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Preliminary Structural Integrity Assessment of the i-SMR Containment Vessel under a Hydrogen DDT Condition Using LS-DYNA

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1. Introduction

This study focuses on the development of structural integrity assessment technology for the metallic containment vessel of an innovative small modular reactor (i-SMR) [1] subjected to severe accident conditions involving high-concentration combustible gas explosion. This is intended to show, in accordance with the requirements of 10 CFR 50.44 [2], that the i-SMR design is capable of establishing and maintaining safe shutdown, preserving accident-mitigating functions, and ensuring the structural integrity of the containment during combustion loading and during the post-combustion recovery (e.g., 10 CFR 50.44(b)(3) and (c)(3)-(5)).

The containment vessel is very important for protecting the reactor pressure vessel from external hazards and preventing the release of fission products. In severe accident scenarios, hydrogen and oxygen may accumulate over extended periods, leading to the potential for high-concentration explosions [3]. Ensuring the pressure vessel's structural integrity under such conditions is therefore essential for proving the inherent safety of i-SMR.

While domestic research on the structural integrity of SMR containment vessels under explosion loads remains limited, international studies such as those by NuScale have evaluated peak pressures and impulse durations resulting from hydrogen deflagration-to-detonation transition (DDT) loads, and have proposed assessment methodologies coupled with finite element dynamic response analysis [4]. NuScale showed that the reactor containment vessel remains within the safety margins prescribed by the ASME code [5].

For the need of such structural integrity assessments, this study applies an assessment methodology to the case of hydrogen DDT within i-SMR. Pressure–time history curve is derived and subsequently applied in dynamic finite element analyses of the i-SMR containment vessel. The objective is to verify compliance with the safety criteria stipulated in the ASME code, thereby contributing to the licensing basis for i-SMR.

2. Structural Integrity Assessment of the i-SMR Containment Vessel under DDT Condition

2.1 Modeling of the i-SMR containment vessel

Due to intellectual property rights issues related to the i-SMR, the following information has been excluded from this paper: the diameter and thickness of the containment vessel, the material properties of the containment vessel, and the amounts of hydrogen and oxygen generated within the containment vessel over 72 hours after a severe accident. Fig. 1 shows the modeling for containment vessel of i-SMR for finite element analysis to assess structural integrity under combustible gas explosion condition. The modeling was simplified as a pressure vessel excluding penetrations and specific components. Also, we performed sensitivity calculations for optimized mesh size, resulting in the use of solid elements with mesh size of 0.2 m. The upper section consists of 118,328 elements and 37,971 nodes, while the lower section consists of 161,104 elements and 51,952 nodes. A 1/2 half-symmetry modeling was applied to reduce computational time. External support structures and the internal reactor pressure vessel were excluded from the analysis. The properties of vessel materials were defined according to the ASME code and validated with experimental data [6]. Boundary conditions for symmetry modeling and gravitational loading were also defined.

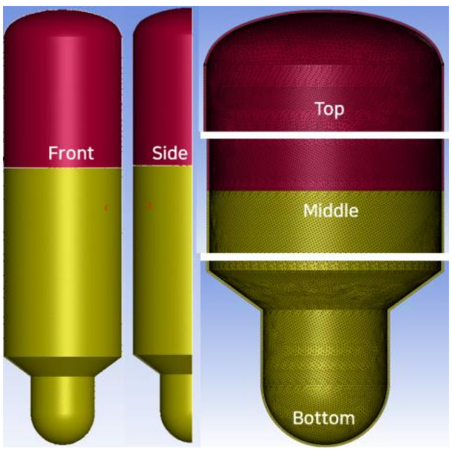

Fig. 1. Modeling of the i-SMR Containment Vessel.

2.2 Calculation of DDT peak pressure & duration time

For all accident scenarios, the atmosphere inside the i-SMR containment vessel does not reach flammable conditions, as steam constitutes the majority mole fraction while oxygen generation remains negligible. Nevertheless, in order to assess the structural integrity of the containment vessel, we have derived the peak pressure and duration time of a potential DDT event based on the calculated oxygen and hydrogen generation.
According to a series of preliminary calculations we performed the initial pressure inside the containment vessel ranges from 0.39 to 1.08 MPa after 72hrs of severe accident.
The deflagration pressure can be calculated as follows [5]:

$$P_{deflagration} = P_{initial} R_{CJ} \tag{2.1}$$

Where P represents pressure and R_{CJ} is the ratio of the C-J pressure over the initial pressure. Deflagration does not occur under conditions with negligible oxygen fraction. However, when the atmospheric composition reaches flammable conditions, the deflagration pressure is known to be approximately 1–2 times the initial pressure, Therefore, R_{CJ} was conservatively set to 2. The detonation pressure was taken as twice the deflagration pressure, and reflected pressure is calculated as:

$$P_{detonation} = 2P_{deflagration} \tag{2.2}$$

$$P_{reflection} = P_{detonation} \Pi_{refelction} \tag{2.3}$$

$$\Pi_{refelction} = \frac{5\gamma+1+\sqrt{17\gamma^2+2\gamma+1}}{\gamma} \tag{2.4}$$

Where γ is specific heat ratio at the C-J conditions. Regarding γ of hydrogen is 1.4 [7], the reflection pressure was 2.51 times the detonation pressure.

$$P_{DDT} = P_{reflection} F_{DDT} \tag{2.5}$$

Where DDT amplification factor (F_{DDT}) is normally taken as 1–5 [8]. Accordingly, the DDT pressure range was estimated as 10.8 – 54.1 MPa. For conservative assumption, the highest peak pressure was chosen for the simulation. Fig. 2 shows the DDT pressure-time curve.

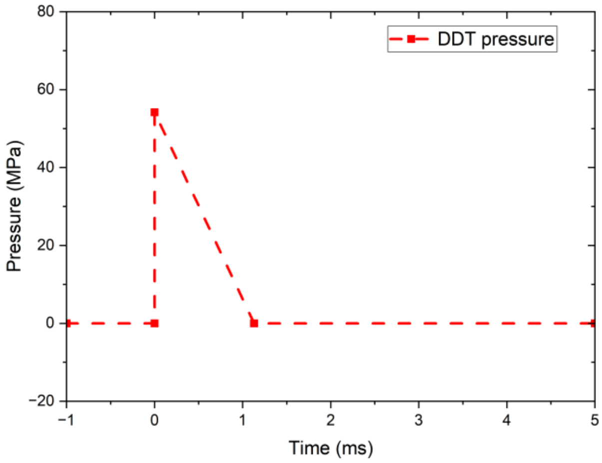

Fig. 2. DDT pressure - time curve.

2.3 Finite element model setup in LS-DYNA

LS-DYNA was employed to evaluate the structural integrity of the containment vessel. This program offers strong capabilities in modeling large deformations and material nonlinearity [9].
Symmetry constraints applied through *BOUNDARY_SPC_SET. Solid elements (*SECTION_SOLID, ELFORM=1) were used to represent vessel thickness, and Lagrangian formulation was adopted. Material properties of SA-508 Gr.3 Cl.2 and XM-19 steels were implemented using *MAT_PIECEWISE_LINEAR_PLASTICITY, incorporating plasticity, strain-rate effects, and experimental stress–strain data via *TABLE definitions, based on ASME Section II.D. The pressure–time histories were defined with *DEFINE_CURVE and applied as internal surface loads using *LOAD_SEGMENT_SET and *SET_SEGM, while gravity loading was modeled with *LOAD_GRAVITY_PART. In the actual containment vessel, the top and bottom are connected and supported via bolted joints. In the present simulation, these connections were simplified, and *TIED_SURFACE_TO_SURFACE was used to model the attachment.

2.4 Structural integrity assessment of i-SMR containment vessel

Structural integrity assessment was performed using LS-DYNA, adopting a conservative assumption in which the DDT load was simultaneously applied across the entire internal surface of the containment vessel. Fig. 3 shows the von-Mises stress distribution in the containment at the time when the peak stress occurred. The result showed that the maximum stresses occurred at the top and bottom regions of the containment vessel. In an actual containment vessel, there are several penetrations and stress concentrations are expected at such discontinuities. Therefore, additional analysis that explicitly account for penetrations is also required to achieve more realistic assessments.

To assess the calculation results compared to the ASME Service Loading Limit for Level C, stress linearization was carried out in accordance with ASME Section III, NB-3200 [4]. Stresses were categorized into membrane, bending, and local membrane components. Table I summarizes the linearization results in comparison with the ASME design criteria. The analysis demonstrated that, under a hydrogen DDT event within the i-SMR containment vessel, the resulting stresses remained within the allowable limits prescribed by the ASME's criteria.

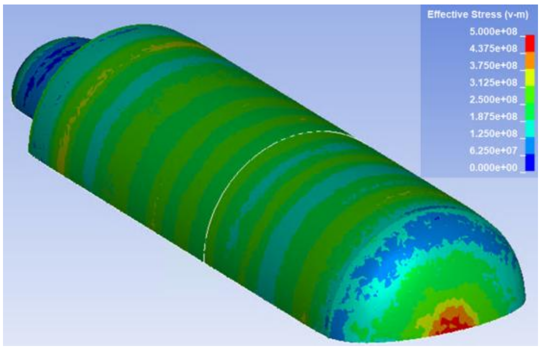

Fig. 3. Calculation result (von-Mises stress).

Table I. Calculation result compared to stress limit for ASME Level C service loading

Stress	Criteria	Calculation result
Membrane	$\mathrm{Max}(1.2S_m, 1.0S_y)$ = 405 MPa	240.5 MPa
Local membrane	$\mathrm{Max}(1.8S_m, 1.5S_y)$ = 675 MPa	358.8 MPa
Local membrane + Bending		399.7 MPa
Triaxial	$4.8S_m$ = 988.8 MPa	757.2 MPa

3. Conclusions

In this study, we performed a preliminary structural integrity assessment of the i-SMR containment vessel subjected to hydrogen deflagration-to-detonation transition (DDT) loads using LS-DYNA. The containment vessel was modeled under conservative assumptions, including the application of uniform internal surface pressure without accounting for penetrations or internal structures.

Dynamic response analyses indicated that the maximum von Mises stresses occurred at the top and bottom regions of the containment vessel. Although the simplified model excluded penetrations, stress concentrations are expected at such discontinuities in the actual vessel, indicating the need for further analyses that explicitly include these features.

Stress linearization in accordance with ASME Section III, NB-3200 showed that all membrane, local membrane, and combined stresses remained within the ASME Service Level C allowable limits. Triaxial stress evaluations also confirmed sufficient safety margins against yield criteria.

The results confirm that the i-SMR containment vessel maintains its structural integrity under conservative DDT loading scenarios. Comparative insights with NuScale's published analyses further support the validity of the applied methodology and its applicability to licensing evaluations.

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