Hydrogen Explosion Assessment Procedure, Criteria and Qualification for SMR Steel Containment Vessels (SCVs)

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1. Introduction

Ensuring the structural integrity of the containment vessel is one of the critical challenges in severe accident management during the development and licensing of Small Modular Reactors (SMRs). Unlike conventional large light water reactors, which predominantly adopt prestressed concrete containment vessels(PCCVs), leading SMR designs such as NuScale and SMART employ high-strength steel containment vessels(SCVs) to facilitate factory fabrication and modular construction. While this design shift dramatically reduces containment volume, it simultaneously introduces a novel safety concern: the potential for significantly elevated hydrogen concentrations per unit volume under accident conditions.

Hydrogen is generated in large quantities during reactor core damage through the high-temperature oxidation of zirconium(Zr) cladding by coolant water. In the aftermath of the Fukushima Daiichi accident, regulatory authorities have strongly mandated that containment vessels must not fail due to hydrogen combustion or detonation, even under severe accident conditions beyond the design basis. Although the small free volume of an SMR SCV presents the disadvantages of rapid hydrogen partial pressure buildup, it also offers the advantage of maximizing pressure resistance through the inherently high design pressure and ductility of steel.

This study clarifies the regulatory criteria for determining whether an internal hydrogen explosion assessment is required for SMR SCV designs, proposes a step-by-step technical procedure and methodology for conducting such an assessment when required, and details the structural integrity acceptance criteria for evaluating results.

2. Criteria for Determining Assessment Necessity (Regulatory Screening Criteria)

In SMR projects, the decision to perform a hydrogen explosion assessment is governed by rigorous regulatory requirements and phenomenological criteria. The primary filters are the U.S. Nuclear Regulatory Commission’s (NRC) 10 CFR 50.44 [1] and the corresponding technical standards of Korean Nuclear Safety and Security Commission (NSSC).

2.1 Regulatory Requirements: Enhanced Standards for Advanced Reactors

Early nuclear regulations considered only a limited quantity of hydrogen generated during design basis accidents (e.g., 5% of cladding mass), but the revised 10 CFR 50.44(c) (effective 2003) and the corresponding NSSC regulations apply more conservative standards to advanced water-cooled reactors, including SMRs.

2.2.1 100% Cladding-Coolant Reaction Condition

Regulations require that SMRs and other new reactor designs must be capable of accommodating the hydrogen generated by 100% oxidation of the active fuel region cladding metal with water, as expressed by:

$$Z_r + 2H_2O \rightarrow Z_rO_2 + 2H_2 + heat \tag{1}$$

This requirement ensures a deterministic safety margin, even for probabilistically improbable scenarios. Given the small free volume of an SMR containment relative to its core size, the resulting volumetric hydrogen concentration can readily exceed the flammability limit (4%) or the deflagration-to-detonation transition (DDT) threshold(approximately 18% or above.

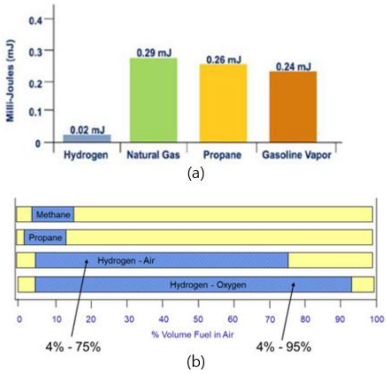

Fig.1 Hydrogen ignition energy(a), flammability range(b) [2]

2.1.2 Non-Inerted Atmosphere Condition

If the containment is permanently inerted with nitrogen during normal operation, maintaining sufficiently low oxygen concentration, hydrogen combustion can be precluded entirely. However, most SMRs maintain an air-filled atmosphere during normal operation for operational efficiency and maintenance accessibility. Consequently, SMRs operating under a non-inerted atmosphere may form flammable mixtures and must therefore conduct assessments demonstrating either hydrogen control capability or structural integrity [3].

2.2 Physical and Design Screening Criteria: The 10% Concentration Limit and Exemption Logic

10 CFR 50.44(c)(2) limits hydrogen concentration during and after an accident to 10% by volume. However, due to the small volume characteristics of SMRs, maintaining compliance with this 10% limit – even with large passive autocatalytic combiners (PARs) – may be physically infeasible during instantaneous hydrogen release events.

This creates a critical bifurcation point in determining assessment necessity:

- Concentration Control Strategy: If hydrogen concentration can be maintained below 10% through PARs or ignitors, the burden of detailed structural analysis for explosion pressure is reduced.

- Structural Protection Strategy (Exemption Request): If the concentration is expected to exceed 10%, but the SCV's pressure resistance capability is sufficiently high to maintain structural integrity even in the event of hydrogen combustion, detailed hydrogen combustion/explosion pressure assessment and structural integrity evaluation become mandatory. NuScale adopted this strategy and successfully obtained regulatory approval for an exemption from the 10% concentration limit requirement.

2.3 Decision Matrix for Assessment Necessity

The criteria for determining the necessity of assessment are summarized in Table 1.

Table 1: Decision Matrix

Criterion	Screened Out (No Assessment)	Assessment Required	Note
Applicable regulation	Licensed before Oct. 16, 2003	New License after 2003 (10 CFR 50.44 (c))	Most SMRs
Containment atmosphere	Permanently inerted (N2 filled)	Non-inerted (air-filled)	Presence of O_2 enables combustion
Hydrogen source	<75% cladding oxidation assumed	100% active fuel cladding oxidation	Regulatory upper bound
Design strategy	10% concentration control demonstrable	Concentration >10% expected or structural protection relied upon	Structural integrity demonstration required if control fails
Internal geometry	Open large space (simple geometry)	Complex compartments, piping, obstacles	FA and DDT potential assessment needed

3. Assessment Procedure and Methodology

Once the need for a hydrogen explosion assessment has been established, simple static calculations alone are insufficient to satisfy regulatory requirements. A multi-stage methodology integrating thermal-hydraulic and structural analyses is required to characterize complex flow and combustion behavior within SMR containment. The following standardized procedure is based on the latest technical guidance from OECD/NEA and IAEA, as well as precedent SMR licensing cases.

- Step 1: Accident Scenario Selection and Source Term Definition
  - Scenario Selection: Scenarios posing the greatest risk of core, such as loss-of-coolant accident (LOCA), station blackout(SBO), or total loss of feedwater(TLOFW), are typically selected. For SMRs, multiple release locations (e.g., lower or upper containment) must be considered, as the hydrogen release location varies with pipe break position [4].

  - Hydrogen concentration calculation:
    - Regulatory source term: Per 10 CFR 50.44, total hydrogen mass is calculated assuming complete oxidation of all zirconium in the active fuel region.
    - Release rate calculation: Severe accident analysis codes such as MELCOR, MAAP, or RELAP5 are used to compute time-dependent hydrogen and steam release rates, which serve as boundary conditions for three-dimensional analyses.

- Step 2: Three-Dimensional Hydrogen Distribution and Mixing Analysis (CFD)
  SMR containments have narrow and complex internal flow paths due to integrated steam generators, pressurizers, and densely arranged modular components. The "well-mixed" assumption risks missing a localized high-concentration hydrogen pocket.

- Step 3: Flame Acceleration (FA) and Deflagration-to-Detonation Transition (DDT) Screening
  This step is most critical in the assessment. The key question is not simply "will ignition occur?" but "will the resulting flame accelerate into a detonation capable of destroying the containment?" The OECD/NEA Sigma-Lambda criterion is the established framework for this evaluation.

- Flame Acceleration (FA) Assessment: Sigma(σ) Critrion [5]
  Flame acceleration is driven by the expansion of combustion gases. When the expansion ratio exceeds a critical threshold, the flame can accelerate to near-sonic velocities.
  - Assessment index (σ) = $\rho_{unburned}/\rho_{burned}$ (density ratio = expansion ratio)
  - Decision criterion: In regions with obstacles, σ > $\sigma_{critical}$ (typically 3.75) indicates flame acceleration potential [6]
- DDT Assessment: Seven-Lambda (7λ) Criterion [7]
  For an accelerated flame to transition into a detonation accompanied by a shock wave, the geometric dimension of the space must be sufficiently large relative to the detonation cell size.
  - Assessment index: L (characteristic length, e.g. compartment width or diameter) vs. λ (detonation cell width of the mixture)
  - Detonation cell width: A measure of mixture reactivity; high steam content or low hydrogen concentration increases λ making detonation less likely.
  - Decision criterion: L > 7 λ indicates DDT is geometrically feasible; if L < 7 λ, DDT is geometrically precluded.

- Step 4: Combustion Load Definition

Structural analysis loads are determined based on the FA / DDT screening results.

- Scenario A (Detonation Precluded): When DDT conditions are not satisfied (e.g., L<7 λ), the adiabatic isochoric complete combustion (AICC) pressure is computed as the most conservative quasi-static equivalent load, assuming instantaneous combustion of all hydrogen without shock wave formation [8].

- Scenario B (Detonation Possible): When DDT cannot be precluded, detailed detonation simulations are required to derive time-history dynamic pressure profiles. Local detonation pressures can be several times the AICC pressure, with durations on the order of milliseconds [9].

- Step 5: Structural Integrity Analysis (FEA)

The determined loads are applied to a three-dimensional finite element method (FEM) of the SCV. Depending on load characteristics, either static analysis or explicit dynamic analysis is performed.
For example, a realistic hydrogen explosion simulation can be performed considering an Eulerian medium, such as water or air, inside or outside the containment vessel.

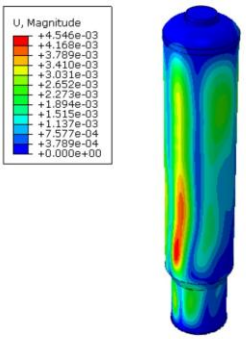

Fig. 2 Hydrogen explosion simulation in the containment vessel of NuScale Power Module using CEL (Coupled Eulerian and Lagrangian method

4. Acceptance Criteria for Assessment Results

To demonstrate SCV structural integrity, the assessment results must satisfy recognized technical standards. Because the SMR SCV is a metallic structure, the primary applicable standard is ASME Boiler and Pressure Vessel Code (BPVC) Section III, Division 1, Subsection NE (Class MC components).

4.1 Differentiated Acceptance Criteria by Combustion Mode

Pass/fail criteria are applied differently based on the severity and frequency of the combustion phenomenon.

Table 2: Loading Conditions

Loading Condition	Applicable Scenario	ASME Service Level	Notes
Design basis load	Localized combustion, residual H2 during PAR operation	Level C (Emergency)	Minimize structural deformation; consider reusability
Severe accident load	Detonation from 100% cladding oxidation	Level D (Faulted)	Focus on preventing rupture and maintaining containment function (plastic deformation permitted)

4.2 Detailed Stress and Strain Criteria

4.2.1 Stress-Based Criteria (Quasi-static loads such as AICC)

- Level C: Primary membrane stress (P_m < 1.2 S_m (design stress intensity) or 1.0 S_y (yield strength), whichever is greater.
- Level D: Primary membrane (P_m) < 0.7S_u (ultimate tensile strength), reflecting the capacity to sustain significant loading without fracture.

4.2.2 Strain-Based Criteria (Impulsive loads such as detonation)

For high-rate impulsive loads such as detonation, elastic analysis may be physically meaningless or excessively conservative. Plastic strain-based acceptance criteria are therefore appropriate and are accepted practice by the NRC and the nuclear industry.

- General membrane regions: Effective plastic strain ($\epsilon_{plastic,eq}$) < 1.5% [10]

- Local discontinuity regions: Higher strains are permissible at penetrations, nozzles, and other stress concentration points, governed by:

$$\varepsilon_{allowable} = \epsilon_{uniaxial}/TF \qquad (2)$$

where TF is the triaxiality factor. Local strains up to 10~15% may be acceptable but must be verified through detailed analysis.

However, further research is needed to establish more rigorous strain-based acceptance criteria. In particular, the currently adopted effective strain limit for membrane regions lacks a universally validated empirical foundation specific to hydrogen detonation loading conditions, and its application relies heavily on engineering judgement and precedent from analogous impulsive load scenarios. Systematic experimental investigations and high-fidelity numerical studies are needed to characterize the dynamic fracture behavior of SCV materials under biaxial and triaxial stress states induced by rapid internal pressure transients. Furthermore, the triaxiality factor (TF) used in deriving allowable local strains is currently determined on a case-by-case basis without standardized guidance. Establishing consensus-based, code-backed framework would significantly enhance the consistency, defensibility, and predictability of hydrogen explosion qualification for SMR steel containment vessels.

5. Conclusions

Internal hydrogen explosion assessment for SMR steel containment vessels is a mandatory licensing requirement under contemporary nuclear regulatory frameworks. The extreme source terms of 100% cladding oxidation combined with non-inerted atmospheric operation imposes stringent safety demonstration requirements on SMR designs.

The principle conclusions of this investigation are as follows:

- Assessment Necessity: All non-inerted water-cooled SMRs licensed after 2003 must demonstrate either hydrogen control or structural integrity under 100% cladding oxidation scenarios.
- Assessment Methodology: Three-dimensional CFD-based detailed distribution analysis combined with OECD/NEA Sigma-Lambda screening for flame acceleration and DDT is technically appropriate and represents the state of practice.
- Acceptance Criteria: For explosion loads under severe accident conditions, ASME Section III Level D is applicable. For impulsive loads, strain-based criteria with an effective plastic strain limit of 1.5% would be a rational and defensible standard. However, there are still some ambiguities and a lack of consensus regarding the determination of reasonable criteria. Therefore, further relevant studies are required.

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