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A study of large break LOCA in the AP1000 reactor containment

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ABSTRACT

In this paper, one of the most dangerous accidents in reactor containments known as Loss of Coolant Accident (LOCA) in its worst condition called large LOCA has been modelled. The specific type of large LOCA is DECL (Double Ended Cold Leg) break which means a total guillotine type of break in cold leg pipe. When 'LOCA' occurs, the coolant itself is lost, then in this case that happens with pipe break or any kind of losing, the danger of core melting is possible. This modelling is performed in two volumes method in AP1000 reactor which is one of the most sophisticated safe reactors that has ever been built. Its safety systems provide a large variety of safety margins. One of the most important safety features in AP1000 is its passivity. This advantage provides many simplifications to enhance the safety, reliability, construction, operation, maintenance, investment, protection and plant costs. Therefore, it is worthwhile and makes sense to perform the analysis of a most dangerous accident in one of the most secure reactors. The modelling software applied in our analysis is MATLAB, and the results are compared with the AP1000 safety, security and environmental reports.

1. Introduction

During a severe accident, a large amount of radioactive fission products is generated and the goal of the containment system is to avoid or limit the release of these fission products to the external environment (Oriolo and Paci, 2000). This goal is achieved through restriction of accidents or by using containment safety systems limiting the dangerous effects of the event. Therefore, the containment plays a basic role in safety. AP1000 is a two loop 1000 MWe pressurized water reactor (PWR) with passive safety features and extensive plant simplifications that enhances the construction, operation, maintenance, and safety (Cummins et al., 2003). First we look at the major advances of AP1000 design over conventional plant designs. AP1000 safety features rely on natural driving forces, such as pressurized gas, gravity flow, natural circulation flow, and convection. These features do not use active components, such as pumps, fans, chillers, or diesel generators. The features are designed to function without active safety support systems, such as AC power, component cooling water, service water and HVAC (Heating Ventilation and Air Conditioning) (Saiu and Frogheri, 2005). AP1000 safety features establish and maintain core cooling and containment integrity indefinitely, with no operator action or AC power following basic design faults. These systems contain significantly fewer components, reducing required tests, inspections, and maintenance, also their readiness is easily monitored (The AP1000 DCD, 2007). The *Loss of coolant accident* (LOCA) is most likely to occur in 'water cooled reactors', where the stored energy content of the high pressure, high temperature coolant may be released to the containment by rupture of an exposed pipe. HTGR systems with their primary coolant loops contained entirely within the reactor vessel are not as readily susceptible to extensive coolant loss. The low pressure sodium coolant in LMFBRs is not also subject to such rapid removal.

2. Mathematical formulation

In this simulation, containment is divided into two cells, the first cell is the lower part of the containment that pipeline breakage happens there and the second cell is in the upper part of the containment. In this section, equations of mass and energy conservation for water and steam in both cells and equation of momentum conservation for steam and water transform between two cells has been written. By solving these three equations for both cells give us the pressure and temperature of water and steam each cell. Air partial pressure has been calculated using perfect gas

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law for each cell. At the end, total pressure and temperature of each cells has been calculated. In the following equations of mass, energy and momentum conservation have been defined, then these relations are written for both cells.

Conservation of Mass Equation:

$$\frac{dM}{dt} = \dot{m}_{in} - \dot{m}_{out} = \sum_i \dot{m}_i \tag{1}$$

Where $\dot{m}_{in}$ is the entry mass flow rate to cell, and $\dot{m}_{out}$ is the external mass flow rate of cell.

Conservation of Energy Equation:

$$\frac{dU_{c.v}}{dt} = \dot{Q}_{c.v} - \dot{W}_{c.v} + \dot{m}_i e_i - \dot{m}_e e_e + \dot{W}_{flow\ in} \tag{2}$$

Where

$$\begin{aligned} \dot{W}_{flow\ in} &= FV = \int PVdA = Pv\dot{m} \\ \frac{dU_{c.v}}{dt} &= \dot{Q}_{c.v} - \dot{W}_{c.v} + \dot{m}_i(e_i - P_i v_i) - \dot{m}_e(e_e - P_e v_e) \end{aligned} \tag{3}$$

Therefore, the Eq. (3) can be rewritten as follow:

$$\begin{aligned} \frac{dU_{c.v}}{dt} = {} & \dot{Q}_{c.v} - \dot{W}_{c.v} + \sum \dot{m}_i\left(h_i + \frac{1}{2}v_i^2 + gZ_i\right) \\ & - \sum \dot{m}_e\left(h_e + \frac{1}{2}v_e^2 + gZ_e\right) \end{aligned} \tag{4}$$

Whereas volume of cells is constant therefore:

$$\dot{W}_{c.v} = P_i\frac{dV_i}{dt} = 0$$

Conservation of Momentum Equation for flow between cell i and cell j:

The calculation of the mass flow rate between two connected cells is based on the following momentum equation:

$$\frac{d\dot{m}_{ij}}{dt} = \left(\Delta P - C_{FC}\frac{|\dot{m}_{ij}|\dot{m}_{ij}}{\rho(A)^2}\right)\frac{A}{L} \tag{5}$$

Where $\dot{m}_{ij}$ is the mass flow rate between cell 1 and cell 2, t is the time, ΔP is the pressure difference between connected cells, CFC is the flow-loss coefficient, ρ is the fluid density, A is the cross-sectional area and L is the inertial length. The A/L ratio is specified as the "*vavl*" parameter in the CONTAIN code and has a strong influence on the results of atmosphere stratification simulation. The flow-loss coefficient CFC was set equal to 1.0 for all EV (Stamps, 1998).

For first cell:

Conservation of Mass Equation:

$$\int_{m_1^t}^{m_1^{t+\Delta t}} dm_1 = \int_t^{t+\Delta t} (\dot{m}_B - \dot{m}_{12})dt \tag{6}$$

Where $\dot{m}_B$ is the entry mass flow rate of Break (double ended of Cold Leg) to cell 1 and $\dot{m}_{12}$ is the entry mass flow rate of cell 1to cell 2.

Conservation of Energy Equation:

$$\begin{aligned} \int_{U_1^t}^{U_1^{t+\Delta t}} dU_1 = \int_t^{t+\Delta t} \Bigg(& \dot{m}_B\left(h_B + \frac{1}{2}v_B^2 + gZ_B\right) \\ & - \dot{m}_{12}\left(h_{12} + \frac{1}{2}v_{12}^2 + gZ_{12}\right) - \dot{Q}_{1-st}\Bigg)dt \end{aligned} \tag{7}$$

Where h_B is the entry enthalpy rate of Break 1 to cell 1, h_{12} is the entry enthalpy rate of cell 1 to cell 2, and $\dot{Q}_{1-st}$ is heat transfer between cell 1 and structure.

For second cell:

Conservation of Mass Equation:

$$\int_{m_2^t}^{m_2^{t+\Delta t}} dm_2 = \int_t^{t+\Delta t} \dot{m}_{12}dt \tag{8}$$

Conservation of Energy Equation:

$$\int_{U_2^t}^{U_2^{t+\Delta t}} dU_2 = \int_t^{t+\Delta t} \left(\dot{m}_{12}\left(h_{12} + \frac{1}{2}v_{12}^2 + gZ_{12}\right) - \dot{Q}_{2-st}\right)dt \tag{9}$$

Where $\dot{Q}_{2-st}$ is heat transfer between cell 2 and structure.

Conservation of Momentum Equation between two cells:

$$\int_{\dot{m}_{12}^t}^{\dot{m}_{12}^{t+\Delta t}} d\dot{m}_{12} = \int_t^{t+\Delta t} \left(\Delta P_{12} - C_{FC}\frac{|\dot{m}_{12}|\dot{m}_{12}}{\rho_{12}(A_{12})^2}\right)\frac{A_{12}}{L_{12}}\,dt \tag{10}$$

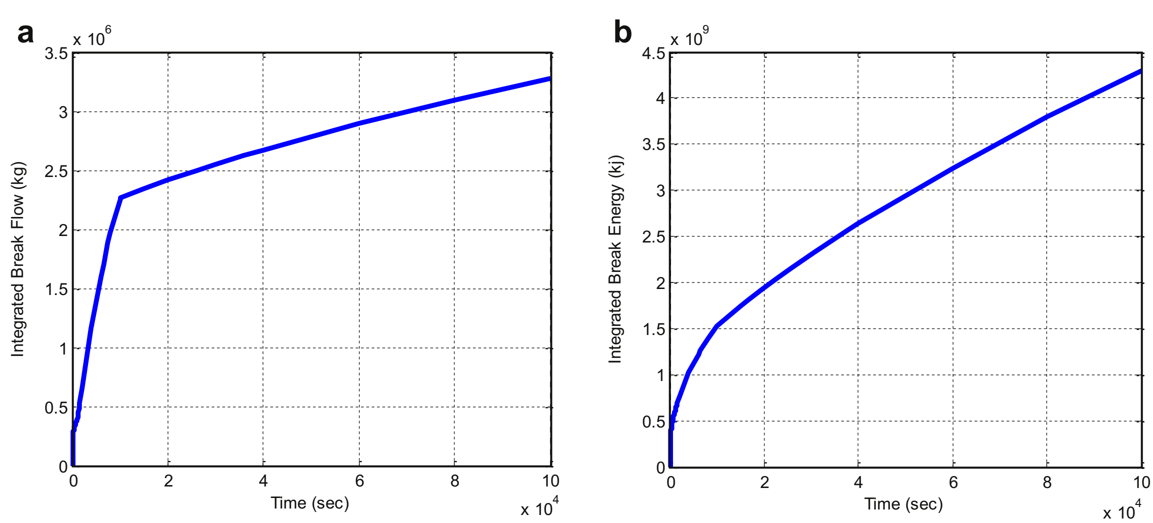

Fig. 1. (a) Distribution of integrated mass flow (water and steam) Released with time, (b) Distribution of integrated energy released with time (The AP1000 European DCD, 2007a).