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Comparison of Regulatory Methodologies and Cases for SMR Combustible Gas Control: NuScale SMR vs SMART100

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1. Introduction

The Fukushima nuclear accident resulted in hydrogen explosions, leading to the release of radioactive material. This accident has highlighted the critical importance of combustible gas control, strengthening the need for stringent regulatory standards and guidelines. In conventional large pressurized water reactors (PWRs), the reinforced concrete containment buildings have a large free volume, allowing for the installation of multiple hydrogen control systems and devices.

However, small modular reactors (SMRs), which are currently under development, have much smaller containment volumes and incorporate various design differences. Therefore, a comprehensive review is needed to determine whether existing regulations on combustible gas control measures adequately address the unique design characteristics of SMRs [7, 9]

Notably, many existing regulatory standards and guidelines for combustible gas control are expected to face challenges in adequately addressing the limited containment volume and vacuum containment design of SMRs.

In this study, we systematically compile and compare the regulatory frameworks for combustible gas control in the United States, a leader in SMR technology, and South Korea in a tabular format. Furthermore, we summarize the licensing cases of SMRAT100 and NuScale SMR.

2. Analysis of Domestic and International Nuclear Reactor Design Characteristics

The design characteristics of containment buildings, containment vessels (CNV), and combustible gas control requirements were compared and summarized among domestic large PWRs, the NuScale SMR, and the i-SMR.

2.1 Design Characteristics of Domestic Large PWRs

In large domestic PWRs, the containment system consists of a reinforced concrete containment building and an internal steel liner. The presence of internal compartments gives the containment a structurally complex characteristic.

The hydrogen monitoring system is equipped with a dedicated sampling pump; samples collected from the reactor building are cooled and subsequently transferred to an analytical device for hydrogen concentration monitoring [1, 7].

2.2 Design Characteristics of NuScale SMR

NuScale SMR employs a steel CNV, with an internal free volume that is approximately one-hundredth of that found in large PWRs, making the installation of hydrogen control and monitoring systems more challenging.

Since the CNV has no internal compartments and features a simple structure, any hydrogen generated disperses quickly, minimizing the likelihood of localized high-concentration regions. Furthermore, since the reactor coolant system (RCS) and the CNV are integrated, coolant from the RCS enters the CNV in the event of an accident, forming a mixed atmosphere [8].

Uniquely, the CNV is maintained under vacuum. The Containment Evacuation System (CES), which sustains this vacuum, also analyzes vented gases to monitor hydrogen and oxygen concentrations [8].

2.3 Design Characteristics of i-SMR

For the domestically developed i-SMR, the free volume available for combustible gases is expected to be smaller than that of large PWRs. However, considering the power difference between the NuScale SMR (77 MWe) and the i-SMR (170 MWe), the i-SMR may have a larger free volume than the NuScale SMR. Ultimately, this will depend on detailed design specifications.

3. Analysis of Domestic and International Regulatory Requirements and Methodologies

Domestic regulatory requirements for combustible gas control are applied separately based on Design Basis Accidents (DBA) and Beyond Design Basis Accidents (BDBA). In contrast, in the United States, regulatory requirements for combustible gas control are comprehensively stipulated in 10 CFR 50.44 without such distinctions.

3.1 Internal Regulatory Requirements and Methodology Analysis

3.1.1 Combustible Gas Control – DBA

[KINS/RG-N07.08, Rev. 4] 7.8 Control Combustible Gas in Nuclear Containment [2]

Mixed Atmosphere
A.4) After a DBA occurs, it must be ensured that performance during the required operation time.
A.5) It must demonstrate that the atmosphere can be mixed to prevent localized accumulation of combustible gas.

Control Combustible Gas
A.1) The combustible gas control system can control hydrogen generated through various processes in the nuclear containment.
C.1) During a DBA, the calculation of hydrogen and oxygen concentrations and the validity assessment of the combustible gas control system design must be estimated by the given criteria, which must be required valid basis.
D.1) Multiple nuclear installations can share portable hydrogen thermal recombiner.
E.1) Materials that can generate hydrogen due to corrosion must be identified, and their use must be appropriately limited.

Equipment Survivability
A.3) The combustible gas control system must not affect the integrity and safety functions of the reactor containment.

Monitoring
A.2) Under accident conditions, instrumentation must be provided to continuously monitor hydrogen concentration as well as the performance of systems and equipment. In addition, the main control room should be supplied with ongoing indicators and information related to hydrogen concentration.
B.1) The flammable gas control system and additional equipment must be designed to allow for periodic operation inspections and operability tests.

Hydrogen Concentration Limit	
4 v/o (-6v/o)	- The hydrogen concentration can increase up to a maximum of 6 v/o assuming that oxygen of 5 v/o or more exists in the reactor containment and hydrogen in excess of 2 v/o is combusted. - In this case, safety-related equipment must not be subjected to conditions exceeding the design limits, and the operator must provide appropriate analysis results and validation test results

Ventilation and Purification System
E.1) The containment ventilation and purification system can be separate systems or part of other systems.

** Classification criteria A. Design of the combustible gas control system / B. Inspection and testing / C. Assessment of design feasibility / D. Equipment sharing / E. Combustible gas ventilation and purification*

3.1.2 Combustible gas Control – BDBA

[KINS/RG-N016.02, Rev.4] 16.2 Assessment of severe accident mitigation capability [3].

General Regulatory Position
1) Accident scenarios should be selected based on engineering judgment and probabilistic safety assessment results for each factor threatening the integrity of the reactor containment, and a deterministic analysis should be conducted to assess severe accident mitigation capability
2) When conducting deterministic analysis, realistic assumptions and methodologies can be applied. However, uncertainties included accident progression and analysis methodologies should be considered

Combustible Gas Combustion or Explosion
1) The containment integrity analysis for combustible gas combustion or explosion assumes the amount of hydrogen generated by the reaction of all effective core cladding metal with the coolant (100% metal-water reaction).
A) Even if overpressure occurs due to the sudden combustion of accumulated combustible gases, the containment building must maintain its protective barrier function.
B) Assuming that combustible gases are uniformly distributed within the containment, the hydrogen concentration must be below 10%.
C) The local concentration of combustible gases within the containment must be controlled to prevent large-scale flame acceleration or deflagration-to-detonation transition (DDT).
2) In the case of a prolonged accident, the impact of additional combustible gases, such as carbon monoxide, must also be considered.
3) The concentration of combustible gases must be continuously monitored

3.2. NRC Regulatory Requirements and Methodology

10 CFR 50.44 (c) Requirements for future water-cooled reactor applicants and licensees [10].

Mixed Atmosphere
All containments must have a capability for ensuring a mixed atmosphere during design-basis and significant beyond design-basis accidents.

Combustible Gas Control
The containment should either contain an inert gas or ensure that the hydrogen concentration remains below 10% in an accident where hydrogen is released in an amount equal to that generated by a 100% fuel-coolant reaction. The integrity of the containment must be maintained, and appropriate equipment should be installed to safely manage hydrogen.

Equipment Survivability
Containments must maintain structural integrity during and after the period of hydrogen release. Environmental conditions caused by hydrogen explosions must also be considered, unless it can be demonstrated that such explosions are unlikely to occur.

Monitoring
Equipment must be provided for monitoring oxygen and hydrogen in the containment. The equipment must be functional, reliable, and capable of continuously measuring the oxygen concentration even after a severe accident.

Structural Analysis
The operator must conduct an analysis to demonstrate the structural integrity of the containment. The analysis must use methodologies accepted by the NRC and include justification for structural loads.

3.3 KTA Regulatory Requirements and Methodology

[KTA 2103 (2022-11)] 4.10 Preventing Explosive Hydrogen Mixtures Inside the Containment Vessel [15]

4.10.1 General requirements
Explosion safety criteria require that, under normal operation and DBA conditions, the hydrogen concentration within the containment be controlled to remain at least 0.5 vol% below the lower flammability limit (LFL) of 4.0 vol% in air, taking into account all credible hydrogen sources.

4.10.3 Preventing explosive hydrogen concentrations in the containment vessel after a loss-of-coolant accident (LOCA)
Explosion prevention in the CNV following a LOCA requires forced mixing to avoid local hydrogen accumulation, while recombiners shall maintain concentrations below the lower explosion limit. Monitoring and mitigation systems must remain reliable under post-accident conditions, with active measures triggered at 3.5 vol%.

3.4 ASN Regulatory Requirements and Methodology

[ASN Guide n°22 Version 18/07/2017] Design of PWRs [17]

Section 5.3.1.3
Containment systems in PWRs must be designed to tolerate rapid local hydrogen deflagrations and potential DDT through structural measures such as reinforced internal compartments. To ensure a safe response following a core melt accident, the design must allow for a passive grace period without relying on active residual heat removal systems. Additionally, passive autocatalytic recombiners (PARs) or igniters are required to limit hydrogen concentration and prevent explosive atmospheres, thereby preserving containment integrity during severe accident conditions.

3.5 Comparison of Domestic and International Regulatory Requirements

10CFR50.44 [10].	
10 v/o	When the hydrogen generated from a 100% fuel-cladding coolant reaction is uniformly distributed, the hydrogen concentration in the containment must be limited to below 10% by volume, and the structural integrity and accident mitigation functions of the containment must be maintained.

Section 7.8 – DBA [2]	
4 v/o (-6v/o)	- The hydrogen concentration can increase up to a maximum of 6 v/o assuming that oxygen of 5 v/o or more exists in the reactor containment and hydrogen in excess of 2 v/o is combusted. - In this case, safety-related equipment must not be subjected to conditions exceeding the design limits, and the operator must provide appropriate analysis results and validation test results.

Section 16.2 – BDBA [3]	
10 v/o	Assuming that the hydrogen generated by the reaction of 100% of the core cladding metal with the coolant is even distributed in the reactor containment, the hydrogen concentration should be maintained below 10%.

KTA 2103 – 4.10.1 [15]	
4vol% (3.5vol%)	Hydrogen concentration in the containment must remain at least 0.5 vol% below the lower explosion limit (4.0 vol%), considering all sources. Mitigation shall be triggered at 3.5 vol%.

4. Comparison of Combustible Gas Control Analysis Methodologies for SMART100 and NuScale

4.1 SMART100 Combustible Gas Control Analysis Methodology

SMART100 is an SMR that introduces passive safety concept to SMART, which already received Standard Design Approval in 2012, and increases thermal power from 330MWt to 365MWt [6].

As a result of analyzing the combustible gas mixture in the containment building of SMART100, they found that the hydrogen concentration in the containment building was below 0.5% based on using the CAP code.

Additionally, MELCOR 2.2 and OpenFOAM CFD models were used to analyze the distribution of combustible gases and hydrogen combustion, considering hydrogen generated from the 100% reaction between nuclear fuel cladding metal and coolant.

The applicant evaluated that a space of more than 25 meters is required for detonation to occur at a hydrogen concentration of 30% based on the equivalence ratio, citing the FLAME experiment results from the NUREG/CR-5275 report. As a result, no detonation occurred in the upper region of the containment building, and it was confirmed that neither flame acceleration nor DDT occurred due to the sufficiently low hydrogen concentration [5].

As a result of the review of the SMART100 Standard Design Approval at the 201st Nuclear Safety and Security Commission meeting, the LOCA analysis in the passive safety emergency cooling system, which applied a conservative evaluation methodology, confirmed that SMART100 meets the acceptance criteria, with the highest fuel cladding temperature (352.8℃) without core exposure, maximum cladding oxidation (below 0.0005%), and maximum hydrogen generation (below 0.0002%) [6].

**Conservatively evaluated in accordance with the performance criteria for the emergency core cooling system (NSSC Notice No. 2017-23), considering a small-break loss-of-coolant accident (SBLOCA) where coolant is released through a nozzle with a maximum inner diameter of 50 mm.*
***Maximum cladding temperature : below 1,204℃, Maximum cladding oxidation : below 17%, Maximum hydrogen generation : below 1%*

4.2 NuScale Combustible Gas Control Analysis Methodology

The NuScale SMR demonstrated the ability to properly mix the internal atmosphere within the CNV, maintaining a stable atmosphere that doesn't reach concentrations capable of causing deflagration or detonation. It ensures the atmospheric mixing by decay heat and confirms that there is no local accumulation of combustible gases due to the absence of lower compartments [8].

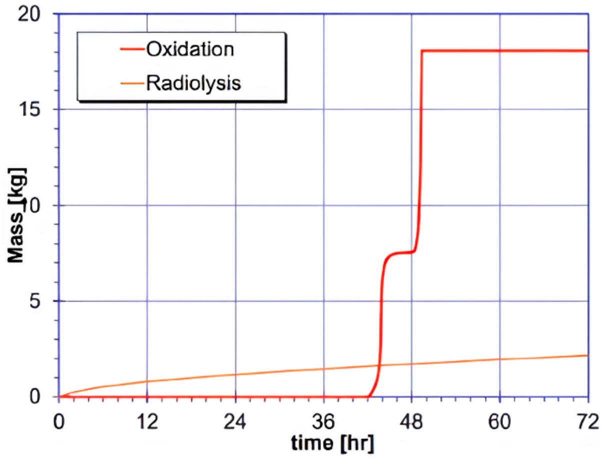

Fig 1. The total amount of hydrogen produced from cladding oxidation and radiolysis was assessed by the U.S. Nuclear Regulatory Commission (NRC) [16]

Hydrogen generation from radiolysis shows a gradual increase over time, whereas cladding oxidation leads to a rapid and significant release beginning around 48 hours, marking the onset of severe core degradation. When the Emergency Core Cooling System (ECCS) was activated at approximately 49 hours after the event initiation, an estimated 18 kg of hydrogen—representing about 19% of the total hydrogen yield expected from complete cladding oxidation—had been produced. The containment integrity was subsequently assessed based on the corresponding AICC (Adiabatic Isochoric Complete Combustion) pressure. [16]

Nuscale Design does not rely on active devices to limiting the hydrogen concentration within the CNV for 72 hours. Additionally, internal components of the CNV are designed to endure the maximum explosion load from deflagration, incident detonation, reflected detonation, and DDT accidents, even in the event of a 100% fuel cladding-coolant reaction.
That is, It does not exceed the pressure capacity during DBA [14].

As a result of structural analyzing of the CNV, it was confirmed that a 60% margin is secured for the design stress limit under reflected explosion loads and a 15% of margin is secured under DDT loads.
Through severe accident analysis, it was quantitatively demonstrated that integrity of the CNV is maintained, and it was confirmed that 85% margin is secured for the design stress limit under Membrane Hoop Strain.
When a LOCA occurs as a DBA, the Reactor Pressure Vessel (RPV) is depressurized through valve opening or rupture, and the reactor coolant is released into the CNV. The released coolant remains in a liquid state as it

condenses on the cool inner walls of the CNV, which is designed to be submerged in the water pool.
Despite this process, if heat cannot be removed effectively, the high-pressure state persists due to the additional generation of steam in the CNV.
Then, coolant recirculated to the RPV through the Reactor-Recirculation-Valve (RRV), to prevent core exposure [14].

5. Conclusion

This study compared the design characteristics of existing large PWRs and SMRs and analyzed the differences between U.S.NRC regulations (10 CFR 50.44), Germany.KTA regulations, France ASN and domestic regulations.

Additionally, it summarized the combustible gas control methodology reports for SMART100 and NuScale SMRs.
In existing large PWRs, the large containment building makes the accumulation and control of combustible gases an important design consideration [1].
On the other hand, SMRs use relatively small containment vessels with a simple internal structure, which limits the available space for installing systems to monitor and control hydrogen concentration. Additionally, combustible gases are more likely to mix rapidly [8].
NuScale SMR demonstrated that hydrogen combustion cannot occur and confirmed through load analysis that structural integrity of the CNV and its safety functions remain unaffected even in the event of hydrogen combustion resulting from a 100% fuel cladding-coolant reaction [11].

Because of these differences, it is difficult to applicate SMRs the existing combustible gas control regulation for existing large PWRs. Therefore, It is necessary to recognize these limitations and make effort to establish appropriate regulations or control strategies that reflect the design characteristic of SMRs.

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REFERENCES

[1] 한국수력원자력. (2022). 신한울원자력 1,2 호기 최종안전성분석보고서. 한국원자력안전기술원.

[2] KINS/RG-N07.08, 원자로격납건물 내 가연성기체 제어

[3] KINS/RG-N016.02, Rev.4, 중대사고 완화능력의 평가

[4] KINS/RG-N016.03, Rev.1, 중대사고 예방 및 완화설비의 기기생존성 평가

[5] SMART100 표준설계인허가 심사보고서 (초안) - 공개본

[6] 대한민국 원자력안전위원회. (2024 년 7 월 11 일). SMART100 표준설계인가 심의 관련 보고.

[7] Korea Hydro & Nuclear Power Co., Ltd. (2018). APR1400 Design Control Document, Tier 2, Chapter 5 - Reactor Coolant System and Connecting Systems: Revision 3. Retrieved from https://www.nrc.gov/docs/ML1822/ML18228A652.pdf

[8] NuScale Power. (2020). Chapter Six Engineered Safety Features: NuScale Standard Plant Design Certification Application. Retrieved from https://www.nrc.gov/docs/ML2022/ML20224A494.pdf

[9] U.S.NRC. (2016). Combustible gas control in containment : Design-specific review standard for NuScale SMR design. Retrieved from https://www.nrc.gov/docs/ML1535/ML15356A356.pdf

[10] U.S.NRC. 10CFR50.44

[11] NuScale Power(2016). “Exemptions PART7”. ML17013A306.

[12] NuScale Power(2016). “Combustible Gas Contrl”. TR-0716-50424.

[13] Regulatory Guide 1.7, “Control of Combustible Gas Concentrations in Containment Following a Loss-of-Coolant Accident”, U.s. NRC, 1978

[14] S. Nuclear Regulatory Commission. (2019). Independent MELCOR Confirmatory Analysis for NuScale Small Modular Reactor (ML19196A306).

[15] KTA Safety Standards Commission, *KTA 2103: Explosion Protection in Nuclear Power Plants with Light Water Reactors – General and Case-Specific Requirements*, KTA Rules, Issue 2022-11, July 2023.

[16] U.S. Nuclear Regulatory Commission, *Reactor Oversight Process Self-Assessment for Calendar Year 2018*, NRC Accession No. ML19312A082, 2019.

[17] Autorité de Sûreté Nucléaire (ASN), Guide n°22: Conception des réacteurs à eau sous pression, Version du 18/07/2017, réalisé conjointement avec l’Institut de radioprotection et de sûreté nucléaire (IRSN).