Nuclear Engineering and Design 325 (2017) 57–67

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Study of strategies to avoid hydrogen deflagration in venting pipelines during severe accident scenarios

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ARTICLE INFO

Keywords:
Mark II
BWR
GASFLOW
Venting strategy
Nitrogen inertization
Volume enlargement

ABSTRACT

Venting timing and duration are key issues for the development and assessment of severe accident guidelines and mitigation alternatives. In BWRs, venting from wetwell has the advantage of gaining fission product scrubbing. In this study, two strategies are investigated to avoid hydrogen deflagration in venting pipelines. The starting point of the vent pipe is a penetration on the wall of wetwell's suppression chamber of a BWR Mark II containment. A three-dimensional pipeline model was developed for the CFD type code GASFLOW, to better determine conditions leading to risk of flame acceleration and hydrogen deflagration. The analysis starts with a base case, in which venting occurs when pressure reaches 4.5 $\mathrm{kg_f/cm^2}$ and the vent pipe is full of air. Then, the first strategy to reduce hydrogen deflagration risk consists of inertization with nitrogen at specific locations along the vent pipe through rupture disks with three opening pressure setpoints (2.0, 3.0. 4.0 $\mathrm{kg_f/cm^2}$). Three different locations are considered in this study. The second strategy is the volume enlargement of the last section of the vent pipeline. Two different expansions additional to the base case were considered for analysis.

The results show that the inertization with nitrogen at the lower pressure setpoints (2.0 and 3.0 $\mathrm{kg_f/cm^2}$) does effectively, for practical applications of safety analysis, highly reduces the risk of flame acceleration anywhere in the vent pipeline. However, lowering the opening pressure value implies earlier venting. If it is preferable to keep the disk opening pressure at the higher pressures (4.0 and 4.5 $\mathrm{kg_f/cm^2}$), the results show that it is necessary to choose an appropriate location to set the rupture disk, to effectively diminish flame acceleration risk. Regarding the second venting strategy, the results show that increasing the volume of the last section of the vent pipe is also an effective way to reduce hydrogen deflagration risk. Thus, although flame acceleration still could occur, those conditions for that to happen will be restricted to a shorter period. For actual practical applications, this second strategy seems more plausible to be carried out, because all relevant changes to the vent pipeline would be focused on the parts already outside reactor building.

1. Introduction

Methodologies for risk assessment studies of severe accidents have been applied for decades now (US NRC, 1990). Containment analysis is a fundamental part of the probabilistic safety assessment level 2 for power reactors, and one key objective of such studies is determining conditions for venting during severe accident scenarios. After the Fukushima accident, a renewed interest in this topic arose quite remarkably. Furthermore, venting timing and duration are key issues for the development and assessment of severe accident guidelines (SAMGs) and mitigation alternatives (SAMAs). Particularly for BWRs, the option of the venting action from the wetwell or drywell becomes an additional relevant decision during the evolution of a severe accident (EPRI, 2012). For those scenarios where steam is being directed to the pressure suppression pool, via the safety/relief valves and pipelines, the former alternative has the advantage of gaining fission product scrubbing.

Additionally, performance of venting actions directly impacts on hydrogen control in containment. In this aspect, it is also necessary to create accurate models of the venting pipelines, since it has been shown that conditions for flame acceleration inside the vent pipe could be reached due to hydrogen concentration (Gómez-Torres et al., 2015). In that study, a model of a vent pipe starting in the drywell of a BWR Mark II containment was created for the CFD-type code GASFLOW (KIT,

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http://dx.doi.org/10.1016/j.nucengdes.2017.10.008
Received 30 May 2017; Received in revised form 2 October 2017; Accepted 4 October 2017
0029-5493/

2011). The accident scenario considered was a SBO simulated with the code MELCOR. As one conclusion of that work, the authors suggested to maintain an inert atmosphere of nitrogen inside the vent pipe to avoid reaching the hydrogen and oxygen mixture concentration required for deflagration.

In this work, two strategies to avoid flame acceleration, deflagration and/or detonation in venting pipelines are proposed and analyzed. The first one is to inertize sections of the venting pipeline, and the second one is to modify its geometry at particular sections. The combination of these two strategies becomes another alternative. To perform the analysis, firstly it is proposed a model of a venting pipeline having its starting point at a penetration on the wall of the suppression chamber of the wetwell of a BWR Mark II containment. This vent pipe still has a connection with other vent pipe coming from a penetration to the drywell. In this design, thus, the first sections of the pipeline are inside the reactor building but not inside the primary containment, and the last two sections are outside the reactor building. The last section discharges laterally above reactor building. This composed pipeline has been modeled with the code GASFLOW. The analysis starts with a base case, in which venting occurs when pressure reaches 4.5 $\mathrm{kg_f/cm^2}$ and the pipeline is full of air and at atmospheric pressure. Then, the option of using nitrogen as a mean to avoid a direct contact of hydrogen and oxygen is investigated. Since nitrogen is already in use as inertizing agent in BWR containments, it could be used inside some sections of the vent pipe via the use of rupture disks having different aperture pressure set points. Three different locations along the pipe vent are considered to set up a rupture disk, and three different pressure set points (2.0, 3.0. 4.0 $\mathrm{kg_f/cm^2}$) for opening the disk are used for the GASFLOW calculations. That is, for the first strategy, nine different venting cases plus the base case are analyzed and discussed. To study the second strategy, it is proposed to enlarge the cross section of the vent pipe at its end section, that is, the part outside the reactor building. Such volume enlargement will decrease the H_2 volumetric fraction in that volume, thus effectively moving away from the flame acceleration region.

In order to calculate the thermodynamic conditions of the containment and discharge mass flows during an SBO, it was necessary to use a simplified analytical model, as an alternative to obtain those data from results of system codes. This model is described next.

2. Calculation of hydrogen source term for GASFLOW

The conjunction of results from system codes as MELCOR, RELAP, MAAP, etc., with CDF-type codes as GASFLOW is a practical practice for analysis of containment behavior during severe accident conditions (Van Dorsselaere et al., 2015; Paladino et al., 2016). The system codes provide with boundary and initial conditions for the CFD code. It is not the purpose of the present analysis to develop and evaluate a coupling approach, but to solve a practical problem based on data calculated with a severe accident code. A simplified model allows to perform a sensitivity study to show the different options for finding solutions to avoid problems in the venting pipe. In this work, a base case of analysis was carried out from given initial and boundary conditions of the containment thermodynamic conditions during the discharge of steam through the safety/relief (SRV) pipelines to the pressure suppression pool (PSP) from an SBO simulated with MELCOR. Then, when the venting action starts, the evolution of containment conditions and the steam and hydrogen source term for the GASFLOW calculation are computed from a simplified model of the evolution of the containment thermodynamic conditions. The steam flow through the SRV pipes provided by MELCOR is the same one used by Gómez-Torres et al. (2015). Then, it is computed the pressure and temperature fields, hydrogen concentration and mass flows inside the vent pipe, from the wetwell to the discharge point above the reactor building.

The proposed model for calculation of the evolution of the thermodynamic state of the PSP and suppression chamber assumes that thermodynamic equilibrium between the liquid and gas volumes has been already achieved. In order to define the source term for a CFD code, as GASFLOW, more accurate data of the wetwell state could be obtained at each time from a safety analysis computer code. This simplified model is an alternative in case there is no access to such tools (Nancy Astrid Solis Alcantara, 2017). The model starts by setting the following equations for energy and mass conservation:

$$U = h_{srv}\dot{M}_{srv} + h_{H2}\dot{M}_{H2} \tag{1}$$

$$\left.\begin{array}{r} \dot{M}_l + \dot{M}_g = \dot{M}_{srv} \\ \dot{M}_g = \dot{M}_{H2} \end{array}\right\rangle \tag{2}$$

and the condition of a constant total volume

$$V_{TOT} = V_g + V_l = M_l v_l(p,T) + M_g v_g(p_{sat}(T),T) \tag{3}$$

where $U,h,\dot{M},V,v$ represent the total energy in the system, enthalpy, mass flow, volume, and specific volume, respectively. The subscripts srv, $H2$, l, g, TOT, and sat refer to safety/relief valves, hydrogen, liquid, gas, total volume, and saturation conditions, respectively. Eq. (1) can also be written in terms of an equation of state for water and ideal gas equations for the non-condensable gases hydrogen and nitrogen as follows

$$U = M_l u_l(p,T) + M_g u_g(p_{sat}(T),T) + M_{N2}Cv_{N2}T + M_{H2}Cv_{H2}T \tag{4}$$

In this equation, pressure p and temperature T are independent variables. Also, the total pressure in the gas volume is the sum of the partial pressures of the steam, hydrogen and nitrogen, that is

$$p = p_{sat}(T) + \frac{M_{N2}R_{N2}T}{V_g} + \frac{M_{H2}R_{H2}T}{V_g} \tag{5}$$

After deriving Eqs. (3)–(5) with respect to time, and using the mass conservation (Eq. (2)) plus some algebra, it can be obtained a system of three nonlinear differential equations, which can be written in matrix form as

$$\begin{pmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{21} & A_{22} & A_{23} \end{pmatrix}\begin{pmatrix} \dot{P} \\ \dot{T} \\ \dot{M}_l \end{pmatrix} = \begin{pmatrix} F_1 \\ F_2 \\ F_3 \end{pmatrix} \tag{6}$$

The coefficients A in that matrix and the right-hand vector F are:

$$A_{11} = M_l\frac{\partial u_l}{\partial p}$$

$$A_{12} = M_l\frac{\partial u_l}{\partial T} + M_g\frac{\partial u_g}{\partial p_{sat}}\frac{\partial P_{sat}}{\partial T} + M_g\frac{\partial u_g}{\partial T} + M_{N2}Cv_{N2} + M_{H2}Cv_{H2}$$

$$A_{13} = u_l - u_g$$

$$F_1 = h_{srv} - u_g(p_{sat,}T)G_{srv} + (h_{H2} - Cv_{H2}T)G_{H2}$$

$$A_{21} = 1$$

$$A_{22} = -\left[\frac{dp_{sat}}{dT} + \frac{p-p_{sat}}{T} - \frac{p-p_{sat}}{V_g}M_g\left(\frac{\partial v_g}{\partial p_{sat}}\frac{\partial p_{sat}}{\partial T} + \frac{\partial v_g}{\partial T}\right)\right]$$

$$A_{23} = -\frac{p-p_{sat}}{V_g}v_g$$

$$F_2 = -\frac{p-p_{sat}}{V_g}v_g G_{srv}$$

$$A_{31} = M_l\frac{\partial v_l}{\partial p}$$

$$A_{32} = M_l\frac{\partial v_l}{\partial T} + M_g\left(\frac{\partial v_g}{\partial p_{sat}}\frac{dp_{sat}}{dT} + \frac{\partial v_g}{\partial T}\right)$$

$$A_{33} = v_l - v_g$$