THERMALHYDRAULIC AND THERMAL ANALYSIS METHODOLOGY OF THE CANDU-3 REACTOR ENDSHIELD FOR A LOSS OF FLOW EVENT

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ABSTRACT

The purpose of this paper is to describe the methodology and results of the design assist analysis done to further optimize the reactor endshield configuration. Due to neutron and gamma radiation absorption and through conduction, convection and radiation from the primary coolant a considerable amount of heat is deposited within the endshield of the CANDU-3 reactor. During normal operating conditions this heat is removed by the endshield cooling system, which is based on forced circulation of water. In the event of a loss of endshield coolant flow the temperature of the water and the endshield structure rise, creating thermal gradients, which in turn generate thermal stresses in the structure. Thermalhydraulic and thermal analysis codes are used to predict the effects of this loss of flow event.

1.0 INTRODUCTION

The CANDU-3 reactor rated at 450 MW of electric power is an advanced reactor developed at AECL CANDU. During the conceptual design of the reactor, various scenarios including loss of endshield flow have been analyzed. This paper examines the thermal effect of this event on the endshield structure.

The CANDU-3 reactor assembly consists of the calandria shell, shield tank, fuel channels, reactivity control units, two endshields and two endwalls. Under normal operating conditions the heat deposited in the endshield is removed by circulating cool water, which is forced into it. During a loss of flow in the endshield the coolant flow is disrupted. However, the heat build up in the endshield continues due to the absorption of neutron and gamma radiation (from nuclear fission inside the fuel channels) by the inner tubesheets and steel balls in the endshields and through conduction, convection and radiation of heat from the primary coolant inside the fuel channel. Due to loss of circulation of endshield water, the temperature of the water rises. The low density hot water moves to the upper portion of the endshield and cold water occupies the lower part. This creates, together with the unequally distributed neutron and gamma radiation, thermal gradients within the endshield structure resulting in thermal stresses. Due to continued heating and lack of adequate circulation of water between the endshield and the shield tank, the water will boil after a certain period. Further stresses will be generated due to pressure build up in the endshield. In addition, effective radiation shielding will decrease. To prevent this, operator action is required. To determine the time for boiling and to calculate the temperature gradient in the structure before boiling, a thermalhydraulic and a subsequent thermal analysis of the endshield is performed. The methodology and the results of the analyses are presented in this paper.

2.0 DESCRIPTION OF ENDSHIELD

Each of the endshields (Figure 1) consists of two circular flat plates called the inner tubesheet and the outer tubesheet, 232 lattice tubes arranged parallel to the horizontal axis between the tubesheets and a peripheral shell called endshield shell. The endshields are surrounded by the endwalls of the shield tank assembly which are, in turn, supported by the vault wall. Each of

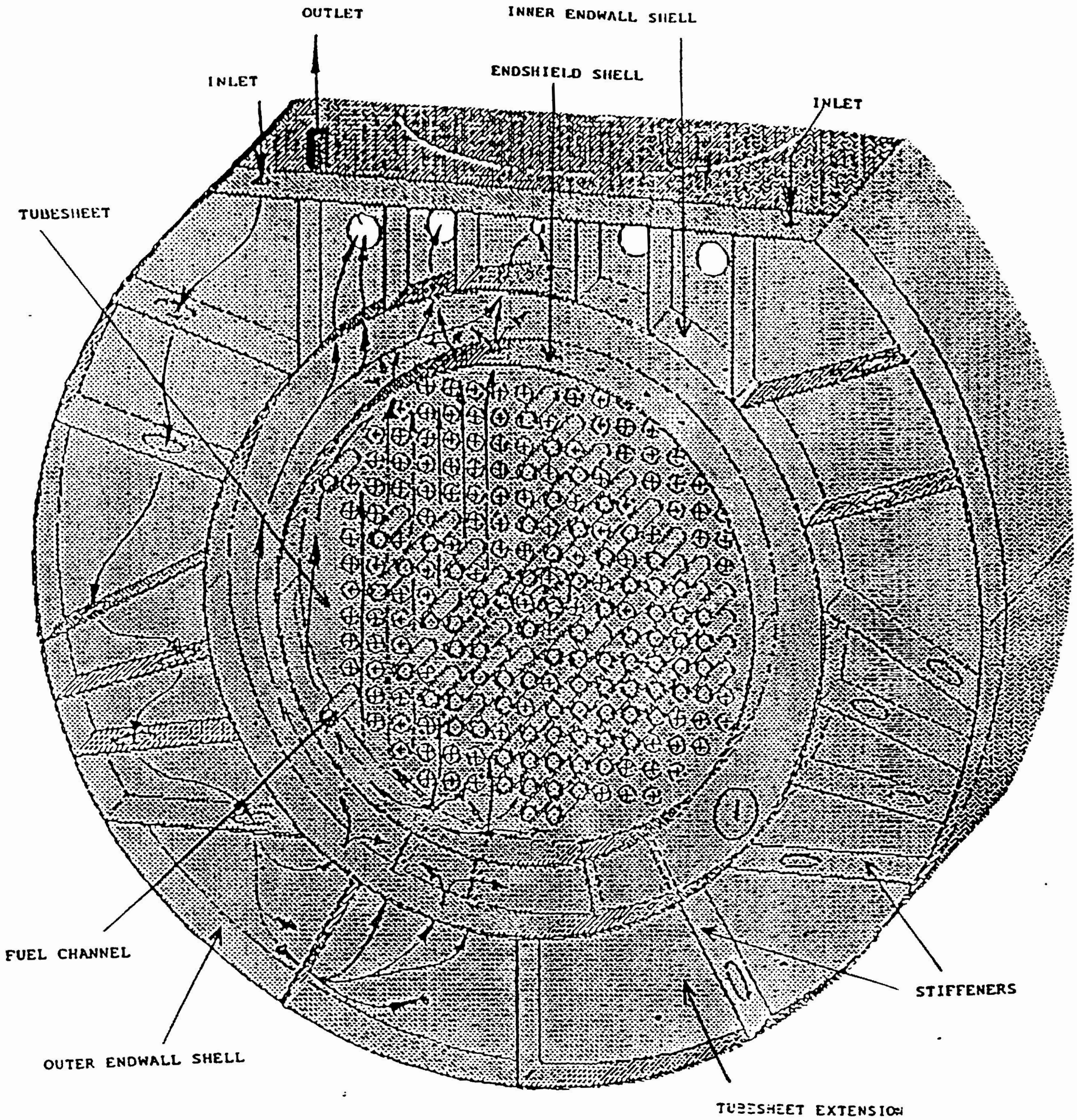


FIGURE 1 - ENDSHIELD

the endwalls consists of an inner and an outer tubesheet extension, two peripheral shells called the inner endwall shell and the outer endwall shell and stiffeners between the shells. To prevent neutron and gamma radiation through the endshields, they are filled with carbon steel balls, which occupy part of the volume of the endshield. The remaining void is filled with light water, which removes the heat deposited in the endshield. The heat is deposited by neutron and gamma radiation absorption and by heat transfer from the primary coolant. Through outlets in the endshield shell and inner endwall shell the hot water can move into the endwall and then to the shield tank, which contains a large amount of cool water.

3.0 THERMALHYDRAULIC ANALYSIS

The thermalhydraulic analysis is performed to calculate the time required to boil the water in the endshield following a loss of flow event. This analysis also provides transient pressure, velocity and temperature fields of the endshield flow prior to boiling. For the analysis the general purpose fluid flow heat-transfer code PHOENICS [Reference 1] is used, which solves the 3D Navier Stokes equations using the finite domain method. The code has the ability to perform a 3D transient analysis of the complex endshield geometry by using body fitted co-ordinates. Two analyses have been performed

i) A steady state analysis with forced flow for normal operating conditions.

ii) A transient analysis for the loss of flow event using the steady state solution as the initial condition.

The end point of the transient analysis is the point, when the first boiling anywhere in the endshield occurs.

The computational model (Figure 2) represents the area occupied by endshield water, which is surrounded by the two tubesheets, their extensions and the outer endwall shell. The endshield shell, the inner endwall shell and the stiffeners between the inner endwall shell and outer endwall shell are modelled using the porosity feature of PHOENICS, which effectively prevents a flow through that area. The space occupied by the steel balls and lattice tubes is also modelled using the same feature. The internal arrangements and flow paths in the endshield are shown in Figure 1.

4.0 THERMAL ANALYSIS

The temperature distribution within the structure is obtained by performing a steady state thermal analysis of the endshield at selected times after the loss of flow using the thermalhydraulic transient results. The finite element code ANSYS [Reference 2] is used for this analysis. The analysis is performed with the following two models

LOCAL MODEL

This is the model (Figure 3) of a single fuel channel with the tubesheets (up to half lattice pitch) attached to it. The model includes the endfitting, the calandria tube extension (CTX), the lattice tube, the CO_2 annulus between the endfitting and CTX and D_2O annulus between the CTX and lattice tube. The aim of the analysis is to calculate the rise of temperature of the tubesheet region surrounding a fuel channel due to heat transfer from the hot primary coolant and due to heat generated within the fuel channel by direct nuclear heat deposition. The geometry of all fuel channels is identical. However, as the boundary conditions for each of the fuel channels are different, because

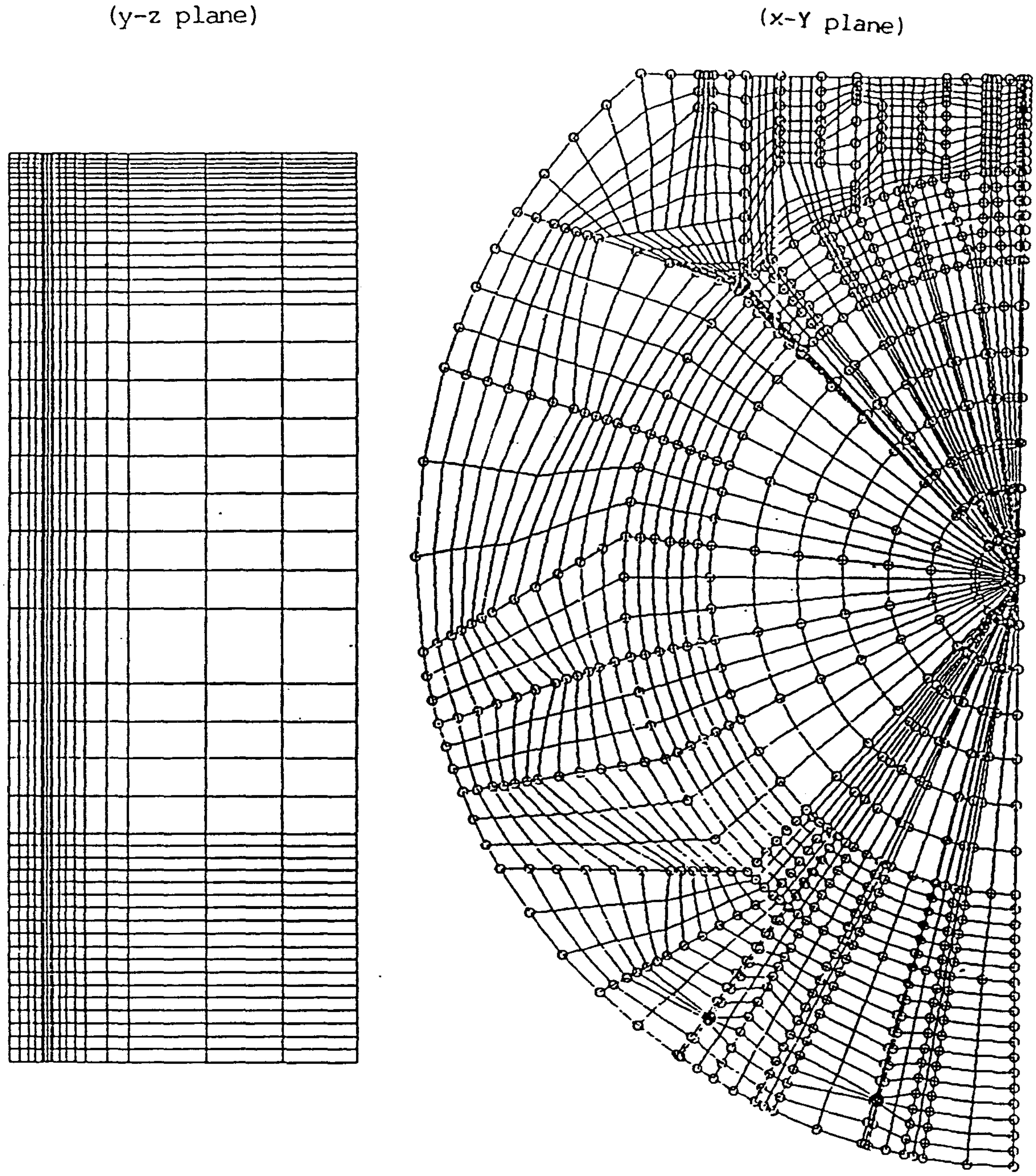


FIGURE 2 - MODEL FOR THERMAL HYDRAULIC ANALYSIS - ENDSHIELD AND ENDWALL

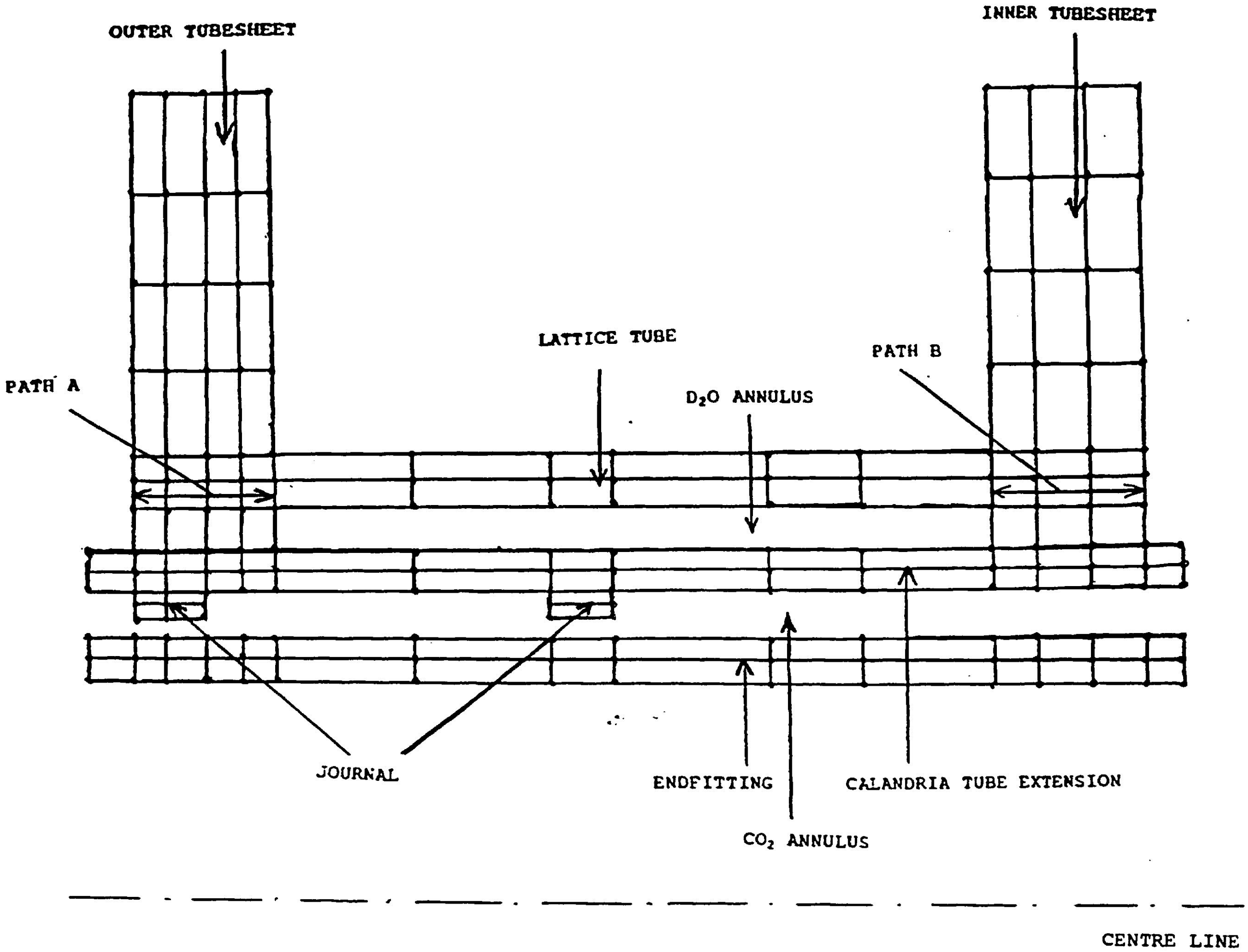


FIGURE 3 - LOCAL MODEL FOR THERMAL ANALYSIS - SINGLE FUEL CHANNEL

of differences in endshield water velocities and temperatures and difference in nuclear heating, the analysis is repeated for nine selected fuel channels. For other locations the rise of temperatures of the attached tubesheets can be obtained by linear interpolation.

GLOBAL MODEL

This 3D model (Figure 4) consists of the inner tubesheet, outer tubesheet, endshield shell and inner endwall shell. Since for the calculation of stresses in the endshield, the temperature distribution within the fuel channels are not required, they are reduced to one dimensional bars between the tubesheets. Their thermal influence, i.e., the heat transferred to the tubesheets from the heat sources inside the fuel channels are calculated in the local model and supplied to the global model as input data. The purpose of the global model is to determine the temperature distribution within the endshield.

Heat transferred from the hot primary coolant through conduction, convection and radiation and nuclear heat generated through neutron and gamma absorption by the fuel channels and by the endshield structure are calculated as follows:

Conduction. Conduction takes place through the endfitting, calandria tube extension, lattice tube and the two tubesheets. Fourier's law is used for the calculation of heat flow rate by conduction as follows :

$$\dot{Q} = K * A * dT/t \tag{1}$$

where $\dot{Q}$ = heat flow rate

K = thermal conductivity
A = cross-sectional area
dT = temperature difference
t = thickness

Although the fuel channels are not exactly axisymmetric, 2D axisymmetric elements having 2D thermal conductivity are used for the conduction simulation.

Convection. Free convection is present outside the outer tubesheet (air) and inside the endshield due to loss of flow (water). Forced convection is present outside the inner tubesheet (D_2O moderator inside the calandria shell) and inside the endftting (primary coolant).

Newton's law of cooling as given below is used for the calculation of heat flow rate by convection :

$$\dot{Q} = h * A * dT \tag{2}$$

The heat transfer coefficient h is calculated from the geometry and from the velocity and temperature of the surrounding medium using empirical equations.

Radiation. Radiation is present in the CO_2 and D_2O annuli between the surfaces surrounding the gases. Since CO_2 and D_2O in gaseous state absorb and emit radiation, the radiation between the gases and the surrounding surfaces are also included in this analysis.

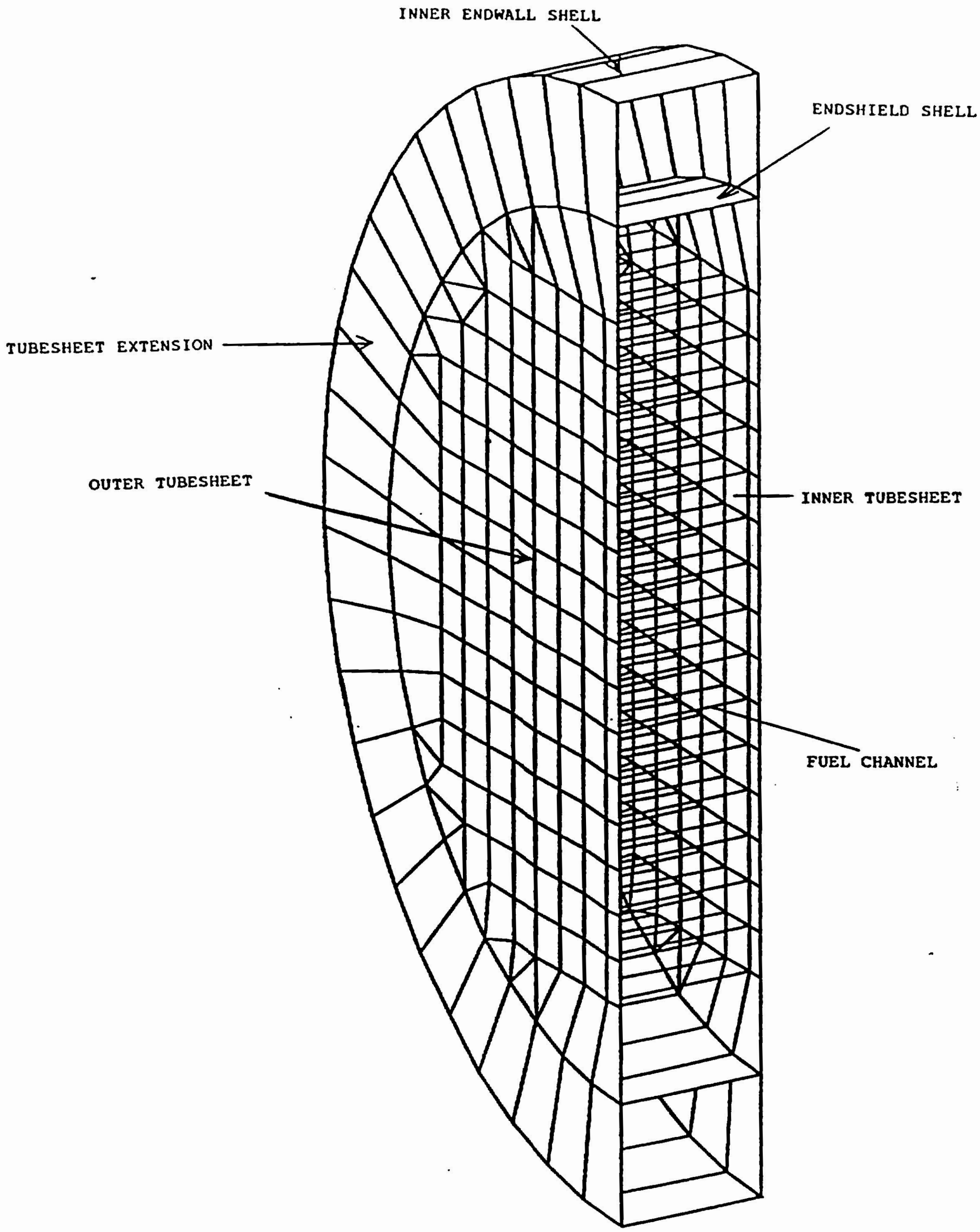


FIGURE 4 - GLOBAL MODEL FOR THERMAL ANALYSIS - ENDSHIELD

The Stefan-Boltzmann law is used to calculate the energy radiated per unit time per unit area as follow :

$$\dot{E}=e*s*F*(T1^4-T2^4) \tag{3}$$

where $\dot{E}$ = energy radiated per unit time per unit area

e = emissivity
s = Stefan-Boltzmann constant
F = form factor
$T1$, $T2$ = absolute temperatures

Nuclear heating. The heat generated by the absorption of neutron and gamma radiation are calculated separately and supplied to this analysis as input data. The amount of nuclear heat depends on the position of the fuel channel. Fuel channels in the middle of the tubesheets generate more heat than those near the endshield shell.

5.0 DISCUSSION OF RESULTS

From the thermalhydraulic analysis, pressure, velocity and temperature fields are obtained. The steady state case (normal operating condition) shows that in the middle of the endshield the water flows upwards. It also indicates that the flow is well distributed with no stagnation zones. Close to the sides, the flow is in the opposite direction indicating circulation within the endshield. The temperature field shows a maximum temperature of 73°C at the top of the endshield below the endshield shell.

The transient thermalhydraulic analysis indicates that during loss of forced flow in the endshield the magnitude of the velocity of water decreases roughly by a factor of 5. The flow of water is from bottom to top. Since there is no flow of water through the inlet, the flow in the endshield is due to buoyancy effects resulting from density differences of hot and cold water. As time progresses, there is a slight increase in the maximum velocity due to the effect of larger temperature gradient. But there is not enough natural circulation between the endshield and the shield tank, since the outlet openings are small. As a result the temperature of the endshield water rises continuously. Figure 5 shows the rise of temperature as a function of time. Extrapolation of this curve indicates that the water will boil after about 5.6 minutes. This value is very conservative, since the heat storage capacity of the steel balls and the heat transfer through the internal walls and the boundary walls are not included in the analysis. By including these effects, the time to boil increases to more than 16 minutes.

The subsequent thermal analysis provides the temperature distribution within the structure. The local model shows that heat is transferred from the primary coolant to the endshield water mainly through conduction. The radiation effect is small as the primary coolant is not very hot. Also the CTX acts as a radiation shield. The temperature distribution calculated along the path A and B (Figure 3), where the tubesheets meet the fuel channel, are linearized and used as input to the global model.

The results obtained from the thermal analysis of the global model show that for the inner tubesheet the highest temperature is at the centre of the tubesheet (Figure 6). The reason is that the fuel channels in the centre of the tubesheets generate several times more neutron and gamma radiation than the channels near the endshield shell. As a result heat deposited in the middle of the inner tubesheet is higher than that at the outer edge,

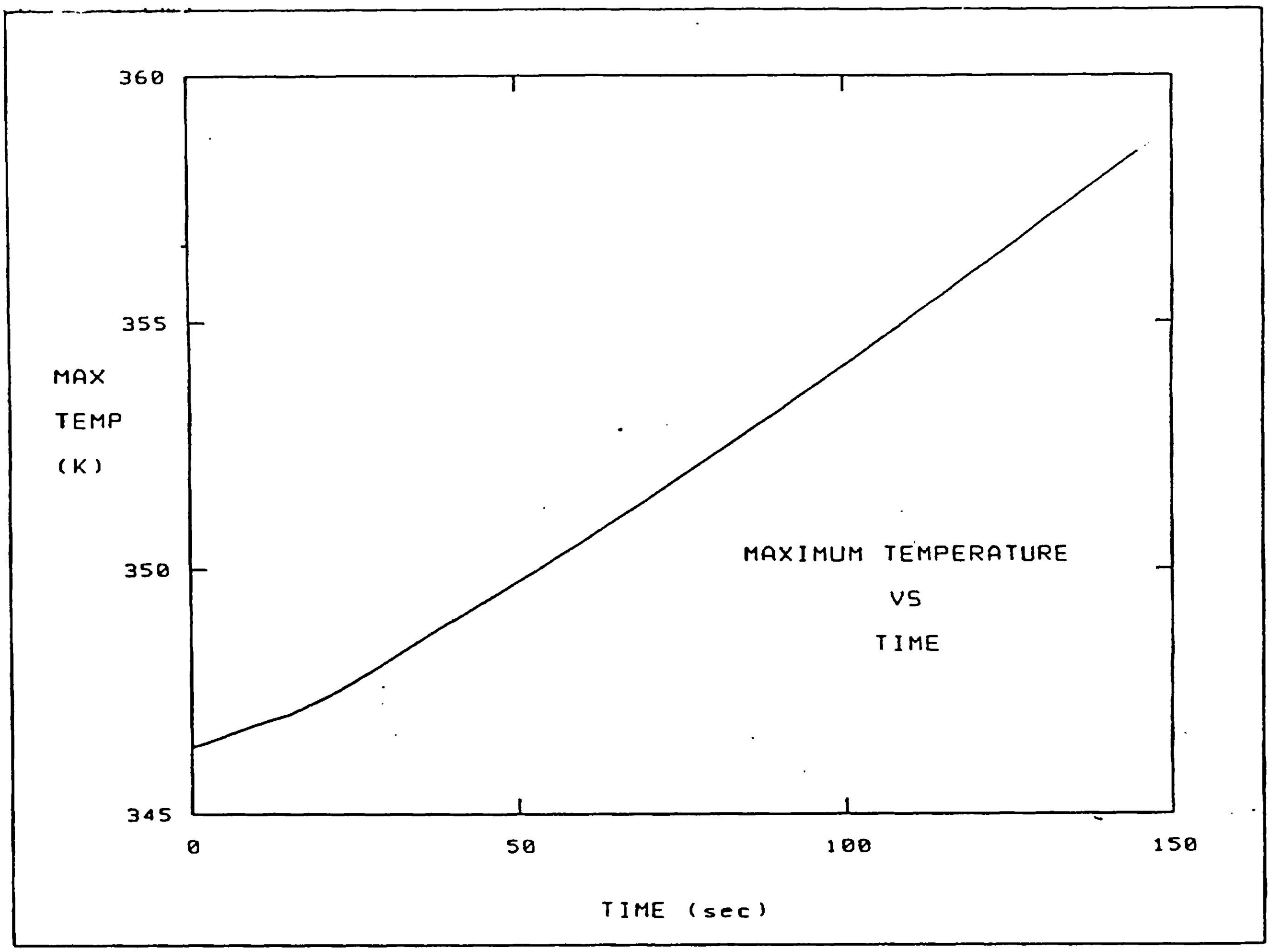
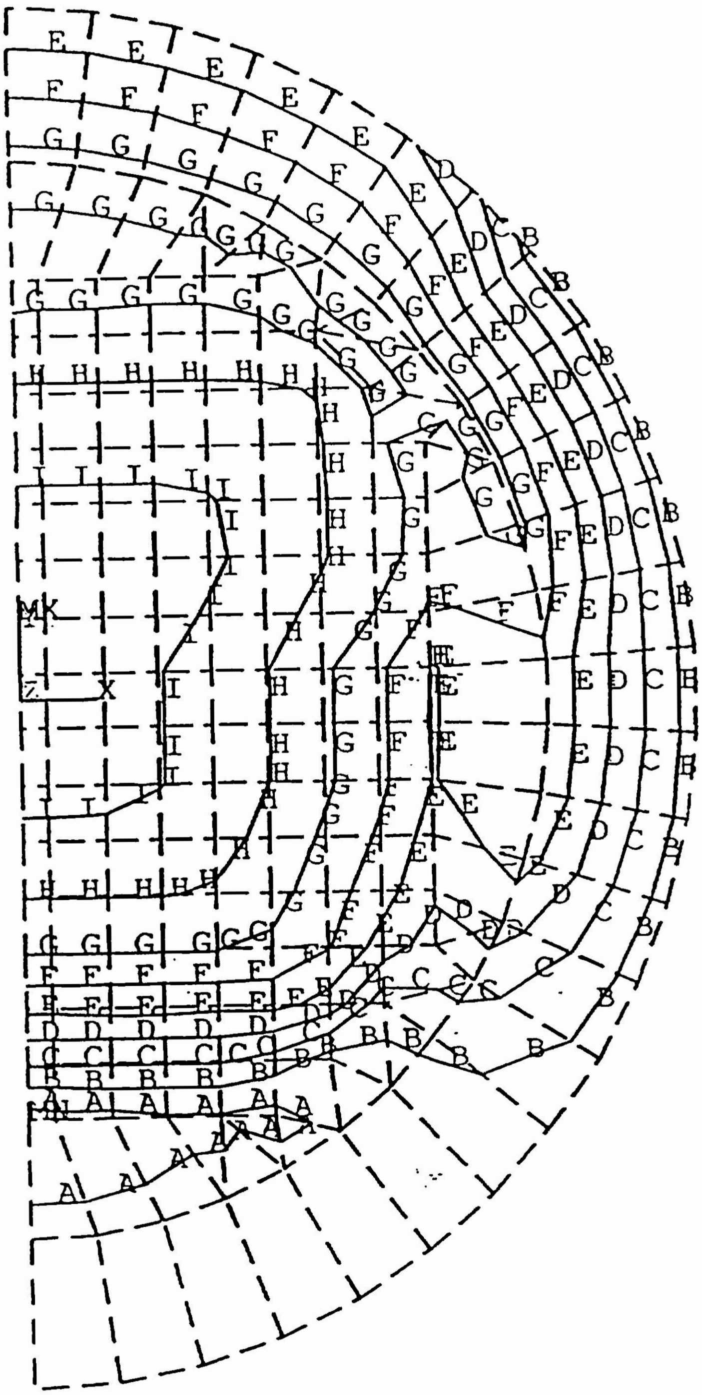


FIGURE 5 - MAXIMUM TEMPERATURE OF WATER IN THE ENDSHIELD AND ENDWALL AS A FUNCTION OF TIME



A =85.53
B =89.338
C =93.146
D =96.954
E =100.763
F =104.571
G =108.379
H =112.187
I =115.996

TEMPERATURES ARE IN ^{o}C

FIGURE 6 - TEMPERATURE DISTRIBUTION - INNER TUBESHEET

influencing the temperature distribution of the inner tubesheet. For the outer tubesheet the highest temperature zone is at the top of the tubesheet (Figure 7), where the endshield water has the highest temperature. The nuclear heating for the outer tubesheet is negligible, as the neutron and gamma radiation are completely absorbed by the inner tubesheet and the steel balls.

6.0 CONCLUSIONS

For the purpose of design assist, thermalhydraulic and thermal analyses have been performed for a loss of endshield flow event to calculate the temperature distribution in the endshield of the CANDU-3 reactor. The analyses indicate that due to inadequate heat removal by natural convection in the endshield the water will boil after 16 minutes with the given configuration. Operator action will be required before this time to prevent boiling in the endshield. Both the tubesheets show a temperature gradient. For the inner tubesheet the gradient is mainly due to the nuclear heating but for the outer one it is due to the temperature gradient of the endshield water. The result of the thermalhydraulic analysis is intended to be used for the optimization of the endshield configuration for improvement of margin to boiling. The temperature distribution obtained from the thermal analysis will be used for the stress analysis of the reactor vessel to determine its structural integrity.

7.0 REFERENCES

[1] ROSTEN, H.I. and SPALDING, D.B., "PHOENICS - Beginner's Guide and Users Manual", CHAM Report Number TR/100. CHAM Ltd., Bakery House, 40 High Street, Wimbledon, London.

[2] DESALVO, G.J. and GORMAN, R.W., "ANSYS Engineering Analysis System - User's Manual", Rev. 4.4, Issued 1989 May 1, Swanson Analysis System Inc.

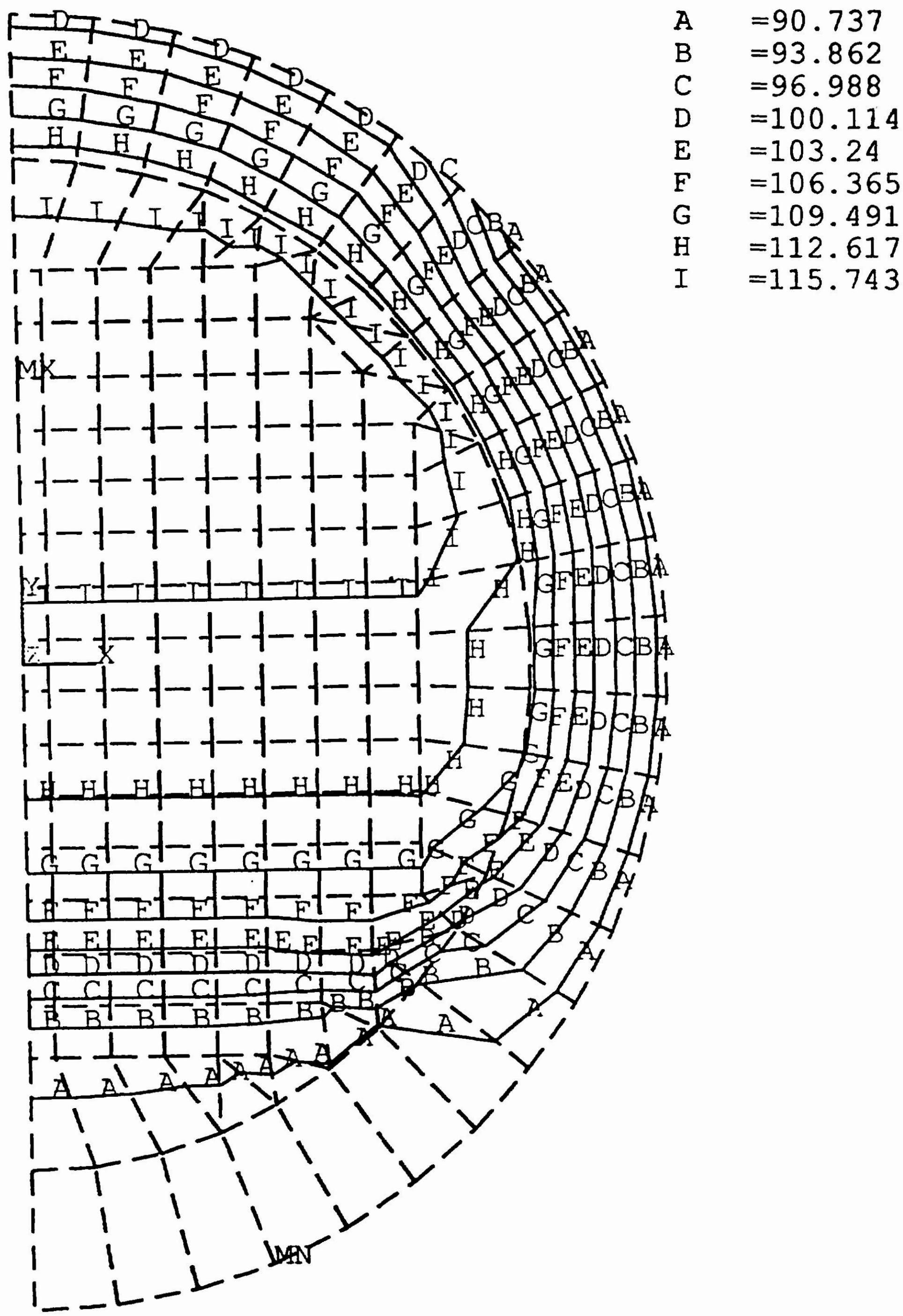


FIGURE 7 - TEMPERATURE DISTRIBUTION - OUTER TUBESHEET