TARGET POWER DEPOSITED TO FLUID CELLS
c
      call dpower (eltim_p,tgstrt,tgdry,
&                target,q1,q2,q3,qd1,qd2,qd3,qdhx,
&                ncell)
c
c COMPUTE NEW TIME (n) FLUID TEMPERATURES:
c
      call energy (flw,tin,tout,tm1,tm2,tm3,thx,tshl,dt,
&                wms1,wms2,wms3,wmshx,wmsshl,wmsin,wmsout,
&                sm1,sm2,sm3,cp,cp1,cp2,cp3,cpshl,
&                qd1,qd2,qd3,qdhx,convh,arshl,
&                tinn,toutn,tmln,tm2n,tm3n,thxn,tshln,
&                ncell,alpha,eps_t,maxit_t)
c
c UPDATE TEMPERATURE ARRAYS:
c
      do i=1,5
        tm1(i) = tmln(i)
        tm2(i) = tm2n(i)
        tm3(i) = tm3n(i)
      enddo
c
      do i=1,3
        thx(i) = thxn(i)
      enddo
c
      tshl = tshln
      tin = tinn
      tout = toutn
c
c UPDATE MEAN TEMPERATURE (LOOP AVERAGE) AND BETA:
c
      iskip = 1
      call tmean (wmsin,wmsout,wms1,wms2,wms3,wmshx,
&                tin,tout,tm1,tm2,tm3,thx,tnot,beta,vis,
&                iskip,ncell)
c

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION)

c COMPUTE FLUID THERMAL CONDUCTIVITY:

c

ifld = 1

call cond1q (tnot,ifld,cond1,dummy)

c

c COMPUTE NEW TIME (n) MASS FLOWRATES WITHIN LOOPS:

c

c (only update flowrates/pressure every nsolve time steps.)

c

if (mod(it,nplot).eq.0) then

tmhr = eltim/conv_tim

write (iout5,1001)

write (iout5,1015) tmhr

write (*,20) esc, tmhr, tendhr

endif

if (mod(it,nsolve).eq.0) then

call momtm (rho,vis,g,beta,rough,zlt,dt,cond1,eltim,

& qd1,qd2,qd3,qdhx,

& fold1,fold2,fold3,foldhx,dfdtmx,

& fnew1,fnew2,fnew3,fnewhx,

& am1,dz1 ,z11 ,dh1 ,frmka1,tm1,

& am2,dz2 ,z12 ,dh2 ,frmka2,tm2,

& am3,dz3 ,z13 ,dh3 ,frmka3,tm3,

& ahx,dzhx,zlhx,dhhx,frmka3,thx,

& pin,pout,flw,flwn,tnot,ncell,ntype,

& eps_m,maxit_m,itrans,icnvg)

c

c "icnvg = 1" is a flag that indicates that the momentum equation

c has not converged. A restart file is printed out and this is used in

c a test program to see what is needed to get convergence.

c

if (icnvg .eq. 1) then

write (iout7,3000) eltim,tin,tout,tshl

stop

end if

3000 format (1x,4g16.8)

c

c SET OLD TIME MASS FLOWRATES TO NEW TIME VALUES

c

do j=1,mxloop

flw(j) = flwn(j)

enddo

c

c Set the old values of the friction factor to the new values:

c

do i=1,ncell(1)

fold1(i) = fnew1(i)

enddo

do i=1,ncell(2)

fold2(i) = fnew2(i)

enddo

do i=1,ncell(3)

fold3(i) = fnew3(i)

enddo

do i=1,ncell(4)

foldhx(i) = fnewhx(i)

enddo

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

c
      endif
c
c
c === WRITE RESULTS OUT TO TECPLOT AND OUTPUT FILES =====
c
      if (mod(it,nplot).eq.0) then
c
c write results to graphics tecplot file:
c
      write(itec,'(17d12.4)') eltim/conv_tim,flw(1),flw(2),flw(3),
&      flw(4),tin-convt,tout-convt,thx(2)-convt,
&      tshl-convt,tm1(2)-convt,tm1(4)-convt,tm2(2)-convt,
&      tm2(4)-convt,tm3(2)-convt,tm3(4)-convt,tnot-convt,
&      pout*convp
c
c MODULE #1 FILE:
      write (itec1,'(8d12.4)') eltim/conv_tim,tin-convt,
&      tm1(1)-convt,tm1(2)-convt,tm1(3)-convt,
&      tm1(4)-convt,tm1(5)-convt,tout-convt
c
c MODULE #2 FILE:
      write (itec2,'(8d12.4)') eltim/conv_tim,tin-convt,
&      tm2(1)-convt,tm2(2)-convt,tm2(3)-convt,
&      tm2(4)-convt,tm2(5)-convt,tout-convt
c
c MODULE #3 FILE:
      write (itec3,'(8d12.4)') eltim/conv_tim,tin-convt,
&      tm3(1)-convt,tm3(2)-convt,tm3(3)-convt,
&      tm3(4)-convt,tm3(5)-convt,tout-convt
c
      write (itec4,'(7d12.4)') eltim/conv_tim,tout-convt,
&      thx(1)-convt,thx(2)-convt,thx(3)-convt,
&      tin-convt,tshl-convt
c
c write time results to output file:
c
      write (iout1,1000)
      tmhr = eltim/conv_tim
      write (iout1,1015) tmhr
      write (iout1,1020) tm1(1),tm1(2),tm1(3),tm1(4),tm1(5)
      write (iout1,1020) tm2(1),tm2(2),tm2(3),tm2(4),tm2(5)
      write (iout1,1020) tm3(1),tm3(2),tm3(3),tm3(4),tm3(5)
      write (iout1,1020) thx(1),thx(2),thx(3),tshl
      write (iout1,1030) tin,tout,tnot
      write (iout1,1025) flw(1),flw(2),flw(3),flw(4),pout
      endif
c
      enddo
c
c
c === FORMAT STATEMENTS =====
c
10  format (1x,a1,'[2J')
20  format (1x,a1,'[18;1H','elapsed time = ',f10.4,' hrs',/,
&      'end time = ',f10.4,' hrs',/)
210 format(' VARIABLES = t, Mod-1, Mod-2, Mod-3, Hx, tin, tout,',
&      ' thx, tshl, tldwn, t1up, t2dwn, t2up, t3in, t3out,',
&      ' tavg, pout')

```

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION))

Page: 14 of 40

```

211 format(' VARIABLES = t, t-ih, T-1, T-2, T-3, T-4, T-5, T-oh')
212 format(' VARIABLES = t, t-ih, T-1, T-2, T-3, T-4, T-5, T-oh')
213 format(' VARIABLES = t, t-ih, T-1, T-2, T-3, T-4, T-5, T-oh')
214 format(' VARIABLES = t, t-oh, T-1, T-2, T-3, T-ih, T-shl')
220 format(' ZONE T="Nat Conv - 3 modules", F=POINT, I=',i4)
900 format (a80)
901 format (1X,'The FOLLOWING ARE INPUT DATA AT TIME=3600 SECONDS')
902 format (1X,'THE FOLLOWING ARE TRANSIENT RESULTS')
1000 format (1x,'=====')
1001 format (1x,' ')
1010 format (1x,' it = ',i8)
1015 format (1x,'elapsed time = ',g14.7,' hrs')
1020 format (1x,5g16.8)
1025 format (1x,5g16.8)
1030 format (1x,3g16.8)
2000 format(/,' Results From Calibration Run',/,
& ' -----',/,
& ' Header Pressure Drop =',f6.2,' (psid)',/,
& ' Pump Pressure Drop =',f6.2,' (psid)',/,
& ' loop # flow-cal (kg/s) flow-pred (kg/s)',/,
& ' -----',/)
C
      stop
      end

```

Subroutine energy.f

```

subroutine energy (flw,tin,tout,tm1,tm2,tm3,thx,tshl,dt,
& wms1,wms2,wms3,wmshx,wmssh1,wmsin,wmsout,
& sm1,sm2,sm3,cp,cp1,cp2,cp3,cpshl,
& qd1,qd2,qd3,qdxx,convh,arshl,
& tinn,toutn,tm1n,tm2n,tm3n,thxn,tshln,
& ncell,alpha,eps_t,maxit_t)
C
C *****
C *
C * ROUTINE energy
C *
C * THIS ROUTINE COMPUTES FLUID TEMPERATURES WITHIN EACH LOOP AND
C * IN THE SHELL BASED ON THEIR THERMAL ENERGY BALANCES. THE SET
C * OF EQNS ARE SOLVED BY PICARD ITERATION OVER THE HEADERS AND
C * SHELL WITH MARCHING THRU EACH LOOP IN THEIR FLOW DIRECTION.
C * A VARIABLE IMPLICITNESS (ALPHA) IS USED IN THE FINITE
C * DIFFERENCE REPRESENTATION OF THE EQNS.
C *
C *****
C
      implicit real*8 (a-h,o-z), integer (i-n)
      include 'param.inc'
C
C argument arrays
      dimension wms1(mxnode), wms2(mxnode), wms3(mxnode), wmshx(mxnode)
      dimension tm1n(mxnode), tm1(mxnode), qd1(mxnode),
& sm1(mxnode), cp1(mxnode)
      dimension tm2n(mxnode), tm2(mxnode), qd2(mxnode),
& sm2(mxnode), cp2(mxnode)
      dimension tm3n(mxnode), tm3(mxnode), qd3(mxnode),

```


BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

&      sm3(mxnode), cp3(mxnode)
dimension thxn(mxnode), thx(mxnode), qdhx(mxnode)
dimension flw(mxloop)
dimension ncell(mxloop)

c
c local arrays
dimension gama(mxnode), gamal(mxnode)
dimension tml1(mxnode), tm2i(mxnode), tm3i(mxnode), thxi(mxnode)
dimension err(mxloop)

c
c === COMPUTE EACH LOOP DONOR VARIABLE (GAMA) =====
c
do i=1,mxloop
  gama(i) = one
  if (flw(i).lt.zero) then
    gama(i) = zero
  endif
enddo
do i=1,mxloop
  gamal(i) = one - gama(i)
enddo

c
c === SOLVE LINEAR SET OF ENERGY EQNS =====
c
c INITIALIZE NEW/ITERATE (n/i) TIME FLUID TEMPERATURES TO OLD VALUES
c
m1 = ncell(1)
m2 = ncell(2)
m3 = ncell(3)
m4 = ncell(4)
do i=1,m1
  tml1(i) = tml(i)
  tmln(i) = tml(i)
enddo
do i=1,m2
  tm2i(i) = tm2(i)
  tm2n(i) = tm2(i)
enddo
do i=1,m3
  tm3i(i) = tm3(i)
  tm3n(i) = tm3(i)
enddo
do i=1,m4
  thxi(i) = thx(i)
  thxn(i) = thx(i)
enddo

c
tini = tin
touti = tout
tshli = tshl
tinn = tin
toutn = tout
tshln = tshl

c
c --- PERFORM PICARD ITERATIONS -----
c
c write (22, '()')
```

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION)

Page: 16 of 40

```

c      write (23, '()')
c      write (24, '()')
      htc      = convh*arshl
      alpha1 = one - alpha
      do iter=1,maxit_t

c
c INLET HEADER:
c
      term0 = gama(1)*flw(1) + gama(2)*flw(2) + gama(3)*flw(3)
      &      -gama(4)*flw(4)
      term1 = gama(1)*cp*flw(1)*(alpha*tmli(1) + alpha1*tm1(1))
      term2 = gama(2)*cp*flw(2)*(alpha*tm2i(1) + alpha1*tm2(1))
      term3 = gama(3)*cp*flw(3)*(alpha*tm2i(1) + alpha1*tm3(1))
      term4 = gama(4)*cp*flw(4)*(alpha*thxi(m4) + alpha1*thx(m4))
      hcap = cp*wmsin/dt
      coef = hcap - alpha1*cp*term0
      coefn = hcap + alpha*cp*term0

c
      tini = (coef*tin - term1 - term2 - term3 + term4)/coefn

c
c      sum = flw(4) - (flw(1) + flw(2) + flw(3))
c      write (23,322) iter,sum,tmli(1),tm2i(1),tm2i(1),thxi(m4),
c      &      (gama(k),k=1,4)
c322      format(' iter,sum,tmli(1),tm2i(1),tm2i(1),thxi(m4),gama ',
c      &      i4,9f10.3)
c
c OUTLET HEADER:
c
      term0 = gama(1)*flw(1) + gama(2)*flw(2) + gama(3)*flw(3)
      &      - gama(4)*flw(4)
      term1 = gama(1)*cp*flw(1)*(alpha*tmli(m1) + alpha1*tm1(m1))
      term2 = gama(2)*cp*flw(2)*(alpha*tm2i(m2) + alpha1*tm2(m2))
      term3 = gama(3)*cp*flw(3)*(alpha*tm3i(m3) + alpha1*tm3(m3))
      term4 = gama(4)*cp*flw(4)*(alpha*thxi(1) + alpha1*thx(1))
      hcap = cp*wmsout/dt
      coef = hcap + alpha1*cp*term0
      coefn = hcap - alpha*cp*term0

c
      touti = (coef*tout + term1 + term2 + term3 - term4)/coefn

c
c SHELL OF HEAT EXCHANGER:
c
      term4 = htc*(alpha*thxi(2) + alpha1*thx(2))
      hcap = cpshl*wmsshl/dt
      coef = hcap - alpha1*htc
      coefn = hcap + alpha*htc

c
      tshli = (coef*tshl + term4)/coefn

c
c      write (24,422) iter,thxi(2),tshl,tshli
c422      format(' iter,thxi(2),tshl,tshli ',i4,3f10.5)
c
c MODULE #1 (VERTICAL LATERAL MODULES):
c
      if (flw(1).ge.zero) then
        do i=1,m1
          if (i.eq.1) then

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

        tinlet = alpha*tini + alpha1*tin
    else
        tinlet = alpha*tmli(i-1) + alpha1*tm1(i-1)
    endif
    term1 = cp*flw(1)*tinlet
    hcap = (sm1(i)*cp1(i) + wms1(i)*cp)/dt
    coef = hcap - alpha1*cp*flw(1)
    coefn = hcap + alpha*cp*flw(1)
c
    tmli(i) = (coef*tm1(i) + term1 + qd1(i))/coefn
enddo
else
    do i=1,m1
        if (i.eq.m1) then
            tinlet = alpha*touti + alpha1*tout
        else
            tinlet = alpha*tmli(i+1) + alpha1*tm1(i+1)
        endif
        term1 = cp*flw(1)*tinlet
        hcap = (sm1(i)*cp1(i) + wms1(i)*cp)/dt
        coef = hcap + alpha1*cp*flw(1)
        coefn = hcap - alpha*cp*flw(1)
c
        tmli(i) = (coef*tm1(i) - term1 + qd1(i))/coefn
    enddo
endif
c
c MODULE #2 (ALL REMAINING VERTICAL MODULES):
c
    if (flw(2).ge.zero) then
        do i=1,m2
            if (i.eq.1) then
                tinlet = alpha*tini + alpha1*tin
            else
                tinlet = alpha*tm2i(i-1) + alpha1*tm2(i-1)
            endif
            term1 = cp*flw(2)*tinlet
            hcap = (sm2(i)*cp2(i) + wms2(i)*cp)/dt
            coef = hcap - alpha1*cp*flw(2)
            coefn = hcap + alpha*cp*flw(2)
c
            tm2i(i) = (coef*tm2(i) + term1 + qd2(i))/coefn
        enddo
    else
        do i=1,m2
            if (i.eq.m2) then
                tinlet = alpha*touti + alpha1*tout
            else
                tinlet = alpha*tm2i(i+1) + alpha1*tm2(i+1)
            endif
            term1 = cp*flw(2)*tinlet
            hcap = (sm2(i)*cp2(i) + wms2(i)*cp)/dt
            coef = hcap + alpha1*cp*flw(2)
            coefn = hcap - alpha*cp*flw(2)
c
            tm2i(i) = (coef*tm2(i) - term1 + qd2(i))/coefn
        enddo
    enddo

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

endif
c
c MODULE #3 (ALL HORIZONTAL MODULES):
c
  if (flw(3).ge.zero) then
    do i=1,m3
      if (i.eq.1) then
        tinlet = alpha*tini + alpha1*tin
      else
        tinlet = alpha*tm3i(i-1) + alpha1*tm3(i-1)
      endif
      term1 = cp*flw(3)*tinlet
      hcap = (sm3(i)*cp3(i) + wms3(i)*cp)/dt
      coef = hcap - alpha1*cp*flw(3)
      coefn = hcap + alpha*cp*flw(3)
c
      tm3i(i) = (coef*tm3(i) + term1 + qd3(i))/coefn
c
      write (23,322) iter,i,tini,tinlet,tm3i(i),tm3(i)
c322  format('+ iter,i,tini,tinlet,tm3i(i),tm3(i) ',2i4,4f10.5)
      enddo
    else
      do i=1,m3
        if (i.eq.m3) then
          tinlet = alpha*touti + alpha1*tout
        else
          tinlet = alpha*tm3i(i+1) + alpha1*tm3(i+1)
        endif
        term1 = cp*flw(3)*tinlet
        hcap = (sm3(i)*cp3(i) + wms3(i)*cp)/dt
        coef = hcap + alpha1*cp*flw(3)
        coefn = hcap - alpha*cp*flw(3)
c
        tm3i(i) = (coef*tm3(i) - term1 + qd3(i))/coefn
c
        write (23,323) iter,i,touti,tinlet,tm3i(i),tm3(i)
c323  format('- iter,i,touti,tinlet,tm3i(i),tm3(i) ',2i4,4f10.5)
        enddo
      endif
c
c HEAT EXCHANGER LOOP #4:
c
  if (flw(4).ge.zero) then
    do i=1,m4
      if (i.eq.2) then
        tinlet= alpha*thxi(i-1) + alpha1*thx(i-1)
        term0 = cp*flw(4) + htc
        term1 = cp*flw(4)*tinlet
        term2 = htc*(alpha*tshli + alpha1*tshl)
        hcap = wmslx(i)*cp/dt
        coef = hcap - alpha1*term0
        coefn = hcap + alpha*term0
c
        thxi(i) = (coef*thx(i) + term1 + term2 + qdhx(i))/coefn
      else
        if (i.eq.1) then
          tinlet = alpha*touti + alpha1*tout
        else
          tinlet = alpha*thxi(i-1) + alpha1*thx(i-1)

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

endif
term1 = cp*flw(4)*tinlet
hcap = wshx(i)*cp/dt
coef = hcap - alpha1*cp*flw(4)
coefn = hcap + alpha*cp*flw(4)
c
thxi(i) = (coef*thx(i) + term1 + qdhx(i))/coefn
endif
enddo
else
do i=1,m4
if (i.eq.2) then
tinlet= alpha*thxi(i+1) + alpha1*thx(i+1)
term0 = cp*flw(4) - htc
term1 = cp*flw(4)*tinlet
term2 = htc*(alpha*tshli + alpha1*tshl)
hcap = wshx(i)*cp/dt
coef = hcap + alpha1*term0
coefn = hcap - alpha*term0
c
thxi(i) = (coef*thx(i) - term1 + term2 + qdhx(i))/coefn
else
if (i.eq.m4) then
tinlet = alpha*tini + alpha1*tin
else
tinlet = alpha*thxi(i+1) + alpha1*thx(i+1)
endif
term1 = cp*flw(4)*tinlet
hcap = wshx(i)*cp/dt
coef = hcap + alpha1*cp*flw(4)
coefn = hcap - alpha*cp*flw(4)
c
thxi(i) = (coef*thx(i) - term1 + qdhx(i))/coefn
endif
enddo
endif
c
c TEST FOR CONVERGENCE AND UPDATE NEW (n) TIME FLUID TEMPERATURES:
c
err(1) = zero
do i=1,m1
err(1) = err(1) + abs(tm1i(i) - tm1n(i))
tm1n(i) = tm1i(i)
enddo
c
err(2) = zero
do i=1,m2
err(2) = err(2) + abs(tm2i(i) - tm2n(i))
tm2n(i) = tm2i(i)
enddo
c
err(3) = zero
do i=1,m3
err(3) = err(3) + abs(tm3i(i) - tm3n(i))
tm3n(i) = tm3i(i)
enddo
c

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

      err(4) = zero
      do i=1,m4
        err(4) = err(4) + abs(thxi(i) - thxn(i))
        thxn(i) = thxi(i)
      enddo
c
      errin = abs(tini - tinn)
      errout = abs(touti - toutn)
      errshl = abs(tshli - tshln)
      tinn = tini
      toutn = touti
      tshln = tshli
c
c      write (22,222) iter,tinn,toutn,tshl,tmln(4),tm3n(3)
c222  format(' iter,tinn,toutn,tshl,tml4,tm33 ',i4,5f10.3)
c      write (22,223) (err(k),k=1,4),errin,errout,errshl
c223  format(' err ',4x,7e12.5)
c
      if ((err(1).lt.eps_t) .and. (err(2).lt.eps_t) .and.
&      (err(3).lt.eps_t) .and. (err(4).lt.eps_t) .and.
&      (errin.lt.eps_t) .and. (errout.lt.eps_t) .and.
&      (errshl.lt.eps_t)) then
        goto 1000
      endif
c
      enddo
c
c CONVERGENCE FAILURE:
c
      write (*,200)
      stop
c
c
c
c CHECK INLET AND OUTLET MASS BALANCES VERSUS TIME STEP SIZE:
c
      dt_max = 1.0d10
c
      dflow = flw(4) - (flw(1) + flw(2) + flw(3))
      if (dflow.lt.zero) then
c INLET HEADER:
c      dt_max = -wmsin/dflow
c      elseif (dflow.gt.zero) then
c INLET HEADER:
c      dt_max = wmsout/dflow
c      endif
c
      if (dt.gt.dt_max) then
c      write (*,100) eltim,dt,dt_max
c      stop
c      endif
c
c === FORMAT STATEMENTS =====
c
c100  format (///,' Program Terminated Due to Time Step Size Error',
c      &      ///,' Mass balance error at time = ',f10.4,' sec',
c      &      ///,' Current time step size = ',f10.4,' sec',

```

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION))

Page: 21 of 40

```

c      &      //, ' Max allowed based on headers = ',f10.4,' sec')
200  format (' Program Terminated Due To:',/,
      &      ' ENERGY BALANCE SOLUTION CONVERGENCE FAILURE')
c
1000 continue
      return
      end

```

Subroutine momtm.f

```

subroutine momtm(rho,vis,g,beta,rough,zlt,dt,condl,eltim,
      &      qd1,qd2,qd3,qdhx,
      &      fold1,fold2,fold3,foldhx,dfdtmx,
      &      fnew1,fnew2,fnew3,fnewhx,
      &      am1,dz1 ,z11 ,dh1 ,frmka1,tm1,
      &      am2,dz2 ,z12 ,dh2 ,frmka2,tm2,
      &      am3,dz3 ,z13 ,dh3 ,frmka3,tm3,
      &      ahx,dzhx,zlhx,dhhx,frmka3,thx,
      &      pin,pout,flw,flwn,tnot,ncell,ntype,
      &      eps_m,maxit_m,itrans,icnvg)
c
c *****
c This subroutine solves the four momentum equations (two vertical
c module momentums, one horizontal module momentum, one heat exchanger
c momentum) and the continuity
c equation for the outlet header simultaneously, using Newton's
c method. The values returned are the updated mass flowrates
c in the four loops and the outlet header pressure.
c *****
c
      implicit real*8 (a-h,o-z), integer (i-n)
      include 'param.inc'
c
      dimension a(5,5),b(5),indx(5)
c
      dimension ncell(mxloop), ntype(mxloop)
      dimension flw(mxloop), flwn(mxloop), zlt(mxloop)
c
      dimension tm1(mxnode), am1(mxnode), dh1(mxnode), dz1(mxnode),
      &      z11(mxnode)
      dimension tm2(mxnode), am2(mxnode), dh2(mxnode), dz2(mxnode),
      &      z12(mxnode)
      dimension tm3(mxnode), am3(mxnode), dh3(mxnode), dz3(mxnode),
      &      z13(mxnode)
      dimension thx(mxnode), ahx(mxnode), dhhx(mxnode), dzhx(mxnode),
      &      zlhx(mxnode)
      dimension ra1(mxnode),ra2(mxnode),ra3(mxnode),rahx(mxnode),
      &      ira1(mxnode),ira2(mxnode),ira3(mxnode),irahx(mxnode),
      &      qd1(mxnode),qd2(mxnode),qd3(mxnode),qdhx(mxnode),
      &      fold1(mxnode),fold2(mxnode), fold3(mxnode),foldhx(mxnode),
      &      fnew1(mxnode),fnew2(mxnode), fnew3(mxnode),fnewhx(mxnode)
c
      iout5=22
      iout6 = 23
c
c INITIALIZE NEW TIME MASS FLOWRATES TO PREVIOUS TIME VALUES

```

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION)

Page: 22 of 40

```

c
  do j=1,mxloop
    flwn(j) = flw(j)
  enddo

c
c === SOLVE NON-LINEAR SET OF MASS/MOMENTUM EQNS =====
c
  do iter=1,maxit_m
    call rayleigh(flwn,g,beta,condl,rho,vis,qd1,qd2,qd3,qd4,
&                dh1,dh2,dh3,dhhx,zl1,zl2,zl3,zl4,
&                dz1,dz2,dz3,dzhx,eltim,
&                ncell,ra1,ra2,ra3,rahx,ira1,ira2,ira3,irahx)

c
c MODULE #1 (VERTICAL LATERAL MODULES):
c
  call momloop (rho,vis,g,beta,am1,dz1,zl1,dh1,rough,frmka1,
&              pin,pout,tm1,tnot,flw(1),flwn(1),zlt(1),dt,
&              ra1,ira1,fold1,
&              fm1,df1dm1,df1dpo,ncell(1),ntype(1),itrans,
&              fnew1,eltim,iter)

c
  a(1,1) = df1dm1
  a(1,2) = zero
  a(1,3) = zero
  a(1,4) = zero
  a(1,5) = df1dpo
  b(1)   =-fm1
  elthrs = eltim/3600.0d0
  write (iout5,500)
  write (iout5,502) iter,elthrs
  write (iout5,505) fm1,df1dm1,df1dpo

c
c MODULE #2 (ALL REMAINING VERTICAL MODULES):
c
  call momloop (rho,vis,g,beta,am2,dz2,zl2,dh2,rough,frmka2,
&              pin,pout,tm2,tnot,flw(2),flwn(2),zlt(2),dt,
&              ra2,ira2,fold2,
&              fm2,df2dm2,df2dpo,ncell(2),ntype(2),itrans,
&              fnew2,eltim,iter)

c
  a(2,1) = zero
  a(2,2) = df2dm2
  a(2,3) = zero
  a(2,4) = zero
  a(2,5) = df2dpo
  b(2)   =-fm2
  write (iout5,505) fm2,df2dm2,df2dpo

c
c MODULE #3 (ALL HORIZONTAL MODULES):
c
  call momloop (rho,vis,g,beta,am3,dz3,zl3,dh3,rough,frmka3,
&              pin,pout,tm3,tnot,flw(3),flwn(3),zlt(3),dt,
&              ra3,ira3,fold3,
&              fm3,df3dm3,df3dpo,ncell(3),ntype(3),itrans,
&              fnew3,eltim,iter)

c
  a(3,1) = zero

```


BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

      a(3,2) = zero
      a(3,3) = df3dm3
      a(3,4) = zero
      a(3,5) = df3dpo
      b(3)   = -fm3
      write (iout5,505) fm3,df3dm3,df3dpo
c
c HEAT EXCHANGER LOOP #4:
c
      call momloop (rho,vis,g,beta,ahx,dzhx,zlhx,dhxx,rough,frmkax,
&                pin,pout,thx,tnot,flw(4),flwn(4),zlt(4),dt,
&                rahx,irahx,foldhx,
&                fmhx,dfxdmx,dfxdpo,ncell(4),ntype(4),itrans,
&                fnewhx,eltime,iter)
c
      a(4,1) = zero
      a(4,2) = zero
      a(4,3) = zero
      a(4,4) = dfxdmx
      a(4,5) = dfxdpo
      b(4)   = -fmhx
      write (iout5,505) fmhx,dfxdmx,dfxdpo
c
c OUTLET HEADER CONTINUITY BALANCE:
c
      call outhdr (flwn,fmout,dfotd1,dfotd2,dfotd3,dfotdx)
c
      a(5,1) = dfotd1
      a(5,2) = dfotd2
      a(5,3) = dfotd3
      a(5,4) = dfotdx
      a(5,5) = zero
      b(5)   = -fmout
      write (iout5,511) flwn(1),flwn(2),flwn(3),flwn(4),fmout
      write (iout5,511) fmout,dfotd1,dfotd2,dfotd3,dfotdx
c
c SOLVE FOR NEWTON ITERATE BY LU DECOMPOSITION:
c
      n = 5
      np = 5
      call ludcmp (a,n,np,indx,d)
      call lubksb (a,n,np,indx,b)
c
c UPDATE NEW TIME MASS FLOWRATE ARRAY AND OUTLET HEADER PRESSURE:
c
      write (iout6,510) iter,flwn(1),flwn(2),flwn(3),flwn(4),pout
      write (iout6,510) iter,(b(i),i=1,5)
      do i=1,mxloop
cc      if (j .lt. 20) then
          flwn(i) = flwn(i) + b(i)
cc      else
          flwn(i) = flwn(i) + 0.5*b(i)
cc      endif
      enddo
cc      if (j .lt. 20) then
          pout = pout + b(5)
cc      else

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

cc      pout      = pout + 0.5*b(5)
cc      endif
c
c TEST FOR CONVERGENCE:
c
      err1 = abs(b(1))/(abs(flwn(1))+eps_m)
      err2 = abs(b(2))/(abs(flwn(2))+eps_m)
      err3 = abs(b(3))/(abs(flwn(3))+eps_m)
      err4 = abs(b(4))/(abs(flwn(4))+eps_m)
      err5 = abs(b(5))/pout
c
      if ((err1.lt.eps_m) .and. (err2.lt.eps_m) .and.
&      (err3.lt.eps_m) .and. (err4.lt.eps_m) .and.
&      (err5.lt.eps_m*100.0d0)) then
          icnvg = 0
          goto 1000
      endif
      enddo
      write (iout6,501)
      write (iout6,500)
      write (iout6,501)
c
c CONVERGENCE FAILURE:
c
      icnvg = 1
      write (*,530)
      go to 1000
cc      flwn(4) = flwn(1)+flwn(2)+flwn(3)
cc      stop
c
c === FORMAT STATEMENTS =====
c
cc 20  write (*,500)
cc      write (iout6,520)ii
cc      write (iout6,510)flwn(1),flwn(2),flwn(3),flwn(4),pout
cc      write (iout6,510)err1,err2,err3,err4,err5
c 100  continue
c
500  format (1x,'*****')
501  format (1x,' ')
502  format (1x,i6,' time = ',g16.8)
505  format (1x,3g16.8)
510  format (i5,5g16.8)
511  format (1x,5g16.8)
520  format (1x,' ii = ',i6)
530  format (' Program Terminated Due To:',/,
&      ' MASS/MOMENTUM SOLUTION CONVERGENCE FAILURE')
c
1000 continue
      return
      end

```

Subroutine momloop.f

```

subroutine momloop (rho,vis,g,beta,am,dz,zl,dh,rough,frmka,
&
&      pin,pout,tm,tnot,flow,flown,zlt,dt,ra,ira,
&      fold,fm,dfdm,dfdp,ncell,itype,itrans,

```

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION))

Page: 25 of 40

```

      &                fnew,eltim,iter)
C
C *****
C *
C * ROUTINE momloop
C *
C * THIS SUBROUTINE CALCULATES THE VALUE OF THE "F" EQUATION AND
C * THE PARTIAL DERIVATIVES WITH RESPECT TO THE "DELTA" VARIABLES
C * FOR THE MOMENTUM EQUATION FOR EACH SPECIFIED FLOW LOOP. THESE
C * VALUES ARE USED IN THE SOLUTION OF THE NON-LINEAR MOMENTUM
C * EQUATIONS BY NEWTON'S METHOD WHEN THE VARIOUS FLOW LOOPS ARE
C * CONNECTED.
C *
C * ITYPE = 1 FOR MODULES
C * ITYPE = 2 FOR HEAT EXCHANGER
C *
C *****
C
      implicit real*8 (a-h,o-z), integer (i-n)
      include 'param.inc'
C
      dimension tm(mxnode),am(mxnode),dh(mxnode),dz(mxnode),zl(mxnode)
      dimension fric(mxnode), fricp(mxnode), ra(mxnode),ira(mxnode),
      &          fold(mxnode),fnew(mxnode)
C
C CALCULATE VALUES FOR THE FRICTION FACTORS:
C
C CALCULATE PERTURBED FLOWS AND FRICTION FACTORS:
C
      eps      = 1.0d-4
      if (flown .ge. 0.0)then
        flownp = flown + eps
      else
        flownp = flown - eps
      end if
C
      write (19,('eltim,iter: ',f10.6,i5)) eltim/3600.0d0,iter
      do i=1,ncell
        ed = rough/dh(i)
        re = (abs(flown)*dh(i))/(vis*am(i))
        rep = (abs(flownp)*dh(i))/(vis*am(i))
C
        rap = ra(i)*((flown/flownp)**.25d0)
        rap = ra(i)
C
        call frict(re,ed,ra(i),ira(i),fric(i))
        call frict(rep,ed, rap,ira(i),fricp(i))
cc      dfrctp = fricp(i)-fric(i)
cc      dffdt = (fric(i)-fold(i))/dt
cc      dffabs = abs(dffdt)
cc      if (dffabs .gt. dfdtmx)then
cc        dffdt = sign(dffdt,dfdtmx)
cc      endif
cc      fric(i) = fold(i) + dffdt*dt
cc      fricp(i) = fric(i) + dfrctp
      fnew(i) = fric(i)
    enddo

```

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION))

Page: 26 of 40

```

C
C CALCULATE THE VALUE OF THE FUNCTION AND THE JACOBEAN ENTRIES:
C
      sum = zero
      do i=1,ncell
        sum = sum + (one - beta*(tm(i)-tnot))*am(i)*dz(i)
      enddo
      bterm = rho*g*sum
C
C COMPUTE FTERM AT CURRENT ITERATE AND PERTURBED POINTS:
C
      sum = zero
      sump = zero
      do i=1,ncell
        sum = sum + fric(i)*zl(i)/(dh(i)*am(i))
        sump = sump + fricp(i)*zl(i)/(dh(i)*am(i))
      enddo
      fterm = (sum + frmka)/(two*rho)
      ftermp = (sump + frmka)/(two*rho)
C
C COMPUTE ATERM AT CURRENT ITERATE:
C
      if (itrans.eq.0) then
        aterm = zero
      else
        aterm = zlt/dt
      endif
C
C === COMPUTE FUNCTION AND DERIVATIVES BASED ON LOOP TYPE =====
C
      if (itype.eq.1) then
C
C CALCULATE FUNCTION AT CURRENT ITERATE AND PERTURBED POINTS:
C
        fm = pin*am(1) - pout*am(ncell) + bterm
        &      + aterm*(flow - flown) - flown*abs(flown)*fterm
        fmp = pin*am(1) - pout*am(ncell) + bterm
        &      + aterm*(flow - flownp) - flownp*abs(flownp)*ftermp
C
C ESTIMATE FUNCTION DERIVATIVE NUMERICALLY BY SIMPLE FORWARD
C DIFFERENCING FOR FLOW TERM AND ANALYTICALLY FOR PRESSURE TERM:
C
        if (flown.ge. 0.0) then
          dfdm = (fmp - fm)/eps
        else
          dfdm = (fm - fmp)/eps
        end if
        dfdpo = -am(ncell)
      else
C
C CALCULATE FUNCTION AT CURRENT ITERATE AND PERTURBED POINTS:
C
        fm = pout*am(1) - pin*am(ncell) + bterm
        &      + aterm*(flow - flown) - flown*abs(flown)*fterm
        fmp = pout*am(1) - pin*am(ncell) + bterm
        &      + aterm*(flow - flownp) - flownp*abs(flownp)*ftermp
C

```

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION))

Page: 27 of 40

c ESTIMATE FUNCTION DERIVATIVE NUMERICALLY BY SIMPLE FORWARD
 c DIFFERENCING FOR FLOW TERM AND ANALYTICALLY FOR PRESSURE TERM:

```

c
      if (flwn .ge. 0.0) then
        dfdm = (fmp - fm)/eps
      else
        dfdm = (fm - fmp)/eps
      end if
      dfdpo = am(1)
    endif
c
      return
    end
  
```

Subroutine rayleigh.f

```

subroutine rayleigh (flwn,g,beta,condl,rho,vis,qd1,qd2,qd3,qdhx,
&                  dh1,dh2,dh3,dhxx,zl1,zl2,zl3,zlhx,
&                  dz1,dz2,dz3,dzxx,eltime,
&                  ncell,ra1,ra2,ra3,rahx,ira1,ira2,ira3,irahx)
c
c *****
c *
c * ROUTINE rayleigh
c *
c * THIS ROUTINE COMPUTES EACH FLUID CELL RAYLEIGH NUMBER.
c * A RAYLEIGH NUMBER DEFINED FOR MIXED CONVECTION FLOW IS
c * COMPUTED FOR EACH FLUID CELL BASED ON HEATING/COOLING AND
c * CURRENT FLOW DIRECTION.
c * A FLAG (ira) IS SET INDICATING IF CELL IS IN:
c *
c * ira = 1 FOR HEATED UPFLOW (OR COOLED DOWNFLOW)
c * ira = 0 FOR HORIZONTAL HEATED, COOLED, OR ADIABATIC FLOW
c * ira = -1 FOR HEATED DOWNFLOW (OR COOLED UPFLOW)
c *
c *****
c
c      implicit real*8 (a-h,o-z), integer (i-n)
c      include 'param.inc'
c
c argument arrays
      dimension ra1(mxnode), ra2(mxnode), ra3(mxnode), rahx(mxnode)
      dimension ira1(mxnode), ira2(mxnode), ira3(mxnode), irahx(mxnode)
      dimension qd1(mxnode), qd2(mxnode), qd3(mxnode), qdhx(mxnode)
      dimension dh1(mxnode), dh2(mxnode), dh3(mxnode), dhxx(mxnode)
      dimension zl1(mxnode), zl2(mxnode), zl3(mxnode), zlhx(mxnode)
      dimension dz1(mxnode), dz2(mxnode), dz3(mxnode), dzxx(mxnode)
      dimension flwn(mxloop)
      dimension ncell(mxloop)
c
c === CALCULATE EACH FLUID CELL RAYLEIGH NUMBER =====
c
      iout3 = 17
      eps = 1.0d-2
      prop = g*beta*(rho**2)/(vis*condl)
      ramax = 12.0d0
c
  
```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

cc      prop = 0.0
c
cc
cccc      write (iout3,990)prop
990      format (1x,'PROP = ',g16.8)
          elhrs = eltim/3600.0
cc
          m1 = ncell(1)
          m2 = ncell(2)
          m3 = ncell(3)
          m4 = ncell(4)
c
c MODULE #1 (VERTICAL LATERAL MODULES):
c
          flown = abs(flwn(1))
          do i=1,m1
              ral(i) = (prop*abs(qd1(i))*(dh1(i)**4)/
&                      (zl1(i)*flown))**.25d0
              if (ral(i) .gt. ramax)ral(i)=ramax
cccc          if ((i .eq. 2) .or. (i .eq. 4))
cccc          &      write (iout3,1000)i,dh1(i),zl1(i),flown,qd1(i),ral(i)
cccc 1000 format (1x,i6,5g14.7)
          enddo
c
c MODULE #2 (ALL REMAINING VERTICAL MODULES):
c
          flown = abs(flwn(2))
          do i=1,m2
              ra2(i) = (prop*abs(qd2(i))*(dh2(i)**4)/
&                      (zl2(i)*flown))**.25d0
              if (ra2(i) .gt. ramax)ra2(i)=ramax
cccc          if ((i .eq. 2) .or. (i .eq. 4))
cccc          &      write (iout3,1000)i,dh2(i),zl2(i),flown,qd2(i),ra2(i)
          enddo
          write (iout3,1000)elhrs,ral(2),ral(4),ra2(2),ra2(4)
          1000 format (5g14.7)
c
c MODULE #3 (ALL HORIZONTAL MODULES):
c
          flown = abs(flwn(3))
          do i=1,m3
              ra3(i) = (prop*abs(qd3(i))*(dh3(i)**4)/
&                      (zl3(i)*flown))**.25d0
              if (ra3(i) .gt. ramax)ra3(i)=ramax
          enddo
c
c HEAT EXCHANGER LOOP #4:
c
          flown = abs(flwn(4))
          do i=1,m4
              rahx(i) = (prop*abs(qd4(i))*(dh4(i)**4)/
&                      (zl4(i)*flown))**.25d0
              if (rahx(i) .gt. ramax)rahx(i)=ramax
          enddo
c
c === SET HEATING/COOLING UP/DOWN FLOW STATE =====
c

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```
c
c MODULE #1 (VERTICAL LATERAL MODULES):
c
    flown = flwn(1)
    do i=1,m1
        point = dz1(i)
c --- HEATED -----
        if (qd1(i).gt.zero) then
            if (point.lt.zero) then
                if (flown.ge.zero) then
c --- heated upflow
                    iral(i) = 1
                else
c --- heated downflow
                    iral(i) = -1
                endif
            elseif (point.gt.zero) then
                if (flown.ge.zero) then
c --- heated downflow
                    iral(i) = -1
                else
c --- heated upflow
                    iral(i) = 1
                endif
            else
c --- horizontal
                    iral(i) = 0
                endif
c --- COOLED -----
            elseif (qd1(i).lt.zero) then
                if (point.lt.zero) then
                    if (flown.ge.zero) then
c --- cooled upflow
                        iral(i) = -1
                    else
c --- cooled downflow
                        iral(i) = 1
                    endif
                elseif (point.gt.zero) then
                    if (flown.ge.zero) then
c --- cooled downflow
                        iral(i) = 1
                    else
c --- cooled upflow
                        iral(i) = -1
                    endif
                else
c --- horizontal
                        iral(i) = 0
                    endif
                else
c --- ADIABATIC -----
                        iral(i) = 0
                    endif
                enddo
            enddo
c
c MODULE #2 (VERTICAL LATERAL MODULES):
```

BLANKET SAFETY ANALYSIS FOR LOFA
(NATURAL CIRCULATION)

```

c
  flown = flwn(2)
  do i=1,m2
    point = dz2(i)
c --- HEATED -----
    if (qd2(i).gt.zero) then
      if (point.lt.zero) then
        if (flown.ge.zero) then
c --- heated upflow
          ira2(i) = 1
        else
c --- heated downflow
          ira2(i) = -1
        endif
      elseif (point.gt.zero) then
        if (flown.ge.zero) then
c --- heated downflow
          ira2(i) = -1
        else
c --- heated upflow
          ira2(i) = 1
        endif
      else
c --- horizontal
          ira2(i) = 0
        endif
c --- COOLED -----
      elseif (qd2(i).lt.zero) then
        if (point.lt.zero) then
          if (flown.ge.zero) then
c --- cooled upflow
            ira2(i) = -1
          else
c --- cooled downflow
            ira2(i) = 1
          endif
        elseif (point.gt.zero) then
          if (flown.ge.zero) then
c --- cooled downflow
            ira2(i) = 1
          else
c --- cooled upflow
            ira2(i) = -1
          endif
        else
c --- horizontal
            ira2(i) = 0
          endif
        else
c --- ADIABATIC -----
            ira2(i) = 0
          endif
        enddo
c
c
c MODULE #3 (HORIZONTAL LATERAL MODULES):
c

```


BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION)

```

        flown = flwn(3)
        do i=1,m3
            point = dz3(i)
c --- HEATED -----
            if (qd3(i).gt.zero) then
                if (point.lt.zero) then
                    if (flown.ge.zero) then
c --- heated upflow
                        ira3(i) = 1
                    else
c --- heated downflow
                        ira3(i) = -1
                    endif
                elseif (point.gt.zero) then
                    if (flown.ge.zero) then
c --- heated downflow
                        ira3(i) = -1
                    else
c --- heated upflow
                        ira3(i) = 1
                    endif
                else
c --- horizontal
                        ira3(i) = 0
                    endif
            elseif (qd3(i).lt.zero) then
                if (point.lt.zero) then
                    if (flown.ge.zero) then
c --- cooled upflow
                        ira3(i) = -1
                    else
c --- cooled downflow
                        ira3(i) = 1
                    endif
                elseif (point.gt.zero) then
                    if (flown.ge.zero) then
c --- cooled downflow
                        ira3(i) = 1
                    else
c --- cooled upflow
                        ira3(i) = -1
                    endif
                else
c --- horizontal
                        ira3(i) = 0
                    endif
            else
c --- ADIABATIC -----
                        ira3(i) = 0
                    endif
            enddo
c
c
c MODULE #4 (HEAT EXCHANGER LOOP):
c
        flown = flwn(4)

```

BLANKET SAFETY ANALYSIS FOR LOFA
(NATURAL CIRCULATION)

```
      do i=1,m4
        point = dzhx(i)
c --- HEATED -----
        if (qdhx(i).gt.zero) then
          if (point.lt.zero) then
            if (flown.ge.zero) then
c --- heated upflow
              irahx(i) = 1
            else
c --- heated downflow
              irahx(i) = -1
            endif
          elseif (point.gt.zero) then
            if (flown.ge.zero) then
c --- heated downflow
              irahx(i) = -1
            else
c --- heated upflow
              irahx(i) = 1
            endif
          else
c --- horizontal
              irahx(i) = 0
            endif
c --- COOLED -----
          elseif (qdhx(i).lt.zero) then
            if (point.lt.zero) then
              if (flown.ge.zero) then
c --- cooled upflow
                irahx(i) = -1
              else
c --- cooled downflow
                irahx(i) = 1
              endif
            elseif (point.gt.zero) then
              if (flown.ge.zero) then
c --- cooled downflow
                irahx(i) = 1
              else
c --- cooled upflow
                irahx(i) = -1
              endif
            else
c --- horizontal
                irahx(i) = 0
              endif
            else
c --- ADIABATIC -----
                irahx(i) = 0
              endif
            enddo
c
          return
        end
```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

Subroutine frict.f

subroutine frict(re,ed,ran,iran,zf)

c

c

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c

```

*****
This subroutine calculates the Moody friction factor for a
tube. Inputs are the Reynolds #, the hydraulic diameter, and the
relative roughness. The Darcy friction factor is returned.
*****

```

```

implicit real*8 (a-h,o-z), integer (i-n)

```

```

eps = 1.0d-6

```

```

remst = 25.0d0

```

```

cc    eps = 10.0d0

```

```

rem = dmax1(re,eps)

```

```

cfc1u = 0.11815501d0

```

```

cfd2u = -.29378955d-2

```

```

cfc3u = -0.33784101d1

```

```

cfd4u = 0.11636369d1

```

```

cfc1d = -0.38259936d0

```

```

cfd2d = 0.71433520d-1

```

```

cfc3d = -0.37145261d-2

```

```

This is the mixed convection Rayleigh # multiplier:

```

```

if (ran .le. 1.5d0)then

```

```

    bm = 1.0d0

```

```

else

```

```

    if (iran .gt. 0)then

```

```

        if (ran .le. 8.0d0)then

```

```

            expn = cfc1u*((ran-1.5d0)**2)+cfd2u*((ran-1.5d0)**3)

```

```

            bm = dexp(expn)

```

```

        else

```

```

            expn = cfc3u+cfd4u*(ran-1.5d0)

```

```

            bm = dexp(expn)

```

```

        endif

```

```

    else if (iran .lt. 0)then

```

```

        if (ran .le. 8.0d0)then

```

```

            expn = cfc1d*((ran-1.5d0)**2)+cfd2d*((ran-1.5d0)**3)

```

```

&            +cfc3d*((ran-1.5d0)**4)

```

```

            bm = dexp(expn)

```

```

        else

```

```

            bm = 1.0d0/24.0d0

```

```

        endif

```

```

    else

```

```

        bm = 1.0d0

```

```

    end if

```

```

end if

```

```

if (rem .le. remst)then

```

```

    xx = rem/remst

```

```

    w2 = (xx**2)*(3.0d0-2.0d0*xx)

```

```

    w1 = 1.0d0-w2

```

```

    bm = w1+w2*bm

```

```

ccc    bm = 1.0d0+(bm-1.0d0)*((rem-eps)/(remst-eps))

```

```

end if

```

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION))

Page: 34 of 40

```

c
c Calc. standard friction factor
c
      if (rem.le.2300.0d0) then
        zf = 64.0d0/rem
      elseif (rem.ge.4000.0d0) then
        zf = 1.0d0/((1.14d0
&          - 2.0d0*log10(ed + 21.25d0/(rem**0.9d0)))**2)
      else
        zf = 0.23158d0 - 2.0549d-4*rem
&          + 6.6351d-8*(rem**2) - 6.7336d-12*(rem**3)
      endif
      zf = bm*zf
c
      iout4 = 19
      if (iran.ne. 0)write (iout4,1000)iran,ran,re,bm,zf
1000 format (1x,i5,4g16.8)
      return
      end

```

Subroutine outhdr.f

```

subroutine outhdr (flwn,fmout,dfotd1,dfotd2,dfotd3,dfotdx)
c
c *****
c This subroutine calculates the value of the "f" equation and the
c partial derivatives with respect to the "delta" variables for the
c continuity equation for the outlet header. These values are
c used in the solution of the non-linear momentum equations
c by Newton's method.
c *****
c
      implicit real*8 (a-h,o-z), integer (i-n)
      include 'param.inc'
c
      dimension flwn(mxloop)
c
      fmout = flwn(1) + flwn(2) + flwn(3) - flwn(4)
      dfotd1 = one
      dfotd2 = one
      dfotd3 = one
      dfotdx = -one
c
      return
      end

```

Subroutine tmean.f

```

subroutine tmean (wmsin,wmsout,wms1,wms2,wms3,wmslx,
&               tin,tout,tml,tm2,tm3,thx,tnot,beta,vis,
&               iskip,ncell)
c
c *****
c This subroutine calculates the mean (average) fluid temperature
c over the entire set of flow loops. The coefficient for thermal
c expansion and fluid viscosity are also updated based on new mean
c fluid temperature.

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

c *****
c

```

```

    implicit real*8 (a-h,o-z), integer (i-n)
    include 'param.inc'

```

```

c
    dimension ncell(mxloop), coefb(5), coefv(8)
    dimension tml(mxnode), wms1(mxnode)
    dimension tm2(mxnode), wms2(mxnode)
    dimension tm3(mxnode), wms3(mxnode)
    dimension thx(mxnode), wmslx(mxnode)

```

```

c
    data coefb/ 4.9323453d-03,-6.3224634d-05, 2.8526660d-07,
&              -5.4026781d-10, 3.7406938d-13/

```

```

c
    data coefv/ 2.5217246d+00,-4.3320035d-02, 3.1823267d-04,
&              -1.2943418d-06, 3.1456297d-09,-4.5657684d-12,
&              3.6636052d-15,-1.2534347d-18/

```

```

c
c CALCULATE MEAN TEMPERATURE (LOOP AVERAGE):

```

```

c
    if (iskip.eq.0) then
        totmas = wmsin + wmsout
        do i=1,ncell(1)
            totmas = totmas + wms1(i)
        enddo
        do i=1,ncell(2)
            totmas = totmas + wms2(i)
        enddo
        do i=1,ncell(3)
            totmas = totmas + wms3(i)
        enddo
        do i=1,ncell(4)
            totmas = totmas + wmslx(i)
        enddo

```

```

c
        totemas = wmsin*tin + wmsout*tout
        do i=1,ncell(1)
            totemas = totemas + wms1(i)*tml(i)
        enddo
        do i=1,ncell(2)
            totemas = totemas + wms2(i)*tm2(i)
        enddo
        do i=1,ncell(3)
            totemas = totemas + wms3(i)*tm3(i)
        enddo
        do i=1,ncell(3)
            totemas = totemas + wmslx(i)*thx(i)
        enddo

```

```

c
        tnot = totemas/totmas

```

```

c
c CALCULATE NEW BETA:

```

```

c
        beta = coefb(1) + (coefb(2) + (coefb(3) + (coefb(4)
&              + coefb(5)*tnot)*tnot)*tnot)*tnot
        endif

```

```

c

```

BLANKET SAFETY ANALYSIS FOR LOFA
(NATURAL CIRCULATION)

c CALCULATE NEW ABSOLUTE VISCOSITY (kg/m-s):

c

```

      vis = coefv(1) + (coefv(2) + (coefv(3) + (coefv(4)
&          + (coefv(5) + (coefv(6) + (coefv(7)
&          + coefv(8)*tnot)*tnot)*tnot)*tnot)*
&          tnot)*tnot)*tnot

```

c

```

      return
      end

```

Subroutine condlq.f

subroutine condlq (t,l,condl,dkdt)

c

c

c

c

c

c

c

c

c

c

c

c

c

c

c

c

c

c

```

      implicit real*8 (a-h,o-z), integer (i-n)
      parameter (tconv=273.15d0)
      dimension c1(2), c2(2), c3(2), c4(2), c3x2(2), c4x3(2)

```

c

c

c

```

      data c1(1) / 5.7032432d-1/, c2(1) /1.7996615d-3/,
& c3(1) /-7.2881959d-6/, c4(1) /3.2412245d-9/,
& c3x2(1) /-1.4576392d-5/, c4x3(1) /9.7236735d-9/

```

c

c

c

```

      data c1(2) / 5.6340135d-1/, c2(2) /1.4504443d-3/,
& c3(2) /-7.9650470d-6/, c4(2) /7.1584948d-9/,
& c3x2(2) /-1.5930094d-5/, c4x3(2) /2.1475484d-8/

```

c

```

      tinc = t - tconv
      cond1 = c1(1) + (c2(1) + (c3(1) + c4(1)*tinc)*tinc)*tinc
      dkdt = (c2(1) + (c3x2(1) + c4x3(1)*tinc)*tinc) / cond1

```

c

```

      return
      end

```

Subroutine dpower.f

subroutine dpower (eltime_p,tgstrt,tgdry,

```

& target,q1,q2,q3,qd1,qd2,qd3,qdhx,

```

BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

      &                                ncell)
C
C *****
C *
C * ROUTINE dpower
C *
C * THIS ROUTINE COMPUTES EACH FLUID CELL DEPOSITED DECAY POWERS.
C *
C *****
C
      implicit real*8 (a-h,o-z), integer (i-n)
      include 'param.inc'
C
C argument arrays
      dimension qd1(mxnode), qd2(mxnode), qd3(mxnode), qdhx(mxnode)
      dimension q1(mxnode), q2(mxnode), q3(mxnode)
      dimension ncell(mxloop)
C
C === CALCULATE EACH FLUID CELL DECAY POWER =====
C
      conv_tim = 3600.0d0
      m1      = ncell(1)
      m2      = ncell(2)
      m3      = ncell(3)
      m4      = ncell(4)
      tau     = eltim_p/conv_tim
C
C COMPUTE DECAY FRACTION
C
      if (tau.le.one) then
        write (*,200) tau
        stop
      else
        decay = 3.849d-3*(0.96d0 - 0.363d0*log10(tau))
      endif
C
C COMPUTE TARGET POWER DEPOSITED TO DECOUPLER
C
      if (eltim_p.lt.tgstrt) then
        qtgt = zero
      elseif (eltim_p.gt.tgdry) then
        qtgt = target
      else
        qtgt = target*(eltim_p-tgstrt)/(tgdry-tgstrt)
      endif
C
C COMPUTE BLANKET MODULE POWER DEPOSITED
C
C MODULE #1
      do i=1,m1
        qd1(i) = decay*q1(i)
      enddo
      qd1(2) = qd1(2) + decay*qtgt
C
C MODULE #2
      do i=1,m2
        qd2(i) = decay*q2(i)

```

BLANKET SAFETY ANALYSIS FOR LOFA

Date: 08/06/98

(NATURAL CIRCULATION))

Page: 38 of 40

```

        enddo
c
c MODULE #3
        do i=1,m3
            qd3(i) = decay*q3(i)
        enddo
c
c HEAT EXCHANGER #4
        do i=1,m4
            qdhx(i) = zero
        enddo
c
c === FORMAT STATEMENTS =====
c
200 format (' Program Terminated Due To:',/,
&          ' INITIAL START TIME MUST BE GREATER THAN OR',
&          ' EQUAL TO ONE HOUR',/,
&          ' CURRENT ELAPSED TIME =',f10.3,' hours')
c
        return
        end

```

Subroutine ludcmp.f

```

subroutine ludcmp(a,n,np,indx,d)
c
c *****
c *
c * ROUTINE ludcmp
c *
c * THIS SUBROUTINE PERFORMS LU DECOMPOSITON OF MATRIX A.
c * PARTIAL ROW PIVOTING USED.
c *
c *****
c
        implicit real*8 (a-h,o-z), integer (i-n)
        parameter (nmax=100,tiny=1.0d-20, zero=0.0d0, one=1.0d0)
c
        dimension a(np,np),indx(n),vv(nmax)
c
        d=one
        do 12 i=1,n
            aamax=zero
            do 11 j=1,n
                if (abs(a(i,j)) .gt. aamax) aamax=abs(a(i,j))
11          continue
            if (aamax .eq. zero) pause 'singular matrix'
            vv(i)=one/aamax
12          continue
            do 19 j=1,n
                do 14 i=1,j-1
                    sum=a(i,j)
                    do 13 k=1,i-1
                        sum=sum-a(i,k)*a(k,j)
13                  continue
                    a(i,j)=sum
14                  continue

```


BLANKET SAFETY ANALYSIS FOR LOFA

(NATURAL CIRCULATION))

```

      aamax=zero
      do 16 i=j,n
        sum=a(i,j)
        do 15 k=1,j-1
          sum=sum-a(i,k)*a(k,j)
15      continue
          a(i,j)=sum
          dum=vv(i)*abs(sum)
          if (dum .ge. aamax) then
            imax=i
            aamax=dum
          endif
16      continue
          if (j .ne. imax) then
            do 17 k=1,n
              dum=a(imax,k)
              a(imax,k)=a(j,k)
              a(j,k)=dum
17      continue
              d=-d
              vv(imax)=vv(j)
            endif
            indx(j)=imax
            if (a(j,j) .eq. zero) a(j,j)=tiny
            if (j .ne. n) then
              dum=one/a(j,j)
              do 18 i=j+1,n
                a(i,j)=a(i,j)*dum
18      continue
              endif
19      continue
          return
        end

```

Subroutine lubksb.f

```

subroutine lubksb(a,n,np,indx,b)

```

```

c
c *****
c *
c * ROUTINE lubksb
c *
c * THIS SUBROUTINE PERFORMS FORWARD AND BACKWARD SWEEP OF LU
c * DECOMPOSED MATRIX A GIVEN A RHS VECTOR B FOR SOLUTION.
c *
c *****
c
c      implicit real*8 (a-h,o-z), integer (i-n)
c      parameter (zero=0.0d0)
c
c      dimension a(np,np),indx(n),b(n)
c
c      ii=0
c      do 12 i=1,n
c        ll=indx(i)
c        sum=b(ll)
c        b(ll)=b(i)

```

BLANKET SAFETY ANALYSIS FOR LOFA
(NATURAL CIRCULATION)

```
      if (ii .ne. 0) then
        do 11 j=ii,i-1
          sum=sum-a(i,j)*b(j)
11      continue
        else if (sum .ne. zero) then
          ii=i
        endif
        b(i)=sum
12      continue
        do 14 i=n,1,-1
          sum=b(i)
          do 13 j=i+1,n
            sum=sum-a(i,j)*b(j)
13      continue
          b(i)=sum/a(i,i)
14      continue
        return
      end
```