Numerical Analysis of Pressure Load in a PWR Cavity in an Ex-Vessel Steam Explosion (Postprint)

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Abstract

Ex-vessel steam explosion may happen as a result of melting core falling into the reactor cavity after failure of the reactor vessel and interaction with the coolant in the cavity pool. It can cause the formation of shock waves and production of missiles that may endanger surrounding structures. Ex-vessel steam explosion energetics is affected strongly by three dimensional (3D) structure geometry and initial conditions. Ex-vessel steam explosions in a typical pressurized water reactor cavity are analyzed with the code MC3D, which is developed for simulating fuel-coolant interactions. The reactor cavity with a venting tunnel is modeled based on 3D cylindrical coordinate. A study was performed with parameters of the location of molten drop release, break size, melting temperature, cavity water subcooling, triggering time and explosion position, so as to establish parameters' influence on the fuel-coolant interaction behavior, to determine the most challenging cases and to estimate the expected pressure loadings on the cavity walls. The most dangerous case shows the pressure loading is above the capacity of a typical reactor cavity wall.

Full Text

Preamble

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Abstract: Ex-vessel steam explosion may occur when a molten core falls into the reactor cavity following reactor vessel failure and interacts with coolant in the cavity pool. This phenomenon can generate shock waves and produce missiles that endanger surrounding structures. The energetics of ex-vessel steam explosion are strongly affected by three-dimensional (3D) geometry and initial conditions. This study analyzes ex-vessel steam explosions in a typical pressurized water reactor cavity using the MC3D code, which was developed for simulating fuel-coolant interactions. The reactor cavity with a venting tunnel is modeled in 3D cylindrical coordinates. Parametric studies were performed on the location of molten drop release, break size, melt temperature, cavity water subcooling, triggering time, and explosion position to establish parameter influences on fuel-coolant interaction behavior, identify the most challenging cases, and estimate expected pressure loadings on cavity walls. The most dangerous case exhibits pressure loading exceeding the capacity of a typical reactor cavity wall.

Keywords: Steam explosion, Fuel coolant interaction, Numerical analysis, Severe accident

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INTRODUCTION

Studies on severe accidents in nuclear power plants (NPPs) have been conducted for years, addressing complex problems of multiphase flow and heat transfer. A critical issue in severe accidents is the likelihood and consequences of steam explosions, which may occur when hot core melt contacts coolant water. When the energy of molten corium transfers to coolant water on a timescale shorter than that required for system pressure relief, it induces dynamic loading on surrounding structures [1]. Although NPP safety analyses indicate a low probability of steam explosion occurrence as a severe reactor accident consequence, steam explosions remain a nuclear safety concern that may cause vessel vertical displacement and challenge NPP containment integrity [2–4].

As molten drops fall into cold liquid, hydrodynamic instabilities break up the molten jet and disperse it into the coolant, forming a coarse mixture (approximately 1 cm scale for molten corium and water). Subsequently, film boiling occurs around the molten drops due to the large temperature difference, and a vapor film separates the drops from the coolant. Under certain conditions, such as an external pressure pulse, the vapor film collapses, allowing direct contact between the molten metal and coolant and causing further fragmentation of the molten drops. This leads to a sharp increase in heat transfer area, evaporating the ambient liquid rapidly and generating a high-pressure pulse. This form of destructive instantaneous evaporation, which can propagate and amplify, is called a steam explosion [1]. The steam explosion process is commonly divided into four phases: premixing, triggering, propagation, and expansion [5].

Despite extensive research, the nature of fuel-coolant interaction (FCI) remains complex, modeling of ex-vessel steam explosions is difficult, and analysis results are subject to large uncertainties [6]. Examples of one- and two-dimensional FCI models include the TEXAS code [7] and the PM-ALPHA/ESPROSE codes [8, 9]. Additional experimental and analytical work is needed to advance FCI codes. Beyond uncertainties inherent in modeling FCI processes, other factors affecting explosion energetics include melt release location, break size, melt temperature, cavity water subcooling, and triggering time and position for explosion calculations.

The FCI processes have been modeled using the PM-ALPHA and ESPROSE codes [4]. PM-ALPHA is a two-dimensional code developed by the Jožef Stefan Institute (JSI, Slovenia) and the Atomic Energy Commission (CEA, France). A two-dimensional geometrical model based on a typical pressurized water reactor (PWR) was developed with MC3D [10]. Simulation results of reactor vessel failure indicate that if failure occurs at the vessel bottom, pressure load and impulse distribution are considerably overestimated compared to SERENA test data. This inconsistency is attributed to discrepancies between the two-dimensional Cartesian geometrical model and the prototype reactor.

The Institut de radioprotection et de sûreté nucléaire (IRSN, France) conducted a series of ex-vessel FCI simulations with MC3D based on a typical French PWR. The analysis indicates relatively low pressure load over long duration that may lead to reactor cavity wall rupture, and relatively high pressure over short duration that may also destroy the cavity wall. Additionally, containment failure probability is highest at high reactor vessel pressure, with a large breach, or with relatively low subcooling.

This work aims to predict the consequences of ex-vessel steam explosions in a typical PWR cavity. A 3D calculation model was built using the MC3D code, and analysis was performed on various parameters including melt release location, break size, melt temperature, cavity water subcooling, triggering time, and explosion position to identify the most challenging ex-vessel steam explosion cases.

II. MODELING

A. Introduction of the Computer Code

Simulations were performed using MC3D, a three-dimensional multiphase simulation code developed by IRSN for nuclear safety analysis. The code comprises two modules: PREMIXING for premixing phase calculations and EXPLOSION for explosion calculations. The PREMIXING module [11] describes the core-melting process using a continuous field, discontinuous field, and fuel fragment field, corresponding to melt jet, melt drops, and fine fragments, respectively, in addition to three fields for water, vapor, and non-condensable gas. It simulates the breakup of the melting jet into relatively large drops and their fragmentation into finer drops, as well as heat transfer between melting fuel rods and coolant. The module offers two jet breakup modes. In one mode, the jet-breakup ratio is obtained from standard tests and the molten drop size can be user-specified. In the other mode, the jet breakup rate and molten drop size are defined by local velocity derived from Kelvin-Helmholtz instability. However, this mode is not sufficiently verified; therefore, our simulation adopted the first mode with molten drops sized at 4 mm.

The EXPLOSION module, which considers only two fields related to dispersed fuel, simulates finer fragmentation of molten drops and heat transfer between finer fragments and coolant. Both thermal and hydrodynamic fragmentation processes are considered. The fragment size, defaulting to 100 µm based on KROTOS facility tests [4], can be user-specified.

MC3D assumes that metal alloy is completely melted at temperatures beyond its melting point. However, a solid shell layer forms before the mean temperature of a molten drop falls below the melting point, preventing further fragmentation. Consequently, the explosion process is exaggerated in simulations, which is conservative for safety analysis [11].

After more than ten years of modification and development, MC3D' s reliability has been validated in the OECD SERENA program. The current version is 3.56, though this paper employs an improved numerical method to reduce computing time for large-scale grids and enhance stability.

B. Fragmentation Model [11]

Fragmentation of molten drops is a crucial stage in steam explosions. The fragmentation model determines the triggering time, intensity, and propagation range of steam explosions. The mechanism implemented in MC3D includes thermal triggering and hydrodynamic triggering.

The code uses direct contact between molten drops and coolant as the thermal triggering mechanism leading to drop fragmentation. To determine the initial contact time, fluid acceleration in the grid must be calculated, which is proportional to the pressure difference between coolant around the drop and the vapor film. In the non-linear Rayleigh-Taylor instability stage, fluid acceleration (r_J) can be derived from the Taylor formula:

$$r_J = \frac{2(P_l - P_v)}{\rho_l D_d}$$

where P_l and P_v are coolant and vapor film pressures, respectively; ρ_l is coolant density; and D_d is molten drop diameter. Fragmentation is not continuous in the physical model, but this discontinuity cannot be introduced into computational codes, requiring average values in the grid. Assuming continuous drop size variation and fragment rate, the initial fragmentation time, mass, and fragment diameter can be deduced from the fragmentation model [11].

Fragmentation regulation follows a cosine law:

$$\Gamma_{df-t} = \frac{\Gamma_{frag}\{1 - \cos[2\pi/t_{frag-T}]t\}}{2}$$

where Γ_{df-t} is the thermal fragmentation rate; Γ_{frag} is the fragmentation rate; and t_{frag-T} is the fragmentation time. The maximum fragmentation rate is:

$$\Gamma_{frag} = \frac{2m_{frag}}{t_{frag-T}}$$

where m_{frag} is the fragmentation mass. The other triggering mechanism is hydrodynamic triggering. After explosion, fluids accelerate from their initial velocity due to pressure impact, and sufficiently large velocity differences may lead to fragmentation. Thus, fragmentation caused by hydrodynamic triggering dominates. This can be attributed to peel-off of the hydraulic boundary layer of coolant fluid formed outside molten drops or Rayleigh-Taylor instability caused by acceleration of lower-density coolant near the drop.

Currently, MC3D applies the peel-off mechanism. The fragmentation rate is:

$$\Gamma_{df-h} = \frac{\alpha_d \Delta V_{dc} (\rho_d \rho_c)^{1/2}}{t^*_{frag} D_d}$$

where Γ_{df-h} is the hydrodynamic fragmentation rate; α_d is the volume fraction of molten drops; ΔV_{dc} is the relative velocity between the continuous phase and molten drop; ρ_d is the density of molten drops; ρ_c is coolant density; t^*_{frag} is characteristic time; and D_d is molten drop diameter. A value of $frag = 1$ is recommended (varying from 1 to 1.25).

C. Geometrical Model and Initialization

The geometrical model used in this paper is based on a 1000 MW PWR. However, MC3D simulation would require excessive time if all complex NPP structures were modeled. Therefore, only structures affecting the FCI process are considered.

[Figure 1: see original paper] shows the geometry of the 3D model of nuclear island structures. The modeled nuclear island focuses primarily on the reactor cavity and venting tunnel. Only half of the structures are analyzed due to symmetry. In [Figure 1: see original paper], the red region below the reactor pressure vessel represents coolant water in the cavity and venting tunnel. The numerical grid is adequately refined in this region, which is crucial for simulating the FCI process.

presents the numerical grid in cylindrical coordinates. Each mesh is represented by its coordinate (γ, θ, z) indices. Since only half of the structure is analyzed, only four θ values (0, $\pi/12$, $11\pi/12$, and π) are needed, while there are 20 nodes on the γ axis and 22 nodes on the z axis.

For sensitivity analysis, locations (8, 1, 9) and (11, 3, 3) are selected as reference points at the pressure vessel bottom and cavity wall, respectively [Figure 2: see original paper]. Pressures at these two locations are recorded.

III. SIMULATION AND ANALYSIS

A. Simulation Results of Standard Case

1. Variation of Volume Fraction Distribution Simulation results from both premixing and explosion processes include temperature, pressure, and volume fraction fields. Volume fraction distributions during premixing and explosion after pressure vessel failure and melt release are shown in [Figure 3: see original paper] and [Figure 4: see original paper].

Thermal interaction between melting rods and coolant is much more violent during explosion than during premixing. Consequently, most corium remains below the failure hole location during premixing, while corium disperses and spreads throughout the cavity during explosion.

2. Variation of the Pressure Field [Figure 5: see original paper] shows pressure field variation during the premixing process for the standard case. Pressure decreases slowly without obvious pulses. [Figure 6: see original paper] shows pressure field variation during the explosion process for the standard case. Comparing [Figure 5: see original paper] and [Figure 6: see original paper] reveals that pressure increases rapidly to high levels after explosion triggering, then dissipates slowly. The pressure field distributes non-uniformly in the cavity and varies rapidly. The explosion duration is only 0.05 s, much shorter than the premixing process.

The standard case assumes a pressure vessel failure accident developing from a large-break LOCA. Initial conditions are set to expected conditions at vessel failure, with all subsequent sensitivity analyses compared against this baseline. lists the initial conditions for the standard case.

B. Pressures of the Reference Locations in the Explosion Process

1. Pressures at Different Locations in the Circumferential Direction [Figure 7: see original paper] shows pressures at different locations at the pressure vessel bottom and cavity wall for various θ values during the explosion process. Analysis locations at the pressure vessel bottom are (8, 1, 9), (8, 2, 9), and (8, 3, 9), while cavity wall locations are (11, 2, 11) and (11, 3, 11). The pressure curves for different locations almost overlap, indicating that θ variation has little effect on pressure variation at the pressure vessel bottom.

2. Pressures at Different Locations in the Radial Direction [Figure 8: see original paper] shows pressures at different radial locations at the pressure vessel bottom and cavity wall for the standard case. Analysis locations are (3, 3, 6), (5, 3, 7), and (8, 3, 9) at the pressure vessel bottom [FIGURE:8(a)], and (11, 3, 1), (11, 3, 3), and (11, 3, 11) on the cavity wall [FIGURE:8(b)]. Pressures rise rapidly after triggering, with maximum pressures exceeding 100 bar in [FIGURE:8(a)] and 500 bar in [FIGURE:8(b)]. Within 0.02 s, pressures decrease rapidly toward original levels. Pressure variation in the γ coordinate is not significant. In [FIGURE:8(b)], pressure oscillations are observed, with oscillation amplitude decreasing with distance from the triggering location.

Figure 9: see original paper shows cavity wall pressures versus height during 0–5 seconds in the premixing process. Maximum pressure occurs at about 1 s at the cavity floor and decreases linearly with height toward a constant at the cooling water level. Figure 9: see original paper shows cavity wall pressures during the explosion process. Maximum pressure on the cavity wall occurs about 0.002 s after triggering. Pressure decreases with increasing height, and the explosion dissipates slowly after 0.015 s. The explosion affects pressures on the wall below the coolant water level, while pressures above the cooling water change little during the explosion.

C. Detailed Analysis

1. Sensitivity Analysis of Pressure Vessel Failure Location [Figure 10: see original paper] shows peak pressures and pressure loadings at reference locations (8, 1, 9) and (11, 3, 3) during the explosion process as functions of melt release angle (i.e., pressure vessel failure location variation). Pressure loadings are calculated with an integration period of 0.1 s after triggering.

In [Figure 10: see original paper], the highest pressures and pressure loadings for both locations occur when pressure vessel failure is located at a melt release angle of 50° at the vessel bottom. Pressure and pressure loadings at the pressure vessel bottom are relatively small, while pressure on the cavity wall is high at a release angle of 85°.

2. Sensitivity Analysis of Pressure Vessel Failure Size [Figure 11: see original paper] shows peak pressures and pressure loadings at reference locations (8, 1, 9) and (11, 3, 3) as functions of pressure vessel failure size (0.1 m to 0.8 m) during the explosion process. Pressure loadings are calculated with an integration period of 0.1 s after triggering.

Generally, peak pressure and pressure loadings increase with pressure vessel failure size. In Figure 11: see original paper, the highest pressure loading occurs at a failure diameter of 0.7 m. Since more corium flows out with larger failure size, the capacity for violent interactions increases correspondingly, though not indefinitely.

3. Sensitivity Analysis of Coolant Temperature For different scenarios, coolant water temperature varies from room temperature to saturation temperature at the corresponding pressure. Coolant temperatures of 300 K, 320 K, 340 K, 345 K, 350 K, 355 K, 360 K, 378 K, and 396 K are used to analyze coolant temperature effects on the FCI process. [Figure 12: see original paper] shows pressure peaks and pressure loadings (integrated over 0.1 s after triggering) at reference locations (8, 1, 9) and (11, 3, 3) for these coolant temperatures.

In Figure 12: see original paper, peak pressure increases with coolant temperature on the cavity wall, while at the pressure vessel bottom it initially increases but decreases at coolant temperatures above 340 K. In Figure 12: see original paper, pressure loading maximizes at a coolant temperature of 345 K. Higher coolant temperature means higher metal temperature and vapor volume. While high metal temperature causes violent interaction and high pressure, large vapor volume fraction leads to explosion suppression. Consequently, pressure loading is small at coolant temperatures much lower than or close to saturation temperature.

4. Sensitivity Analysis of Melt Temperature Peak pressures at location (11, 3, 3) (cavity wall) are about 500 bar (and may remain high at even higher fuel temperatures), while peak pressures at location (8, 1, 9) (pressure vessel bottom) increase slightly with melt temperature Figure 13: see original paper. Pressure loadings (integrated over 0.1 s after triggering) at both locations increase with temperature Figure 13: see original paper. Higher melt temperature induces more rapid heat transfer, intensifying the steam explosion.

5. Sensitivity Analysis of Triggering Time In previous calculations, triggering occurred at t = 2.0 s after the FCI process. The effect of triggering time is analyzed at t = 1.40, 1.55, 1.70, 1.85, 1.90, 2.00, 2.10, and 2.20 s. As shown in Figure 14: see original paper, peak pressures at location (11, 3, 3) initially increase but begin decreasing at 1.7 s. Peak pressure at location (8, 1, 9) varies slightly with triggering time. Figure 14: see original paper shows that pressure loadings (integrated over 0.1 s after triggering) at both locations initially increase but decrease after 1.7 s. With longer triggering time, molten metal mass increases, causing more violent interaction. However, with delayed triggering, molten drops interact longer with coolant water, generating more vapor. The vapor volume fraction increases while coolant water volume fraction decreases, reducing the transfer area between molten drops and water. Consequently, less vapor is generated after triggering, and pressure peaks and loadings eventually decrease.

6. Sensitivity Analysis of Triggering Position Based on previous computations, triggering positions are in the interaction zone near the cavity floor. The effect of triggering position is analyzed at heights of 2.13 m, 2.82 m, and 3.39 m. shows the results. Peak pressures at location (11, 3, 3) decrease with increasing triggering position height. Since triggering positions are far from location (8, 1, 9), changes in triggering position do not affect its peak pressure. For both locations, pressure loadings (integrated over 0.1 s after triggering) increase slightly with triggering position height. Triggering position does not significantly affect the FCI process.

D. The Most Dangerous Case

Sensitivity analysis indicates that pressure vessel failure size has the greatest effect on the interaction. The assumed accident involves failure around nearly the entire vessel circumference, allowing substantial molten drops to enter coolant water rapidly. Initial conditions for the most dangerous case are given in . Coolant water temperature is set to 320 K, where both peak pressure and pressure loading reach their maximum, with other parameters based on the above analysis.

[Figure 15: see original paper] shows pressures at location (11, 3, 3) during premixing and explosion processes for the most dangerous case (Case WP) and standard case (Case SP) near the cavity floor. In Figure 15: see original paper, pressure variation for the most dangerous case is much more violent than for the standard case, with a pressure peak of about 8 bar. In Figure 15: see original paper, pressures for both cases increase sharply to a peak initially. Then, the standard case pressure decreases rapidly, while the most dangerous case pressure remains at a very high level for about 20 ms before decreasing slowly. Consequently, the pressure loading for the most dangerous case is much higher and may endanger surrounding structures and challenge containment integrity.

IV. CONCLUSION

An assessment of ex-vessel steam explosion pressure loads in a typical PWR cavity was performed using the MC3D code. To ensure that calculation results qualitatively and quantitatively reflect complex geometry effects of a real reactor cavity, a 3D cylindrical coordinate model was developed for a series of simulations. Parametric analysis was conducted to establish the influence and importance of different parameters on FCI outcomes and identify the most severe steam explosions.

The assumed pressure vessel failure accident developing from a large-break LOCA (LBLOCA) was selected as the standard case, with initial conditions set to expected conditions at vessel failure. Pressures and corresponding pressure loadings at various locations in the pressure vessel cavity were calculated. Results suggest that pressure changes little with location variations at the pressure vessel bottom in the circumferential and radial directions, and on the cavity wall in the circumferential direction. Pressure peaks on the cavity wall decrease with increasing height. The explosion primarily affects pressures below the coolant water surface, while pressures above the water change little during the explosion. The triggering position is at the cavity bottom, with higher pressures at locations closer to the triggering point.

Calculations indicate that the most challenging situation occurs when the pressure vessel failure is located where the melt release angle is 45°. Melt flow rate increases with larger pressure vessel failure size, producing stronger explosions. Pressure loading initially increases but decreases with delayed triggering time. While delayed triggering increases molten metal mass, leading to more violent interaction, it also reduces metal temperature and increases vapor generation. The increased vapor volume fraction eventually reduces pressure loadings. Triggering position variation has little effect on the FCI process.

This study performed numerous simulations systematically searching for the strongest explosions under considered conditions, whereas the Matjaz Leskovar and Mitja Ursic study examined only three melt release location conditions without addressing water level and triggering position effects. The SERENA project analyzed only one central melt pour scenario. This paper identifies the most dangerous scenario after comprehensive sensitivity analysis, suggesting that the pressure peak for the most dangerous case may reach 700 bar and remain high for an extended period, with pressure loading far exceeding 0.1 MPa・s, potentially causing cavity structure failure. The FCI process is so complex that small model changes can significantly influence simulation results, necessitating additional experimental and analytical work for code validation.

REFERENCES

[1] Berthoud G. Annu Rev Fluid Mech, 2000, 32: 573-611.
[2] Theofanous T G. Nucl Eng Des, 1995, 155: 1-26.
[3] Almstroem H, Sundel T, Frid W, et al. Nucl Eng Des, 1999, 189: 405-422
[4] Esmaili H and Khatib-Rahbar M. Nucl Eng Des, 2005, 235:
[5] Corradini M L, Kim B J, Oh M D. Prog Nucl Energ, 1988, 22:
[6] Meigen R. Proceedings of ICAPP' 05, Seoul, Korea, 2005, pp.
[7] Young M F. The TEXAS code for fuel-coolant interaction analysis. Proceedings of ANS/ENS LMFBR Safety Topical Meeting, Lyon-Ecully, France, 1982.
[8] Yuen W W and Theofanous T G. PM-ALPHA: a computer code for addressing the premixing of steam explosions. DOE/ID-10502, 1995.
[9] Theofanous T G and Yuen W W. ESPROSE.m: A computer code for addressing the escalation/propagation of steam explosions, DOE/ID-10501, 1995.
[10] Leskovar M and Uršič M. Nucl Eng Des, 2009, 239: 2444-
[11] Meignen R. Description of the physical models of the explosion application. France: IRSN, 2008.