THERMAL ANALYSIS OF GUARDED PENETRATION ASSEMBLIES IN A REACTOR CONTAINMENT AND COOLING-COIL REQUIREMENTS

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SUMMARY

An improved non-linear method of heat-transfer analysis has been developed to evaluate temperature distributions across the penetration assembly system of the BWR containment drywell wall. The method of analysis utilizes steady-state heat energy balance across the entire assembly consisting of a process pipe at high temperature (600°F), an insulation layer, bellows, guard-pipe sleeve assembly and intermediate air gaps. The heat energy balance accounts for conduction through process-pipe, insulation layer, guard-pipe as well as natural convection (equivalent conduction) and radiation through interposed air layers. The energy reaching cylindrical concrete penetration is conducted through the wall, ultimately dissipating into the ambient environment at a uniform temperature level of 120°F on the outside faces of drywell wall. The heat energy balance utilizes a system of non-linear equations expressed in terms of unknown temperatures in the insulation layer, guard-pipe wall, two annular air layers and the concrete containment wall.

Using two-dimensional formulation conduction in axisymmetric solids is readily expressed in unknown temperatures and the geometric and physical characteristics. While the radiation effects across the annular air layers are conventionally expressed in fourth-order temperature terms, the convection (rather equivalent conduction) through air is formulated using Beckmann's and Jakob's techniques based on well-known Grashof's numbers. This method facilitates computing conductive properties of trapped air layers at higher temperatures. Similarly heat balance across the concrete wall is formulated in terms of temperatures and film coefficient across the wall faces. As a measure of simplification, the containment wall is assumed extended to infinite distance from the penetration point. The entire steady-state analytical modeling leads to a formulation of a system of a set of non-linear equations in unknown temperatures, which can be solved by trial-error method. The properties of air are computed at assumed temperature and revised till the solution to the equation converges.

The method of problem formulation, analytical modeling and corresponding solution procedure have been adapted to proprietary computer code "PENTHERM" in which a number of guard-pipe sleeves and air layers may be introduced arbitrarily. The overall steady-state heat balance equations across the entire system are formulated. The solution technique assures stability and fast convergence, yielding unknown temperatures which are then utilized to evaluate the cooling-coil requirements for the overheated drywell wall keeping the allowable concrete temperatures to 200°F. The method of matrix formulation, initialization and trial-error solution yields a perfect close-form solution to otherwise an extremely complex problem. The initialized temperatures enable computing approximate properties of air, revising repeatedly till convergence is attained.

1. Introduction

In nuclear power plants penetration assemblies are generally provided to protect and guide the mechanical piping systems and electrical conduits through the containment and drywell walls. The piping systems convey fluids at excessively high temperatures and despite proper insulation the surroung concrete walls are overheated causing unwanted cracking. It is the purpose of this paper to determine the amount of heat removal from the guarded penetrations such that the temperatures in the surrounding concrete is limited to permissible levels. The mechanical piping systems that have been identified as being critical and analyzed herein, are the feedwater and mainsteam lines of a BWR system penetrating thru the drywell and containment walls. The mainsteam line for instance conveys the fluid at a substantially high temperature in the vicinity of 650°F. By merely insulating the piping system at the penetration point, temperatures will far exceed the recommended concrete values as per ASME Boiler & Pressure Vessel Code Section III.

Therefore due to safety considerations and to prevent thermal cracking in concrete, heat is removed by a device called cooling coils. It is recommended that these coils be designed and placed axisymmetrically around the penetration assemblies. In the present analysis, the permissible concrete temperature is limited to 200°F and based on this consideration, a thermal analysis is performed considering conduction, convection and radiation effects in the assembly for the heat removal.

2. Problem Formulation & Method of Analysis

The insulated piping system consisting of main steam or feedwater lines as illustrated in Figs. 1 and 2, conveys a heat flux at high temperature T_o, which gradually dissipates to T_w in the insulation layer, T_G in the surrounding axisymmetric Guard-pipe and finally to T_c in the Bellows-Sleeve embedded in the concrete wall. The interposed air-gaps G_1 and G_2 between the process-pipe and Guard-pipe, as well as the Guard-pipe and Bellows-Sleeve, attain mean temperatures of T_{A1} and T_{A2} respectively. As illustrated in the Figs. 2 and 3, the steady state heat energy 'Q_o' of the fluid in the process-pipe, being conducted thru the pipe wall, radiating and convecting thru the intermediate air-gaps, is ultimately conducted away to the concrete wall. The heat energy 'Q_c' conducted thru concrete finally dissipates into the atmosphere thru the film coefficient 'h' at the ambient temperature 'T_A' on both faces of the wall.

Depending upon the mean temperatures in the coaxial air-gaps, the conducting properties of air can easily be evaluated as explained by Holman (1) and Jakob (2). Defining the steady-state quality of heat-energy passing thru the insulation layer as 'Q_w', amount of radiation thru each air-gap as 'Q_{Ri}' (i = 1, 2) and corresponding conduction, based on equivalent conduction of air in coaxial cylinder as outlined in references (1, 2, 3, 4, 5) as 'Q_{Ai}' (i = 1, 2), the equilibrium conditions in the system can be established as:

$$Q_o = (Q_{Ai} + Q_{Ri}) \qquad (1)$$
$$i = 1,\ 2$$

$$Q_w = Q_o \qquad (2)$$

Where: $Q_w = \gamma_e\ (T_o - T_w)$ in which insulation conductivity coefficient γ_e may be expressed as:

$$\frac{1}{\gamma_e} = \frac{\ln\left[1 + \frac{Ri}{(Ri-t)}\right]}{2\pi K_s\ L_D} + \frac{\ln\left[1 + \frac{W}{Ri}\right]}{2\pi K_w\ L_D} \qquad (3)$$

In the above equation, R_i = inside pipe radius, t = wall thickness of the pipe, W = thickness of insulation layer, K_s = conductivity of steel pipe, K_w = conductivity of insulation layer and L_D = length of insulation layer. The quantity of heat 'Q_G' as conducted through the Guard-pipe wall and that transmitted thru the concrete wall as 'Q_c' to the ambient atmosphere may also be related as:

$$Q_G = Q_c \qquad (4)$$

Where: $Q_G = \gamma_g\ (T_{A1} - T_G)$ and γ_g = an equivalent conductivity coefficient of Guard-pipe wall and may be expressed as:

$$\gamma_g = \frac{2\pi K_s\ L_D}{\ln\left[1 + \frac{R_g}{R_g - t_g}\right]} \qquad (5)$$

Assuming no loss or gain of heat at the interfaces between the Guard-pipe wall and enclosed air-gaps, the steady state equilibrium suggests that:

$$Q_G = (Q_{A1} + Q_{R1}) = (Q_{A2} + Q_{R2}) = Q_c \qquad (6)$$

Assuming further that the drywell wall extends to an infinite distance (α) from the penetration, the conduction of heat transfer in an axisymmetric opening may be expressed as:

$$\left\{ r^2\ \frac{d^2}{dr^2} + r\ \frac{d}{dr} - N_c^2\ r^2\theta \right\} = 0 \qquad (7)$$

where: $\theta = (T_r - T_A)$ and $N_c = \left[\frac{2h}{K_c L_D}\right]^{\frac{1}{2}}$, in which

T_r = unknown temperature at a radial distance r,

h = air film coefficient, K_c = conductivity of concrete and

L_D = length of the penetration opening. It may be shown that solution to Eqn. (7) can be expressed in terms of Bessel coefficients K_o and K_1, and finally 'Q_c' as:

$$T_r = \left\{ T_c + T_A\ \left(1 - \frac{K_1\ (N_c r)}{K_o\ (N_c R_o)}\right) \right\} \qquad (8)$$

$$Q_c = (2\pi R_o\ K_c\ L_D)\ \left(\frac{dT_r}{dr}\right)_{r\ =\ R_o} \qquad (9)$$

Equations (8) and (9) can be grouped together and rewritten in the following form.

$$Q_c = (2\pi R_o N_c K_c L_D)\ (T_c - T_A)\ \frac{K_1\ (N_c R_o)}{K_o\ (N_c R_o)} \qquad (10)$$

or briefly: $Q_c = \nu(T_c - T_A)$

3. Evaluating Heat Transfer Quantities Q_{Ai} and Q_{Ri}

Using steady-state equilibrium conditions, it now remains to express air-gap conduction and radiation quantities 'Q_{Ai}' and 'Q_{Ri}' respectively in terms of physical characteristics of air medium to solve for the unknown temperatures T_w, T_{A1}, T_G, T_{A2} and T_G. For simplification and without any loss of accuracy, it may also be assumed initially that:

$$T_G = T_{A2} = T_c \tag{11}$$

The free convection of air (usually termed as an equivalent conduction of air at high temperatures) enclosed in the annular gaps of horizontal coaxial cylindrical tubes has been investigated experimentally by Beckmann (3) and corresponding results are summarized by Jakob (2). With this method, the quantity of heat convected thru the air gap may be expressed as:

$$Q_{Ai} = \frac{2\pi K_{ea}\,\phi\, L_D\,(\Delta T_{Ai})}{\ln\,(R_o/R_i)} \tag{12}$$

$$i = 1,\ 2$$

Where: K_{ea} = equivalent conduction of air, heat flux $\phi(R_o/R_i,\ N_{GR})$, R_o and R_i = the outer and inner radii respectively and N_{Gr} = Graschof number. The radiation thru the coaxial air-gaps may also be expressed as:

$$\begin{aligned} Q_{R1} &= \zeta_1\,(T_w^{\ 4} - T_G^{\ 4}) \\ Q_{R2} &= \zeta_2\,(T_G^{\ 4} - T_c^{\ 4}) \end{aligned} \tag{13}$$

Where: ζ_i = coefficient of radiation of ith air-gap. From equations (11), (12) and (13), steady state heat-balance across each air-gap may be expressed as:

$$\eta_i\,(\Delta T_i) + \zeta_i(\Delta T_i^{\ 4}) = \nu_i\,(T_c - T_A) \tag{14}$$

$$i = 1,\ 2$$

4. Numerical Solution of Non-Linear Equations

The equations (6), (13), (14) are non-linear in nature and may be solved iteratively by assuming $T_w = T_G = T_c$ in Eqns. (13, 14) and then solving approximately for unknown temperatures T_{A1} and T_{A2} at which air-gap properties ν_i and η_i as well as film-coefficient 'h' are initially determined. Equations (14) are solved by trial-and-error to yield unknown temperatures T_G and T_c, which can be reused and process repeated itertatively till an exact heat-balance is obtained across each air-gap, knowing correct air properties and corresponding coefficient ν_i, N_{Gr} and η_i. Once the accurate temperatures T_w, T_{A1}, T_G, T_{A2} and T_c are determined, it may be shown that quantity of heat to be removed from the concrete wall by cooling can be expressed as:

$$Q_E = \left|\eta_2\,(T_G - T_{mc}) + \zeta_2\,(T_G^{\ 4} - T_{mc}^{\ 4}) - \nu_2\,(T_{mc} - T_A)\right| \tag{15}$$

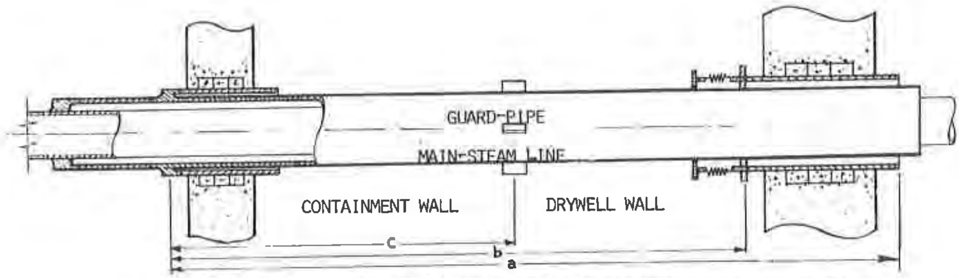

FIG. 1 PENETRATION ASSEMBLY FOR MAIN-STEAM LINE BETWEEN CONTAINMENT WALL AND DRYWELL WALL FOR MARK-III-BWR

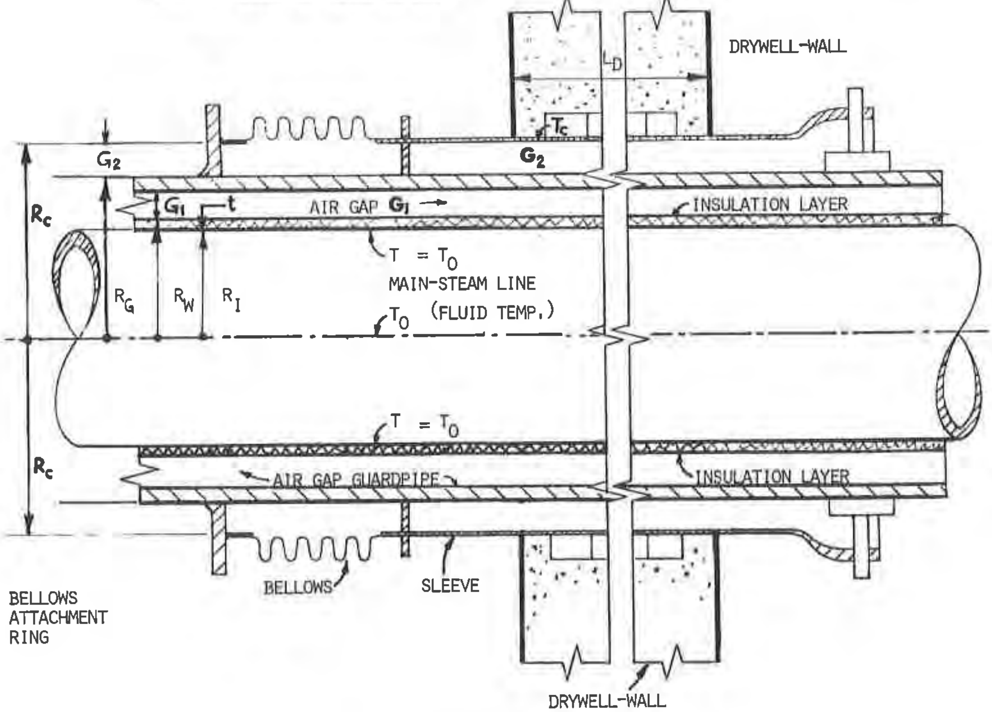

FIG:2 SCHEMATIC DETAILS OF THE PENETRATION ASSEMBLY AT THE DRYWELL WALL SIDE.

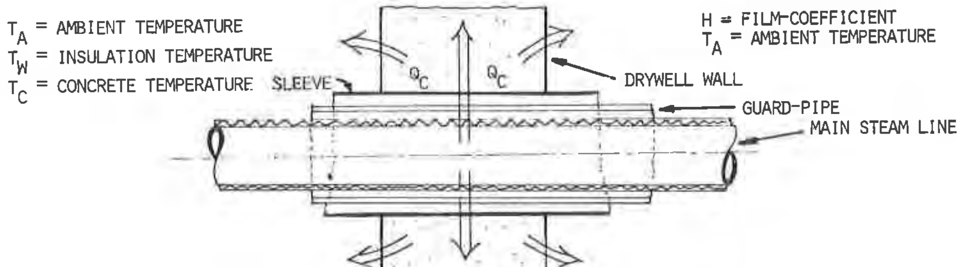

FIG:3 MATHEMATICAL MODEL FOR THE HEAT-TRANSFER ANALYSIS.

in which all quantities are known and T_{mc} = maximum allowable concrete temperature (usually $150^{\circ}F$ to $200^{\circ}F$) and T_A = ambient temperature (usually $120^{\circ}F$). For the numerical problems dealing with penetrations under consideration, an estimate of different temperatures and cooling capacity of the coils can easily be made. This is illustrated for 4 such penetrations in the Table 1, below.

Table - 1: Typical Penetrations and Application to Numerical Problems

No:	Pipe O.D. (inch.)	Fluid Temp. T_o ($^{\circ}F$)	Insulation Thickness (inch.)	Guard Pipe (inch.)	Sleeve O.D. (inch.)	Quantity of Heat Removal From Concrete Wall Btu/Hour
1	24.0	550	3.0	36.0	48.0	3,058
2	20.0	425	2.5	38.0	50.0	1,452
3	18.0	552	3.0	34.0	48.0	2,680
4	8.625	550	3.0	24.0	36.0	2,200

5. Discussions & Conclusion

The purpose of this investigation has been to develop an accurate thermal analysis capability for penetration problems, which can be reliably and efficiently utilized to evaluate amount of heat transfered to the drywell wall. Formulation of an exact set of heat transfer equations and method of analysis have shown both accuracy and quality of results as well as ease and suitability in adapting to digital programing. The set of non-linear equations dealing in unknown temperatures could be easily solved by reduction and trial-and-error. The use of present technique has demonstrated that inclusion of an equivalent conduction of air in the gaps, based on Graschof's numbers, leads to an extraordinary accuracy in simulating the amount of heat on the wall and corresponding excessive quantity to be extracted by cooling coils. The methodology is exact in nature and has been adapted to check complicated penetration geometries otherwise analysed by finite-element techniques. This method can be modified (ref. 5) for transient cases.

6. References

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