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

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Introduction

- The Fukushima nuclear accident underscored the critical importance of controlling combustible gases, as hydrogen explosions led to the release of radioactive materials.
- Emerging small modular reactors (SMRs) introduce unique challenges in this context due to their:
  - *"Much smaller containment volumes"*
  - *"Vacuum-type containment designs"*
- A comprehensive assessment is necessary to determine whether existing regulatory frameworks are adequate for the safe operation of SMRs.

Analysis of Domestic and International Nuclear Reactor Design Characteristics

Characteristics	Large domestic PWRs	NuScale SMR	i-SMR (Expected)
CNV	• Large free volume • Multiple compartments present • Air	• Small free volume • No compartments • Vacuum	• Small free volume • No compartments • Vacuum
System	• Not integrated	• Integrated	• Integrated
Combustible gas component	• 30 (PARs) and 10 hydrogen igniters	• No Combustible gas control systems	• No Combustible gas control systems
Combustible gas Monitoring	• Hydrogen concentration is monitored at the sampling points through the hydrogen monitoring system	• sampling and monitoring of hydrogen concentration from outside the CNV • The system operates under internal pressures up to 250 psi and during (BDBAs)	• External monitoring via the vacuum system is possible, (similar to the NuScale SMR design)

Analysis of Domestic and International Regulatory Requirements and Methodologies

Domestic : hydrogen generated by the reaction of 100% of the core cladding metal with the coolant is even distributed in the reactor containment. 〈 DBA – 4 v/o (-6 v/o), BDBA – 10 v/o 〉

NRC (USA) : 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 v/o, and the structural integrity and accident mitigation functions of the containment must be maintained.

KTA (Germany) : Hydrogen concentration in the containment must remain at least 0.5 v/o below the lower explosion limit (4.0 v/o), considering all sources. Mitigation shall be triggered at 3.5 v/o.

NRC 10CFR50.44	10 v/o
KINS Section 7.8 – DBA	4 v/o (-6 v/o)
KINS Section 16.2 – BDBA	10 v/o
KTA 2103 – 4.10.1	4 v/o (-3.5 v/o)

Comparison of Combustible Gas Control Analysis Methodologies for SMART100 and NuScale

❖ SMART100 is an SMR that incorporates passive safety concept into SMART, which already received Standard Design Approval in 2012, and increases thermal power from 330MWt to 365MWt

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.

Review Meeting	201st Nuclear Safety and Security Commission	Review result of SMART100 Standard Design Approval
Evaluation Content	➢ LOCA	Applied conservative evaluation method for the passive safety emergency cooling system
Peak Fuel Cladding Temperature	➢ 352.8℃	Meets criteria without core exposure
Cladding Oxidation	➢ Below 0.0005%	Confirmed to be within safety limits
Hydrogen Generation	➢ Below 0.0002%	Very low hydrogen production
Overall Evaluation Result	➢ Acceptance Criteria Met	SMART100 design satisfies safety

- The NuScale SMR demonstrated effective internal atmosphere mixing within the CNV, preventing the accumulation of flammable gas concentrations that could lead to deflagration or detonation.
- AICC pressures were assessed both before and after the 72-hour mark during severe accident scenarios, confirming sufficient pressure margins even in the event of a DDT.

Internal Atmospheric Mixing	✓ Stable atmosphere maintained, below flammability or detonation limits Internal atmosphere is mixed by decay heat; no lower compartments prevent gas accumulation
Explosion Load Structural Analysis	✓ 60% margin secured compared to design stress limit under reflected explosion loads Structural integrity confirmed under explosion conditions
DDT Load Structural Analysis	✓ 15% margin secured under Deflagration to Detonation Transition (DDT) loads Structural safety ensured under extreme accident conditions
Membrane Hoop Strain	✓ 85% margin secured against design stress limit Structural integrity quantitatively demonstrated through severe accident analysis
LOCA Response	✓ RPV depressurizes → coolant released into CNV → condensed and remains liquid CNV is submerged in water pool; inner walls remain cool to condense steam
When Heat Removal Fails	✓ Internal pressure remains elevated due to continuous steam generation Potential increase in CNV internal pressure if heat removal is ineffective
RRV Operation	✓ Coolant is recirculated to RPV to prevent core exposure Core safety functions are preserved under heat removal failure scenarios

Conclusions

- This study compared the design characteristics and regulations
  - domestic
  - NRC (USA)
  - KTA (Germany)
- It is difficult to apply the existing combustible gas control regulations for large PWRs to SMRs.

The suitability of installing PARs in NuScale SMR remains under review due to differences in containment configuration and thermal-hydraulic behavior.

Therefore, it is necessary to recognize these limitations, and an effort should be made to establish appropriate regulations or control strategies that reflect the design characteristics of SMRs.

We plan to calculate combustible gas concentrations using MELCOR, evaluate AICC pressure, and assess the containment's structural integrity.