Design Features

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A Scheme for Passive Isolation of the Containment of a Reactor

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Abstract: *Release of radioactivity to the environment in the event of an accident in a reactor can be limited if the containment maintains structural integrity and the isolation system functions properly. A passive isolation scheme will reduce the risk further. This article proposes a passive isolation scheme for an Indian pressurized heavy-water reactor. The scheme works by creating water seals in the ventilation duct when the pressure in the containment rises after an accident. Formation of the seals is studied by solving the one-dimensional hydrodynamic equations. Results are presented for various assumed geometrical and hydraulic parameters and pressure transients in the containment.*

The current generation of pressurized heavy-water reactors (PHWRs) in India employs a double containment with a vapor suppression pool (Fig. 1). The inner primary containment is surrounded by the outer secondary containment. One of the major objectives of the containment and its associated engineered safety features is to control the release of radioactivity (at the ground level as well as through the stack) within the permissible limit both during normal operation and under accident conditions. The containment is designed to withstand the effects of the loss-of-coolant accident (LOCA) and the main steam line break accident (MSLBA). The effects of these accidents are to release, in varying degrees, high enthalpy steam and radioactivity into the containment. The possible paths of release to the environment are shown in Fig. 2.

The release to the environment is reduced by (1) limiting the pressure and temperature in the containment by vapor suppression pool and building coolers; (2) retention of a very large fraction of radioactivity in the suppression pool water and through the use of various filters and pump back systems; and (3) providing physical barriers by way of the primary containment structure, the secondary containment structure, and the containment isolation system. The containment structures are designed to withstand the design basis accident-induced pressure and temperature and maintain a certain degree of leak tightness.[1]

Further, the containment is designed to isolate automatically by closing all the three valves in series in each of the ventilation inlet and exhaust ducts on sensing any of the following: (1) pressure rise in the primary containment, (2) increase in the radioactivity level above a preset limit in the ventilation exhaust duct, and (3) initiation of the emergency core cooling injection.

The electric supply for the instrumentation associated with containment isolation comes from class II (i.e., noninterruptible a-c) power supply. For pneumatically operated devices in the containment isolation system, local air receivers of sufficient capacity are provided. Both the logic and the actuator systems incorporate fail-safe features. It is recognized that so long as the containment maintains structural integrity and the leakage rate does not increase beyond the acceptable

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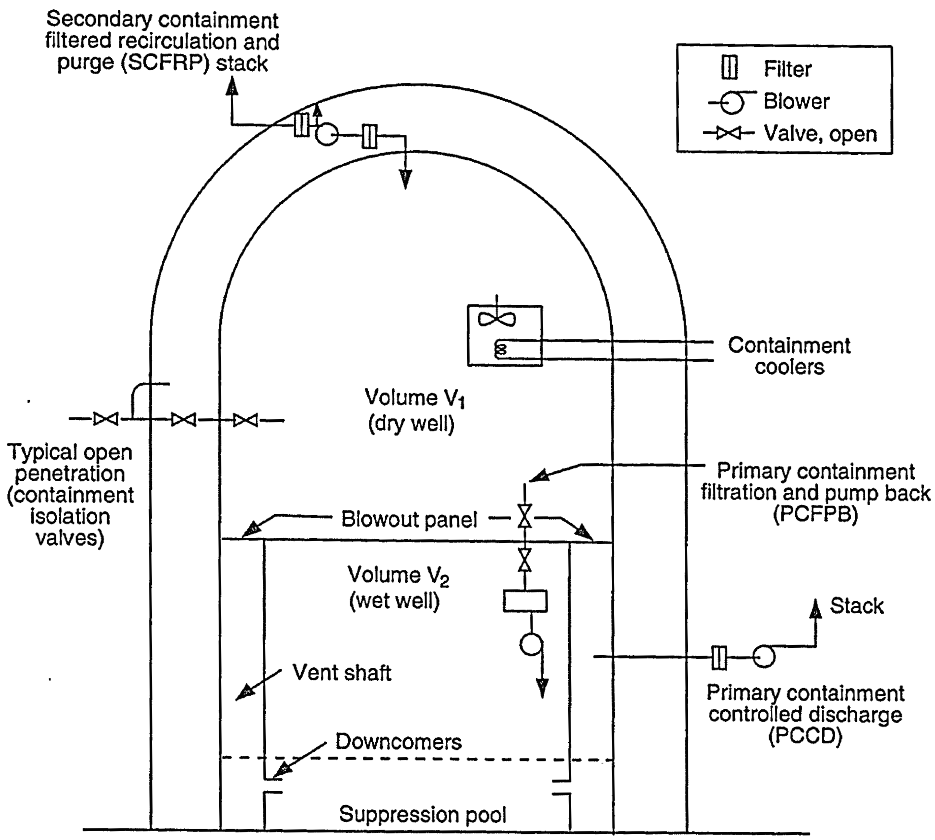

Fig. 1 Schematic of containment and associated safety features.

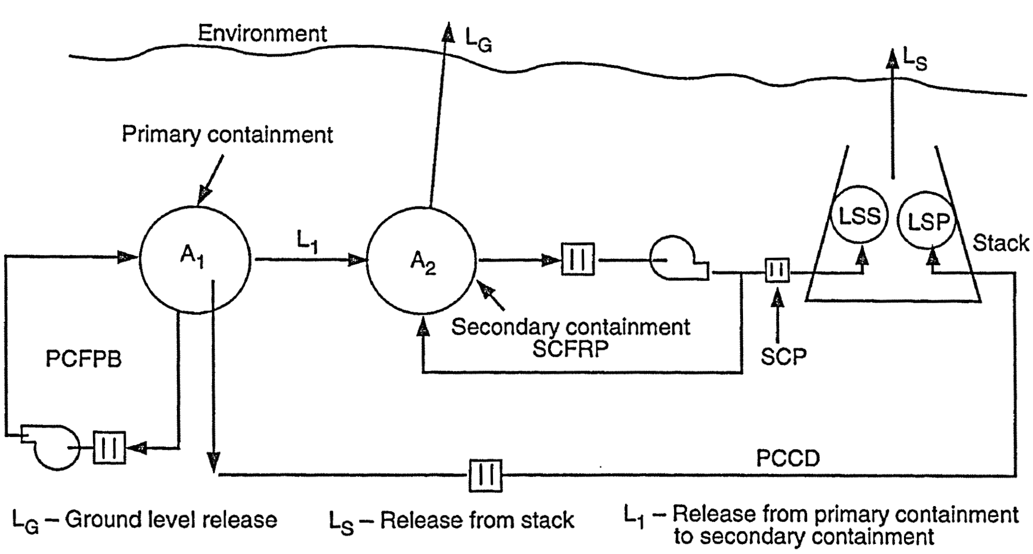

Fig. 2 Double containment-activity release pathways. PCFPB, primary containment filtration and pump back; PCCD, primary containment controlled discharge; SCFRP, secondary containment filtered recirculation and purge; LSS, release from stack as the result of secondary containment; and LSP, release from stack as the result of primary containment.

limit, containment isolation would ensure that there would be no further release of radioactivity to the environment even in the event of an accident. However, in the existing design the basic isolating device (i.e., the valve) is an active component. Thus, despite redundancy, the system remains vulnerable to failure. A reliability analysis carried out indicates that the probability of failure of containment isolation is 2×10^{-4} (Ref. 2). The large volume of the containment of the Indian PHWRs—a necessity from layout consideration—and diverse systems to ensure heat removal from the core over a fairly long period reduce the overall risk to the containment integrity as the result of hydrogen or accidental pressure load.[2,3] Thus improvement in the isolation system through the use of a passive device rather than an active one will be an important step toward limiting the spread of radioactivity in the public domain.

This article presents a scheme for passive isolation of a typical containment system as described previously.

THE PROPOSED ISOLATION SCHEME

The primary containment can logically be divided in two volumes, V_1 and V_2. The high enthalpy systems are housed in V_1, whereas the rest are housed in V_2. V_1 and V_2 are separated by leak-tight walls and floors and are connected during a LOCA or MSLBA through the suppression pool. The ventilation system remains connected to V_2 during normal operation. During an accident, steam and radioactivity, if any, are released to V_1. From V_1 they are transported through the suppression pool (where the steam is condensed), and the air, still containing some activity after scrubbing in the pool, gets into V_2.

Following an accident, the pressure, p_1, in V_1 rises first and increases above the atmospheric pressure, p_a. The rise in p_1 causes the flow to be driven to V_2 through the vapor suppression pool. This causes an increase in the pressure p_2 in V_2. However, it is evident that in the initial phase p_2 will be lower than p_1 by at least the hydrostatic pressure corresponding to the depth of submergence of the downcomer in the suppression pool. A typical pressure transient following a LOCA is shown in Fig. 3 (Ref. 1). In due course of time the pressure p_2 will also be above the atmospheric pressure. It is from this point onward that the isolation system becomes crucial to prevent the spread of radioactivity to the environment.

The passive isolation system is intended to prevent the escape of this air to the environment positively. The proposed scheme is shown in Fig. 4. The line L_2 from

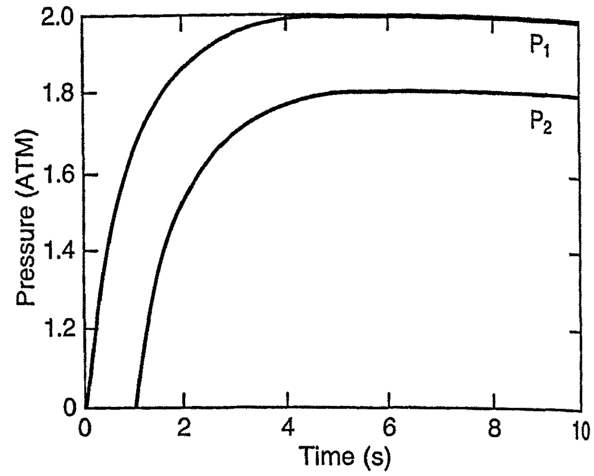

Fig. 3. Typical pressure transient in the containment after a loss-of-coolant accident.

V_2 is a part of the ventilation line, and it is connected to the atmosphere through a long vertical pipe L_1. A U-bend section is provided on the line L_2. L_1 is submerged in a pool of water in tank T_1. The air space above the pool of water in T_1 remains connected to V_1 by a line L_3 and thus is a part of V_1 itself.

Following the rise in pressure p_1 above atmospheric, the water starts rising in L_1. A portion of this water subsequently flows in line L_2 against the pressure p_2. Thus two water columns are created—one in the vertical pipe L_1 and the other in the U-portion of L_2.

For the passive isolation system to be effective, these water columns must be stable, and the pressures in these lines must be such that the air from V_2 cannot escape through the water columns to the atmosphere. The time taken to establish these conditions from the initiation of the accident can be a measure of the efficacy of this system.

From the consideration of static pressure, the height of the water column in L_1 above the junction $(h_4 - h_j)$ should satisfy

$$h_4 - h_j > \frac{p_2 - p_a}{\rho g} \quad \text{when } p_2 \geq p_a \tag{1}$$

further,

$$(h_j - h_2) \leq \frac{p_1 - p_2}{\rho g} \tag{2}$$

From static consideration, the preceding two are necessary conditions for the success of the isolation system.

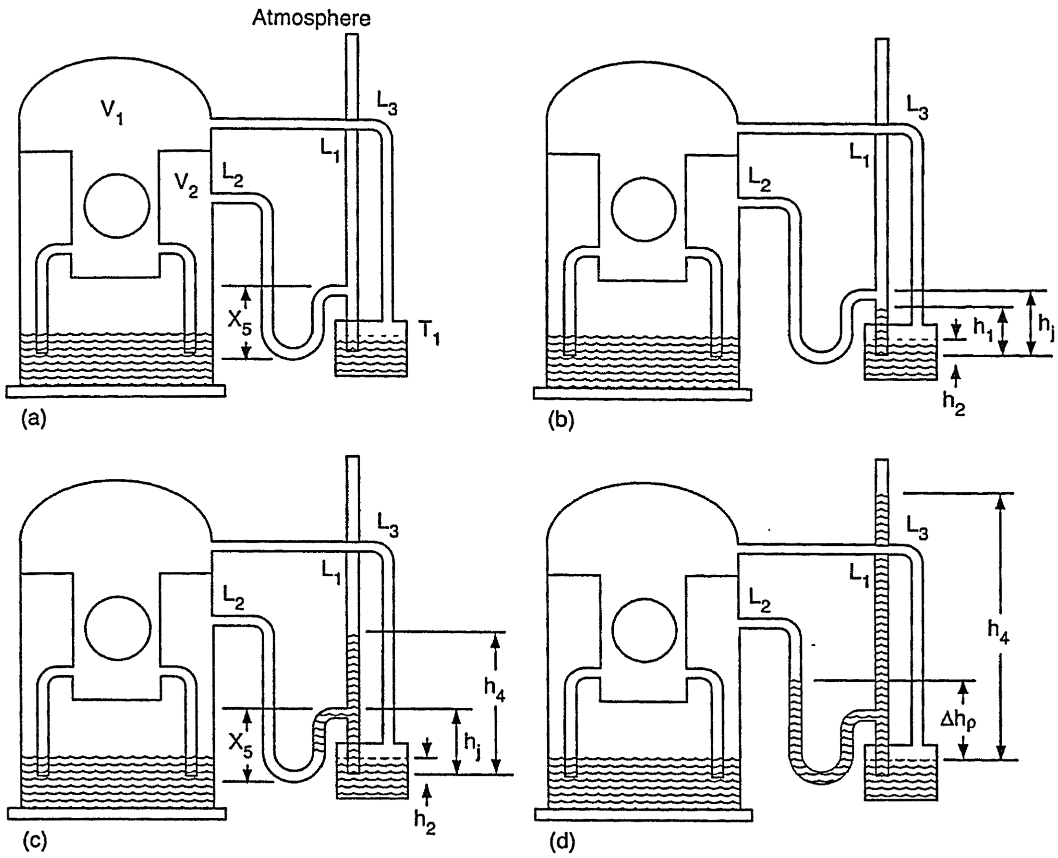

Fig. 4 Schematic passive isolation feature: (a) normal operation, (b) accident condition before flow branching, (c) accident condition after flow branching, (d) accident condition at stable state.

These two equations are valid in the steady state. However, the actual scenario can be predicted only by solving the fluid-dynamic equations. This is elaborated in the next section.

ANALYSIS

The formation of the water columns is analyzed by solving the one-dimensional momentum equation for incompressible flow. For flow of a fluid of density, ρ in the x direction at an angle θ to the vertical, the instantaneous velocity $v(x,t)$ can be obtained from:

$$\frac{\partial v}{\partial t} + \frac{v \partial v}{\partial x} = -\frac{1 \partial p}{\rho \partial x} + g \cos \theta \qquad (3)$$

p includes static pressure and the various losses in the flow path.

The mass flow rate G is given by

$$G = A\rho v \qquad (4)$$

where A is the flow area. Let us first consider the rise of water in the vertical pipe L_1 when p_1 rises above the atmospheric pressure.

Let the area of the tank be A_2 and that of L_1 be A_1. h_1 is the height of the water level in L_1 above the entrance of the pipe (L_1) for $h_1 \leq h_j$; h_2 is the height of the water level in the tank above the entrance of the pipe (L_1); and v_1 and v_2 are the velocities of the fluid in L_1 and in the tank, respectively. Then

$$v_1 = \frac{dh_1}{dt} \text{ and } v_2 = \frac{-dh_2}{dt}$$

where G_1 = mass flow rate in L_1 up to the junction
p_1 = pressure in V_1 acting above the pool surface in the tank
p_j = pressure at the junction of L_1 and L_2
p_2 = pressure in V_2

By continuity,

$$\frac{dh_1}{dt} = \frac{G_1}{A_1\rho} \tag{5}$$

and

$$\frac{dh_2}{dt} = \frac{-G_1}{A_2\rho} \tag{6}$$

Integrating Eq. 3 from region 2 to region 1 and making use of Eqs. 5 and 6,

$$\int_1^2 \frac{\partial v}{\partial t} dx + \frac{1}{2}\left(v_1|v_1| - v_2|v_2|\right) + g(h_1 - h_2) + \frac{p_j - p_1}{\rho} + \frac{K_{12}}{2} v_1|v_1| = 0$$

$$\frac{1}{A_1\rho}\left(h_1 + h_2\frac{A_1}{A_2}\right)\frac{dG_1}{dt} + \frac{1}{2}v_1|v_1|\left(1 - \frac{A_1^2}{A_2^2}\right) + g(h_1 - h_2) + \frac{p_j - p_1}{\rho} + \frac{K_{12}}{2}v_1|v_1| = 0$$

Hence

$$\frac{dG_1}{dt} = \frac{A_1\rho}{\left(h_1 + h_2\frac{A_1}{A_2}\right)}\left\{\frac{p_1 - p_j}{\rho} + g(h_2 - h_1) - \frac{1}{2(\rho A_1)^2}G_1|G_1|\left[K_{12} + \left(1 - \frac{A_1^2}{A_2^2}\right)\right]\right\}$$

$$= \frac{A_1\rho}{(h_1 + h_2 r_1)}\left\{\frac{p_1 - p_j}{\rho} + g(h_2 - h_1) - \frac{1}{2(\rho A_1)^2}G_1|G_1|\left[K_{12} + (1 - r_1^2)\right]\right\} \tag{7}$$

where K_{12} is the coefficient of pressure loss in this section and $r_1 = A_1/A_2$.

Equations 5, 6, and 7 describe G_1, h_1, and h_2 until branching of the flow to the line L_2 takes place at $h_1 = h_j$. Up to this period $p_j = p_a$, where p_a is the atmospheric pressure.

Once the flow branching takes place, h_1 remains constant and the pressure p_j at the junction is decided from the conditions of equilibrium, continuity, and compatibility with the junction pressure.

Let G_3 and G_4 be the mass flow rate in L_2 and in L_1 above the junction, respectively, and h_3 and $(h_4 - h_j)$ be the length of the water columns in these sections of areas A_3 and A_4, respectively ($A_4 = A_1$). Although h_3 is measured from the junction, h_4 is measured from the entrance of L_1. K_{13} and K_{14} are the coefficients of pressure loss in these sections. Then

$$\frac{dh_3}{dt} = \frac{G_3}{\rho A_3} \tag{8}$$

$$\frac{dh_4}{dt} = \frac{G_4}{\rho A_1} \tag{9}$$

$$\frac{dG_4}{dt} = \frac{A_1\rho}{h_4 - h_j}\left[\frac{p_j - p_a}{\rho} + g(h_j - h_4) - \frac{1}{2(\rho A_1)^2}G_4|G_4| - K_{14}\right] \tag{10}$$

$$\frac{dG_3}{dt} = \frac{A_3}{h_3}\rho\left\{\frac{p_j - p_2}{\rho} - gh_3 - \frac{1}{2(\rho A_3)^2}G_3|G_3| \times \left[K_{13} + \left(1 - \frac{A_1^2}{A_3^2}\right)\right]\right\} \quad \text{if } h_3 \leq x_5$$

$$= \frac{A_3}{h_3}\rho\left\{\frac{p_j - p_2}{\rho} + g(h_3 - 2x_5) - \frac{1}{2(\rho A_3)^2}G_3|G_3|\left[K_{13} + \left(1 - \frac{A_1^2}{A_3^2}\right)\right]\right\} \quad \text{if } h_3 > x_5 \tag{11}$$

where x_5 is the length of the shorter arm of the U-tube in L_2 (Fig. 4). By continuity,

$$G_1 = G_3 + G_4 \qquad (12)$$

Equations 5 to 12 are the eight equations in the eight unknowns—G_1, G_3, G_4, h_1, h_2, h_3, h_4, and p_j. These are to be solved simultaneously.

NUMERICAL RESULTS AND DISCUSSION

Equations 5 to 11 are a set of first-order ordinary differential equations of the form

$$\frac{dY_i}{dt} = f_i[(Y), t, C_{ji}] \quad i = 1, 2 \ldots 7 \qquad (13)$$

where (Y) is the vector containing Y_is, and C_{ji}s are various constants. The initial conditions of the variables Y_i are specified. These equations are solved by the fourth-order Runge–Kutta algorithm.

Until the branching of flow takes place at $h_1 = h_j$, the variables involved are G_1, h_1, and h_2 only and $p_j = p_a$, and the solution is straightforward. However, iteration for p_j is necessary subsequently.

For each time step (Δt), a solution is obtained for an assumed value of p_j and the known initial conditions at the beginning of that step. If Eq. 12 is not satisfied, the solution is obtained again, for the same interval, for a different assumed value of p_j. This process is repeated until Eq. 12 is satisfied when the solution proceeds to the next time step.

With the passage of time, the length of the water columns h_3 and h_4 gradually reaches a steady-state value. The time taken for decay of oscillations about this value is more when the overall loss coefficient is lower.

For the pressure transient shown in Fig. 3, a typical level transient is shown in Fig. 5. The various parameters are given in Table 1; h_{10} and h_{20} are the initial values of the variables h_1 and h_2, respectively. The flow resistance for the section ij is designated AK_{ij}. The value of Δt has been chosen to ensure stability and convergence. From Fig. 3 it is seen that p_2 increases above the atmospheric pressure from 1 second after the initiation of the accident. From Fig. 5 it is seen that the water flows consistently in the tube L_2 from about 0.5 second after the accident. Thus the water seal formation is well in time to prevent escape of air from V_2 to the atmosphere for a practical system under consideration.

Defining $h_r = 2x_5 - h_j + h_2$, it is easy to see that in the steady state, $\Delta h_r = h_3 - h_r$ will correspond to the hydrostatic head for the pressure difference $(p_1 - p_2)$. Similarly, in the steady state, $h_4 - h_2$ will correspond to the hydrostatic head for the pressure difference $(p_1 - p_a)$.

Studies have been carried out for varying values of the parameters shown in Table 1.

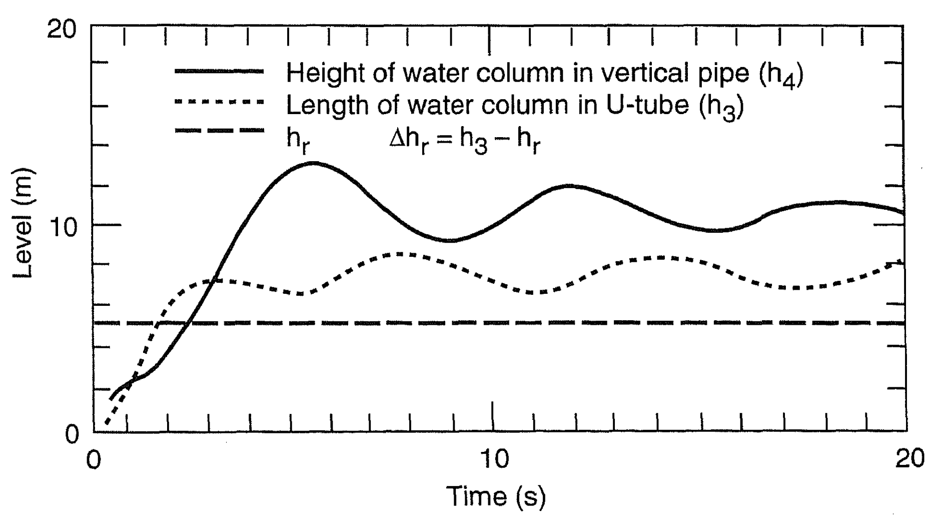

Fig. 5 Level transients in L_1 and L_2: formation of water seal.

Table 1 Parameters Used in Analysis

Value	Parameter				
	h_{10} (m)	h_{20} (m)	h_j (m)	x_5 (m)	A_1 (m^2)
Values for Fig. 5	0.61	0.61	0.91	3.05	0.093
Values for parametric studies	0.61	0.61	0.61, 0.91, 1.22, 1.52	3.05	0.093, 0.186, 0.372, 0.464
	A_2 (m^2)	A_3 (m^2)	AK_{12}	AK_{13}	AK_{14}
Values for Fig. 5	9.30	0.093	2.0	2.5	1.5
Values for parametric studies	1.858, 4.645, 6.50, 9.30, 18.6	0.093, 0.186, 0.372, 0.464	1.0, 2.0, 2.5	1.0, 2.0, 2.5	0.5, 1.0, 1.5, 2.0
	τ (s)	τ_1 (s)	p_{10} (atm)	p_{20} (atm)	t_D (s)
Values for Fig. 5	1.0	1.0	1.0	0.8	1.0
Values for parametric studies	1.0, 2.0	1.0, 2.0	0.85, 0.90, 1.0	0.8, 0.85, 0.9	1.0

Note: p_{10} and p_{20} are parameters appearing in Eqs. 14 and 15.
h_{10} and h_{20} are the initial values of h_1 and h_2.

In all the cases the pressures p_1 and p_2 are represented by the following equations:

$$p_1 = 1 + p_{10}\,[1 - \exp(-t/\tau)] \qquad (14)$$

$$p_2 = 1 + p_{20}\,\{1 - \exp[(-t + t_D)/\tau_1]\} \qquad (15)$$

where τ and τ_1 are time constants and t_D is a delay in the rise of p_2. A_1, A_3, and A_4 have been kept the same in all the cases presented here. These results are only to illustrate the principle, and the values of parameters are chosen to cover the expected range.

From the numerical results it is seen that both h_4 and h_3 oscillate about the steady-state value. This is due to the inertia of the water columns. The amplitude and duration of oscillations are higher for lower values of the loss coefficients.

Certain minimum values for the ratio A_2:A_1 and the depth of submergence of the pipe have to be maintained for the formation of stable water columns. A higher area ratio also reduces the amplitude of oscillations.

The amplitude of levels h_3 and h_4 increases with h_j, the height of the junction of L_1 and L_2 above the entrance of L_2. Water flow was found to be established within 0.5 second within the range of h_j (0.6 to 1.5 m) considered.

Increase in τ, the time constant appearing in the equation for p_1, reduces the amplitudes of h_3 and h_4. Increase in τ_1, the time constant appearing in the equation for p_2, does not significantly alter the amplitude of h_4. However, it increases the amplitude of h_3. The effects of p_{10} and p_{20} on the amplitude of h_3 and h_4 are opposite those caused by τ and τ_1, respectively. An increase in x_5 results in reducing the amplitude of h_4 but increase in h_3. The effect of x_5 on the steady-state level was described earlier. The parameters considered in Table 1 are expected to be in the range of interest.

CONCLUSIONS

A positive and passive isolation scheme has been devised to limit the release of radioactivity from a reactor to the environment in the event of an accident. The constraints in implementing this principle in a design are given as follows:

1. The size of the piping (A_1 and A_3) connected to the ventilation line should not put undue constraint on the normal ventilation function. The tank size and the depth of submergence of L_2 should be adequate to maintain continuity of the water columns at all times. Similarly, the length of the vertical pipe should be adequate to contain the maximum rise.

2. Positive flow should be established in L_2 before p_2 exceeds the atmospheric pressure.

3. During level oscillations in L_1 and L_2, the pressure at the junction should be adequate to prevent escape of air in V_2. Equations 1 and 2 could be used as a guide in this respect. Existence of water in both the limbs of the U-tube will further ensure this.

The present results are for the type of pressure transients shown in Fig. 3, and these cover the period when the pressure in the containment reaches its peak value. However, in the long run, these pressures will start reducing because of cooling and pressure equalization between V_1 and V_2.

As the pressure p_1 reduces, the water level in L_1 starts dropping toward its initial value. However, even with the reduction of p_2, the water in the U-tube is retained because there is no source of pressurization within the volume V_2. In the unlikely event of V_1 cooling faster than V_2, the pressure p_2 may be above p_1 for a short period. This scenario is possible after p_1 and p_2 have gone through the peak values and have started reducing. However, even this situation can be met by a judicious choice of x_5, the height of the shorter limb of the U-tube.

The scheme takes advantage of the difference between p_1 and p_2 after an accident. Among other factors, this depends on the depth of submergence of the downcomers in the vapor suppression pool. This influences the location of the junction of L_1 and L_2. The amount of water in L_1 and L_2 should be adequate to last the entire course of the transient. This consideration, together with those dictated by Eqs. 1 and 2, influences the choice of h_{10}, h_{20}, A_2, and A_3. A_1, A_3, and A_4 are further related to the ventilation duct size. The constants t, t_1, t_D, p_{10}, and p_{20} are obtained by fitting the postaccident pressure transients to Eqs. 14 and 15. After obtaining the nominal values of the parameters from the preceding considerations, some spread is considered to account for possible variations and uncertainties. The height of L_1 should be adequate for the rise in p_1.

The proposed isolation system for the ventilation ducts can, in principle, be applied to beyond design basis accidents as well. Its detailed design has to incorporate all the considerations for a containment-grade structure (e.g., wind effects and seismicity).

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