KNS-26S

Numerical Investigation for Nature & Energy Lab.

Hydrogen Flammability Assessment in SMR Containment Using the CAFT Model

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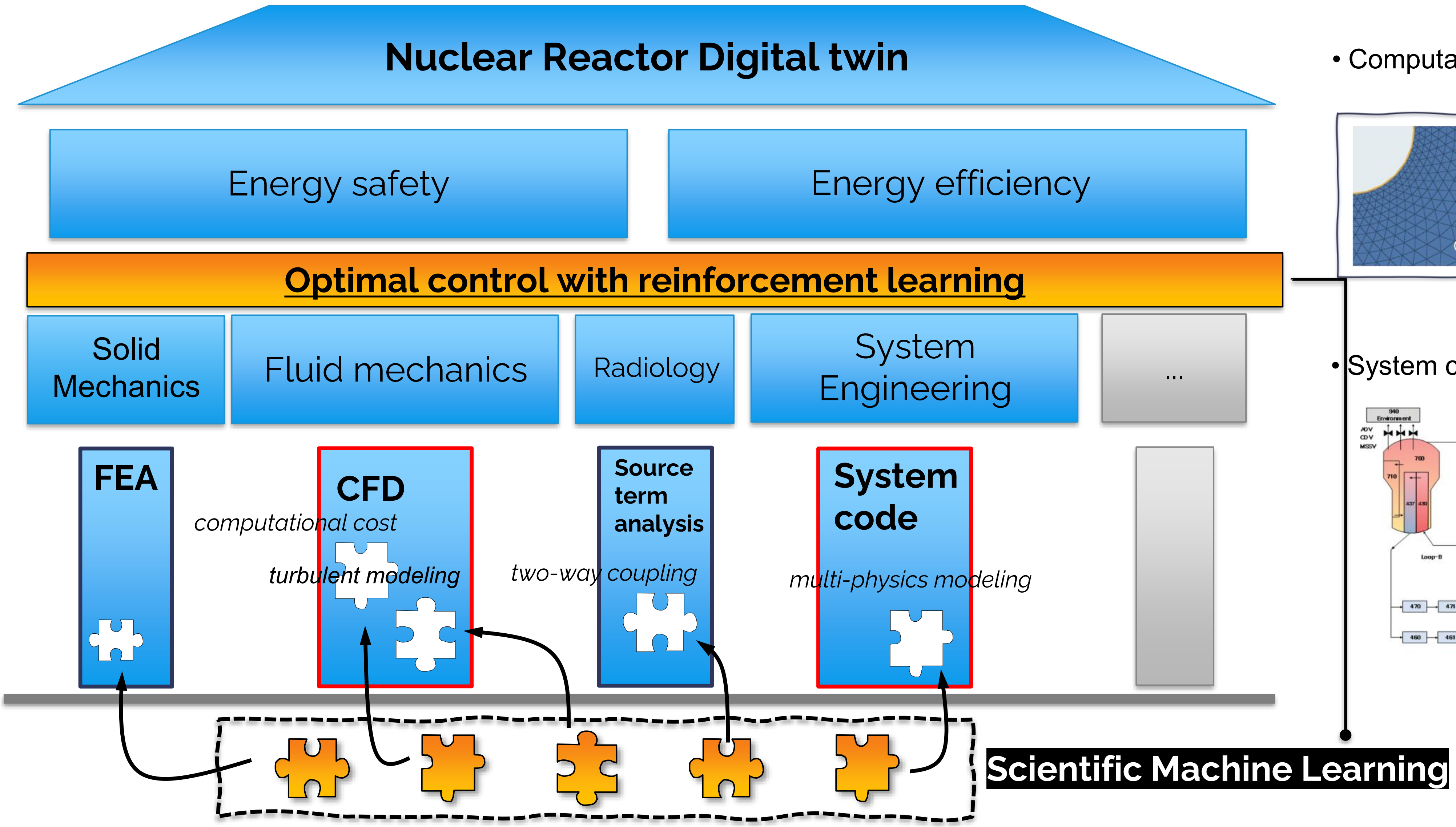
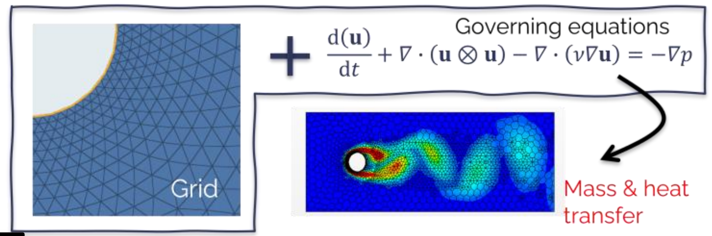
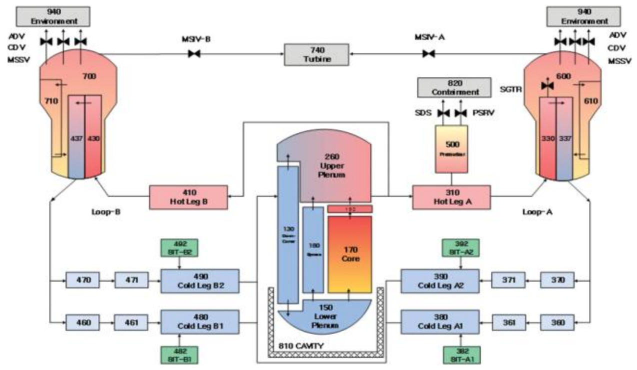
NINE Lab’s Vision



- Computational fluid dynamics (CFD)



- System code (nuclear reactor)



Introduction

Overview

1. What is CAFT model?

- A thermodynamic model that determines flammability by calculating the maximum adiabatic flame temperature of a given gas mixture.

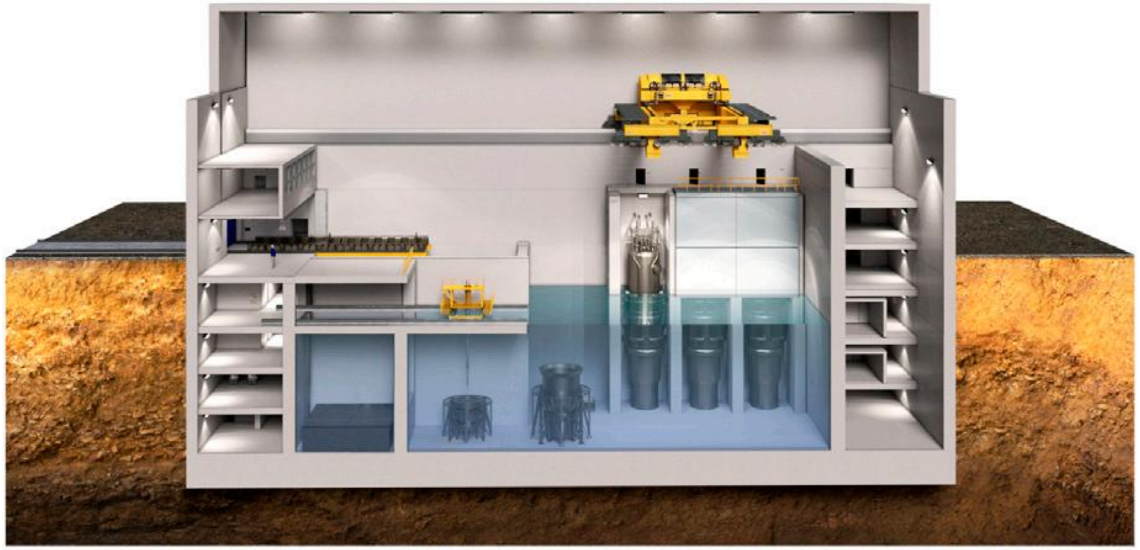
2. Why CAFT model for SMRs?

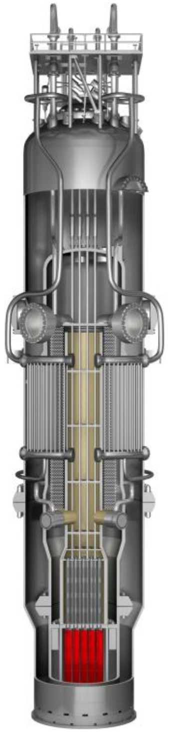
- Experimental data are scarce under hydrogen-rich and high-T/P conditions; the CAFT model overcomes these limits and is applicable to UFL regimes characteristic of SMR vacuum CNVs.

3. Flammability Assessment in NuScale SMR Severe Accident

- CAFT analysis identifies flammable conditions during 44–48 h, integrating the combined contribution of all major species through a single thermodynamic metric — **refining the conservative margins of single-species criteria with a more accurate, energy-based evaluation.**

Introduction





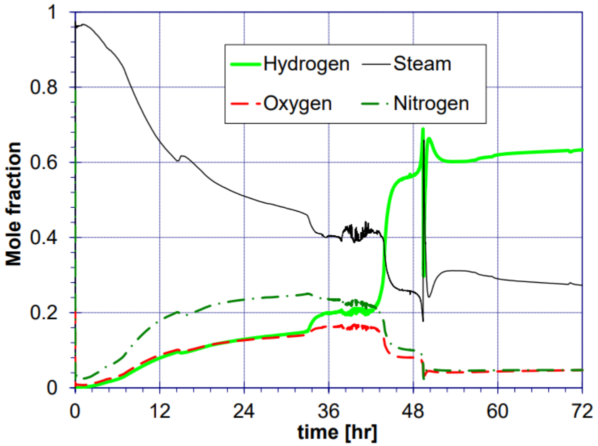


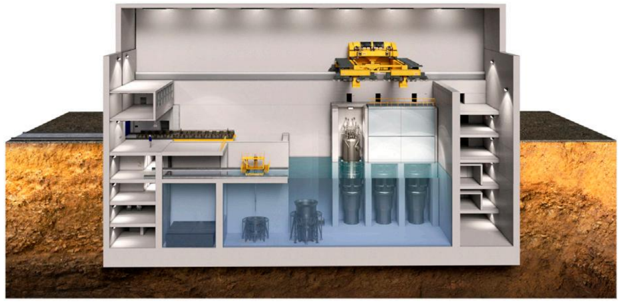
Figure 3.5 Control-volume-averaged containment atmosphere composition

Why Rich-hydrogen Condition?

- **Initial state: NuScale SMR** adopts a vacuum CNV → Low initial O_2 inventory → Combustion-inert atmosphere
- **During Severe Accident:** Massive H_2 generation by Core oxidation + Steam condensation on cold CNV walls reduces steam fraction → **H_2 concentrates rapidly**
- **Consequence:** O_2 production from radiolysis can drive the mixture toward the **Upper Flammability Limit(UFL)**

[1] Welter et al., *Unique safety features and licensing requirements of the NuScale small modular reactor*, Frontiers in Energy Research, 2023

Introduction



NuScale SMR

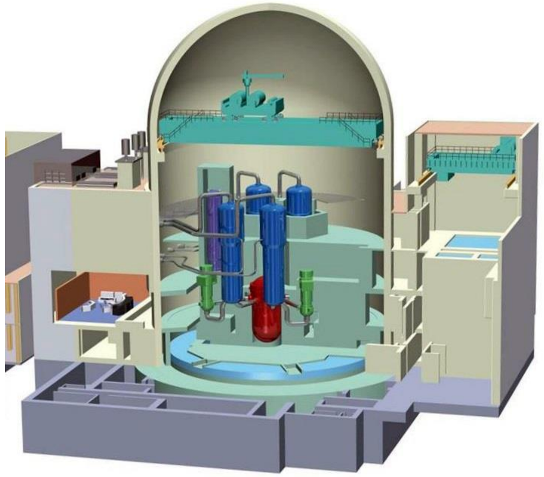
- Small vacuum CNV
- Persistently low O_2 inventory
- H_2 concentrates in CNV

→ **Rich-H_2 condition**

Large PWR

- Large containment volume
- Substantial O_2 inventory throughout SA
- H_2 diluted in large volume

→ **Lean-H_2 condition**



Research Gap

- Conventional flammability assessment tools (e.g., LFL-based criteria, single-species O_2 thresholds) have been **developed and extensively validated for lean-H_2 conditions** typical of large PWR severe accidents.
- However, **their applicability to rich-H_2 conditions—characteristic of SMR vacuum CNVs—has not been systematically verified.**

[1] Kevin Fernandez-Cosials, *ANALYSIS AND IMPROVEMENT OF HYDROGEN MITIGATION STRATEGIES DURING A SEVERE ACCIDENT IN NUCLEAR CONTAINMENTS*, UNIVERSIDAD POLITÉCNICA DE MADRID, 2017

Introduction

Research Objective & Novelty

Objective

- Verify the applicability of the CAFT model under hydrogen-rich conditions characteristic of SMR vacuum CNVs
- Apply the validated CAFT model to a representative NuScale severe accident transient (LCC-05T-03, ERI/NRC 18-202)

Novelty / Contribution

- First application of CAFT-based flammability assessment to SMR vacuum CNV transient data
- Identifies a **previously-unreported flammable window (44–48 h)**

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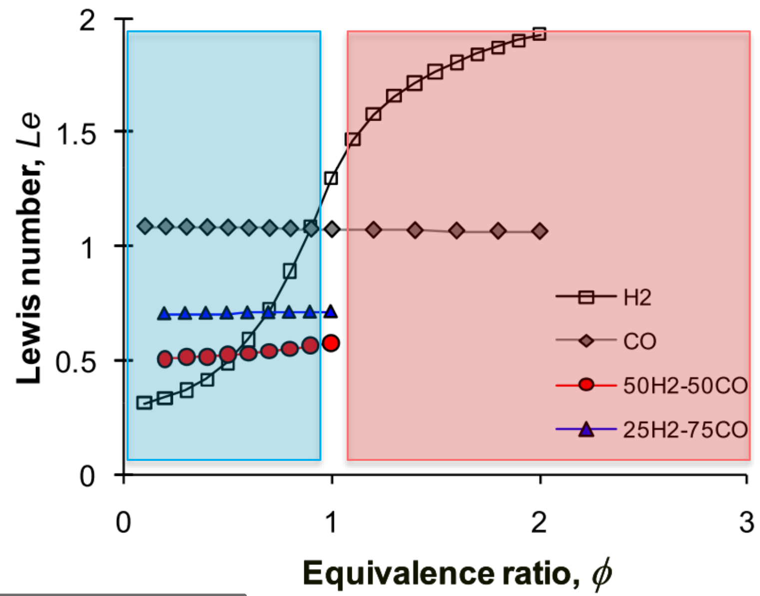
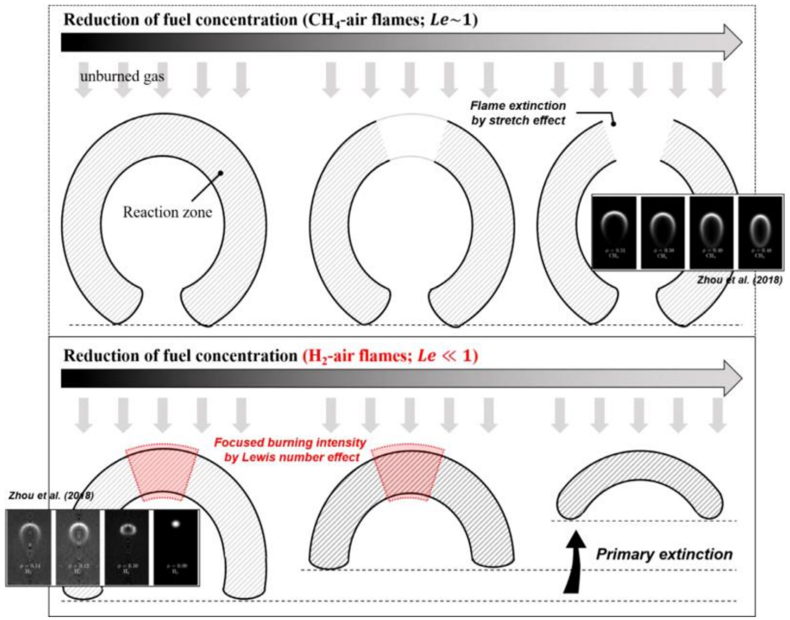
Methodology

$$Le = \frac{Thermal\ diffusivity}{Mass\ diffusivity} = \frac{\alpha}{D}$$



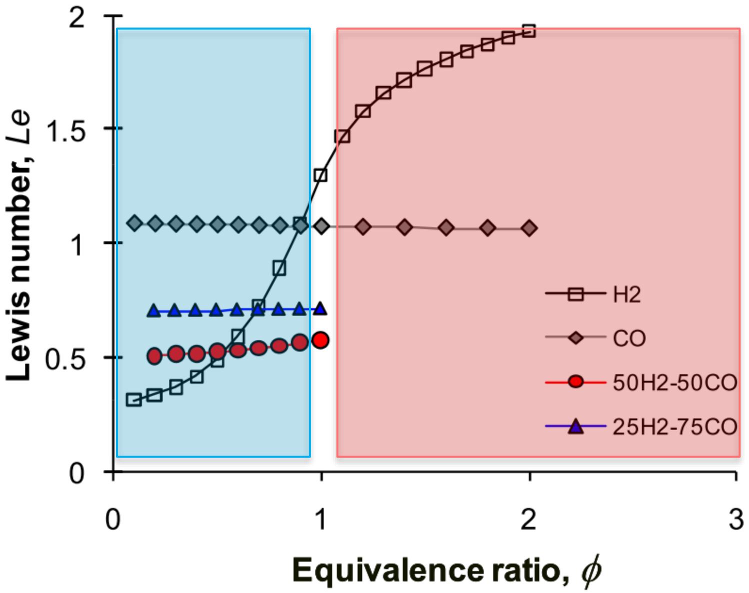


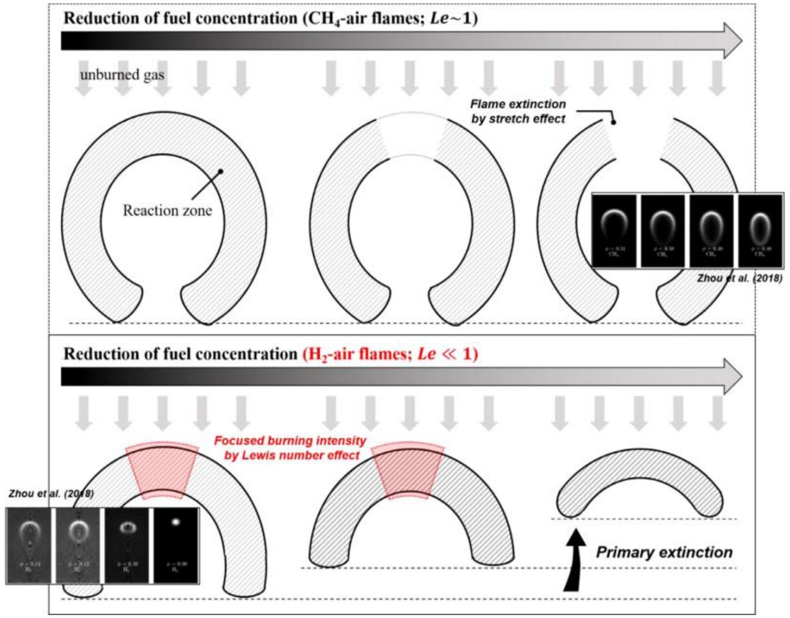
Lean vs Rich : Different Mechanism

Lean hydrogen(φ 〈 1)	Rich hydrogen(φ 〉 1)
Deficient species: H_2	Deficient species: O_2
Mass diffusivity follows H_2 properties	Mass diffusivity follows O_2 properties
Thermo-diffusively unstable flame	Stable, hydrocarbon-like behavior

[1] Burbano et al., *Laminar burning velocities and flame stability analysis of H_2/CO/air mixtures with dilution of N_2 and CO_2*, International Journal of Hydrogen Energy, 2011
[2] Jeon et al., *Identification of the extinction mechanism of lean limit hydrogen flames based on Lewis number effect*, International Journal of Heat and Mass Transfer, 2021.

Methodology



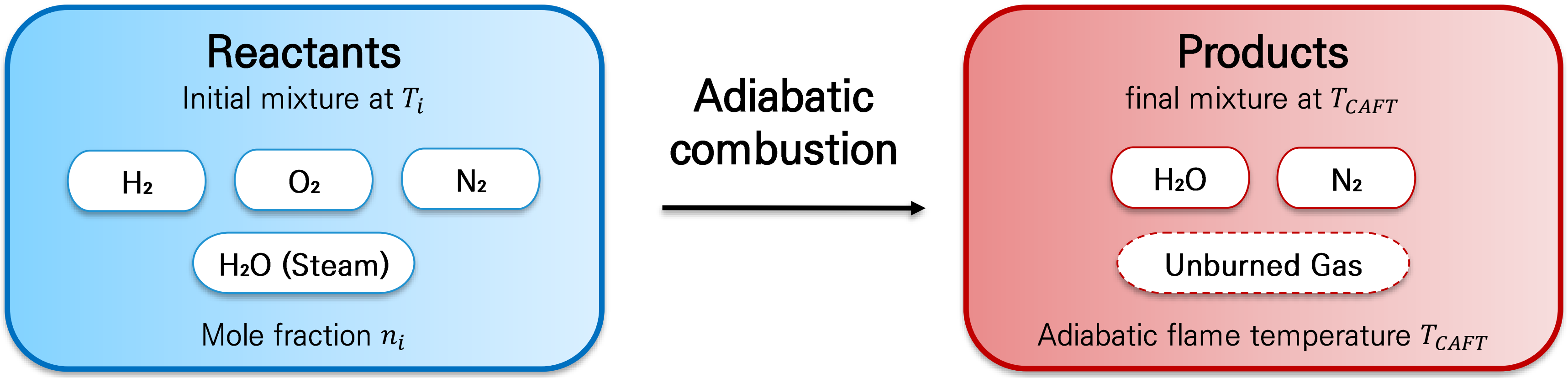


Analogy with Hydrocarbon-Air Flames

- Rich-Hydrogen flames($Le > 1$) share the same diffusion-thermal regimes as hydrocarbon-air flames
- The CAFT model has been extensively validated for hydrocarbon-air-diluent systems including the upper flammability limit prediction.

[1] Burbano et al., *Laminar burning velocities and flame stability analysis of H_2/CO/air mixtures with dilution of N_2 and CO_2*, International Journal of Hydrogen Energy, 2011
[2] Jeon et al., *Identification of the extinction mechanism of lean limit hydrogen flames based on Lewis number effect*, International Journal of Heat and Mass Transfer, 2021.

Methodology – CAFT Model



$$\sum_{reactants} n_i\left[\Delta H_{f,i}^0 + \bar{c}_{p,i}\left(T_i - T_{ref}\right)\right] - \sum_{products} n_i\left[\Delta H_{f,i}^0 + \bar{c}_{p,i}\left(T_{CAFT} - T_{ref}\right)\right] = 0$$

Calculated Adiabatic Flame Temperature (CAFT) Model

- A thermodynamic flammability model that determines combustion feasibility from the **maximum flame temperature** of a gas mixture under **adiabatic, isobaric** conditions.
- Based on the principle of energy conservation: the enthalpy released by complete combustion of reactants equals the sensible enthalpy required to heat the products to the adiabatic flame temperature.
- **Assumption: Well-mixed atmosphere**

[1] Vidal et al., *Evaluation of lower flammability limits of fuel–air–diluent mixtures using calculated adiabatic flame temperatures*, Journal of hazardous materials, 2006.

Methodology – CAFT Model

Core Assumption

- **The adiabatic flame temperature at the flammability limit remains nearly constant, independent of the mixture composition.**
- Rooted in Arrhenius theory: flame propagation requires a threshold peak temperature corresponding to the minimum reaction rate, which is determined primarily by fuel type rather than diluent composition.

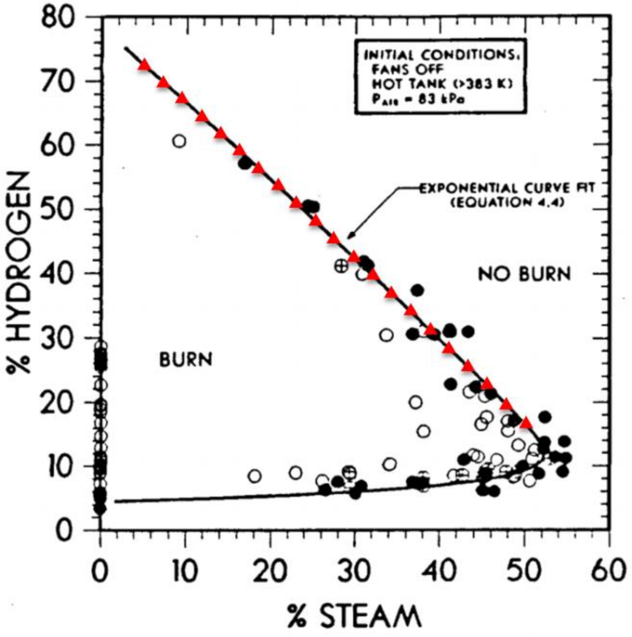
Lower Flammability Limit (LFL)	Upper Flammability Limit (UFL)
$T_{Threshold} \approx$ 610 K	$T_{Threshold} \approx$ 1160 K
Measured at H_2–air LFL (~4 vol% H_2)	Measured at H_2–air UFL (~75 vol% H_2)
CAFT model shows up to ~40% error (resolved with CNAFT)	Validated within ~12% accuracy for H_2–air–steam (next slide)

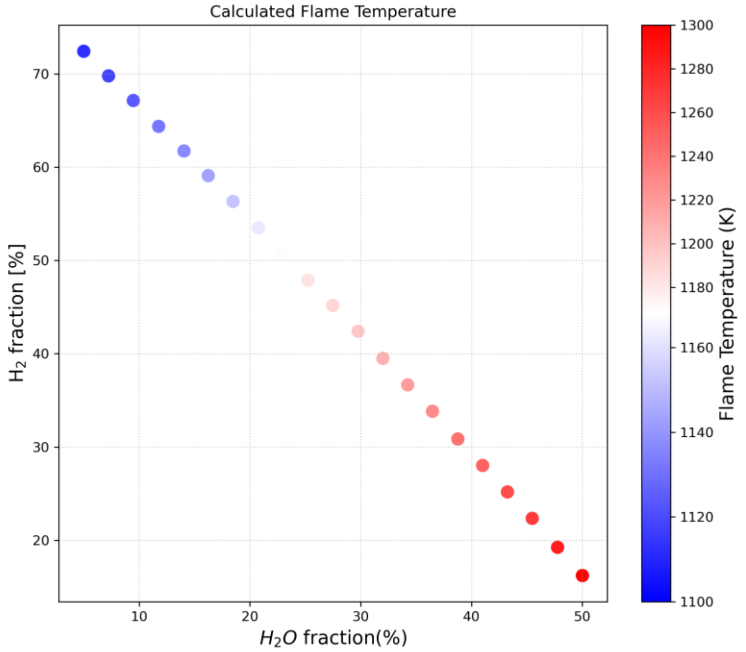
Flammability Criterion

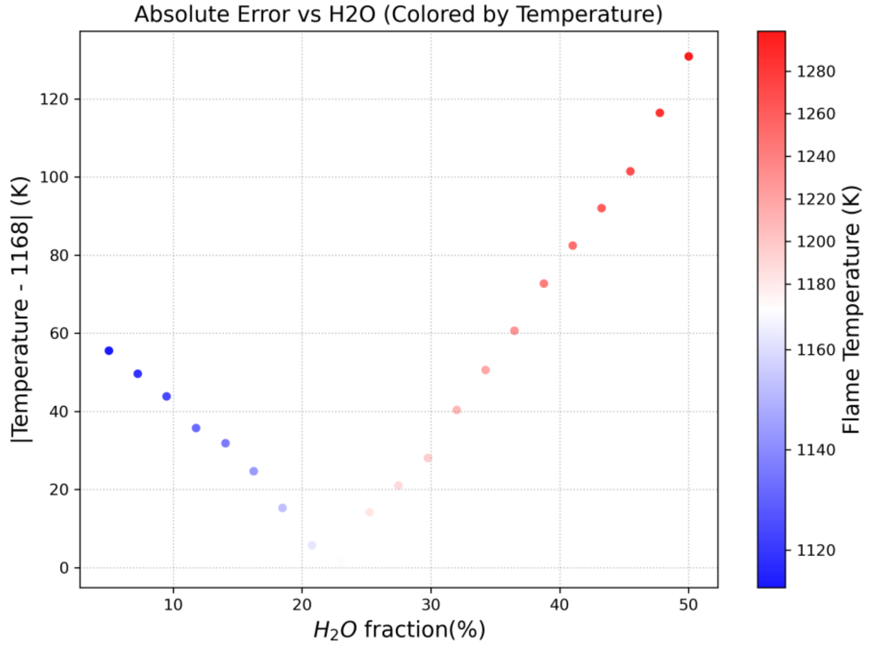
- $T_{CAFT} \geq 1160\ K$ → Flammable
- $T_{CAFT} < 1160\ K$ → Non-flammable

[1] M Terpstra, *Flammability limits of hydrogen-diluent mixtures in air*, University of Calgary, 2012.
[2] Jeon et al., *A flammability limit model for hydrogen-air-diluent mixtures based on heat transfer characteristics in flame propagation*, Nucelar Engineering and Technology, 2019.

Methodology – CAFT Model





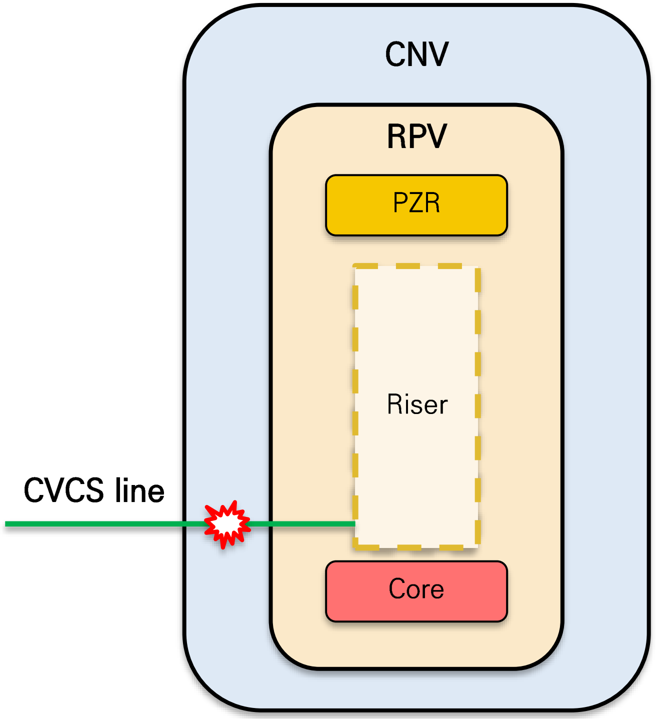


Applicability of CAFT model in Hydrogen-rich conditions

- **Validation**: FITS experiment
- Flame temperature deviation 〈 **12%** ($|T_{CAFT} - 1160K| \leq \sim 140K$)
- UFL prediction deviation 〈 **15%**

[1] Marshall, B. W., *Hydrogen: air: steam flammability limits and combustion characteristics in the FITS vessel*, Sandia National Laboratories, 1986.

Methodology – SMR SA Scenario



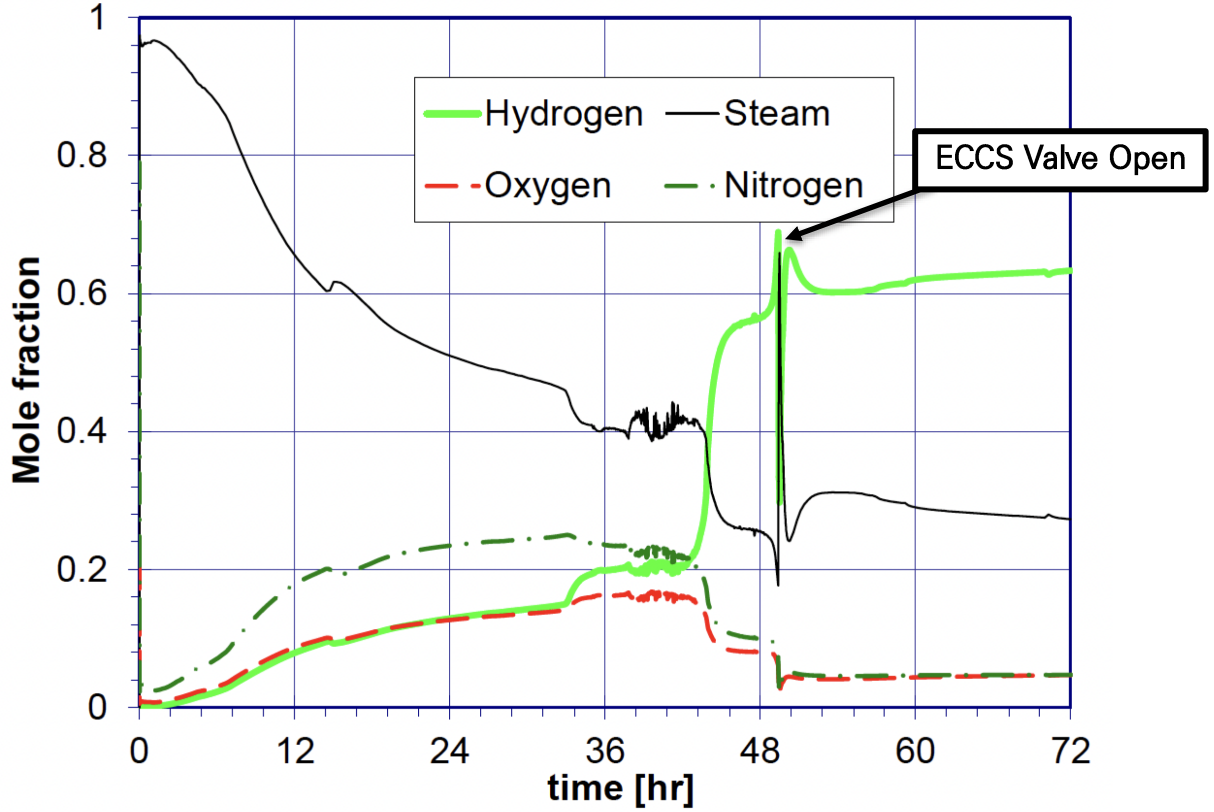
Time	Event
t = 0	CVCS pipe rupture
$t \approx 30$ h	Core uncovery
t = 49.38 h	ECCS valves forcibly opened (Core reflood)
t = 49.38–72 h	Radiolytic O_2 accumulation
t = 72 h	$O_2 \approx 5$ mol%

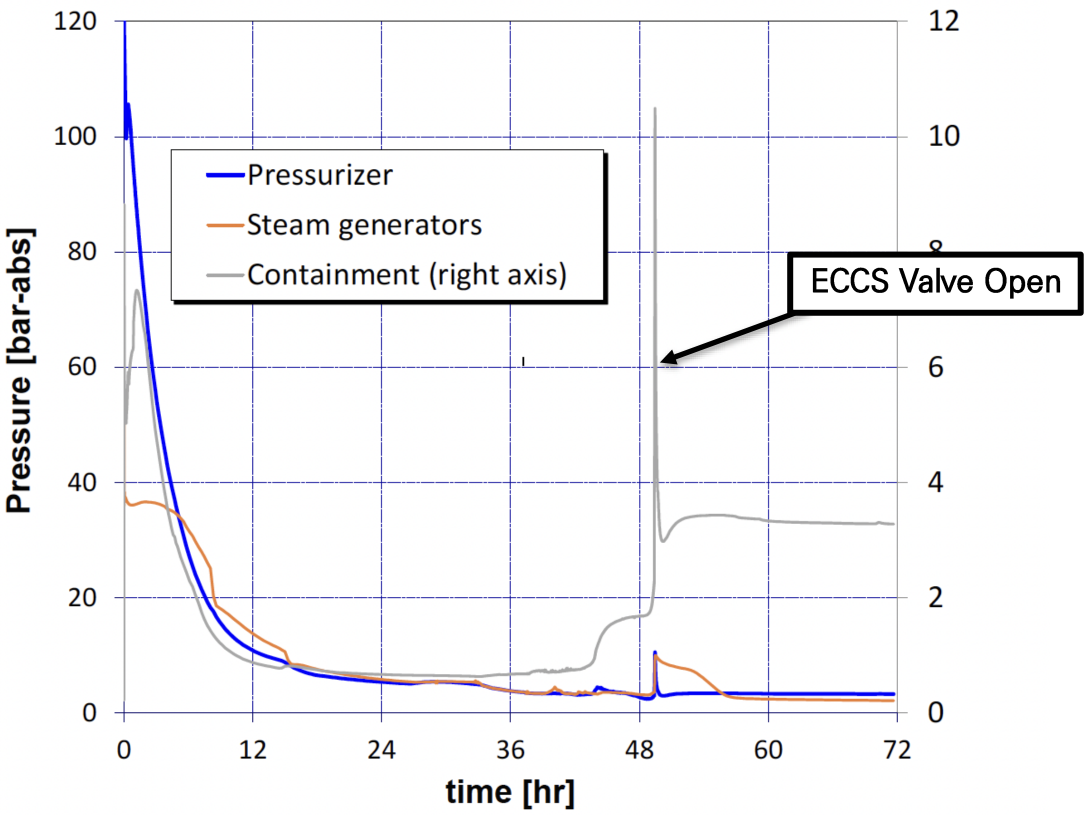
NuScale SMR Severe Accident Scenario (LCC-05T-03)

- **Initiating event:** CVCS line rupture inside the CNV → reactor coolant directly released into the containment volume
- Key features: Closed, single-volume CNV (no gas exchange with environment) → Long-term radiolytic O_2 source persists even after oxidation ceases → Initially H_2-rich condition

[1] *Assessment of Hydrogen Combustion During Severe Accidents in a NuScale Plant Module*, ERI/NRC 18-202, 2019

Methodology – SMR SA Scenario





Since no graph data was provided for the gas temperature, the gas temperature value of 369.65K available in the report was used.

[1] *Assessment of Hydrogen Combustion During Severe Accidents in a NuScale Plant Module*, ERI/NRC 18-202, 2019

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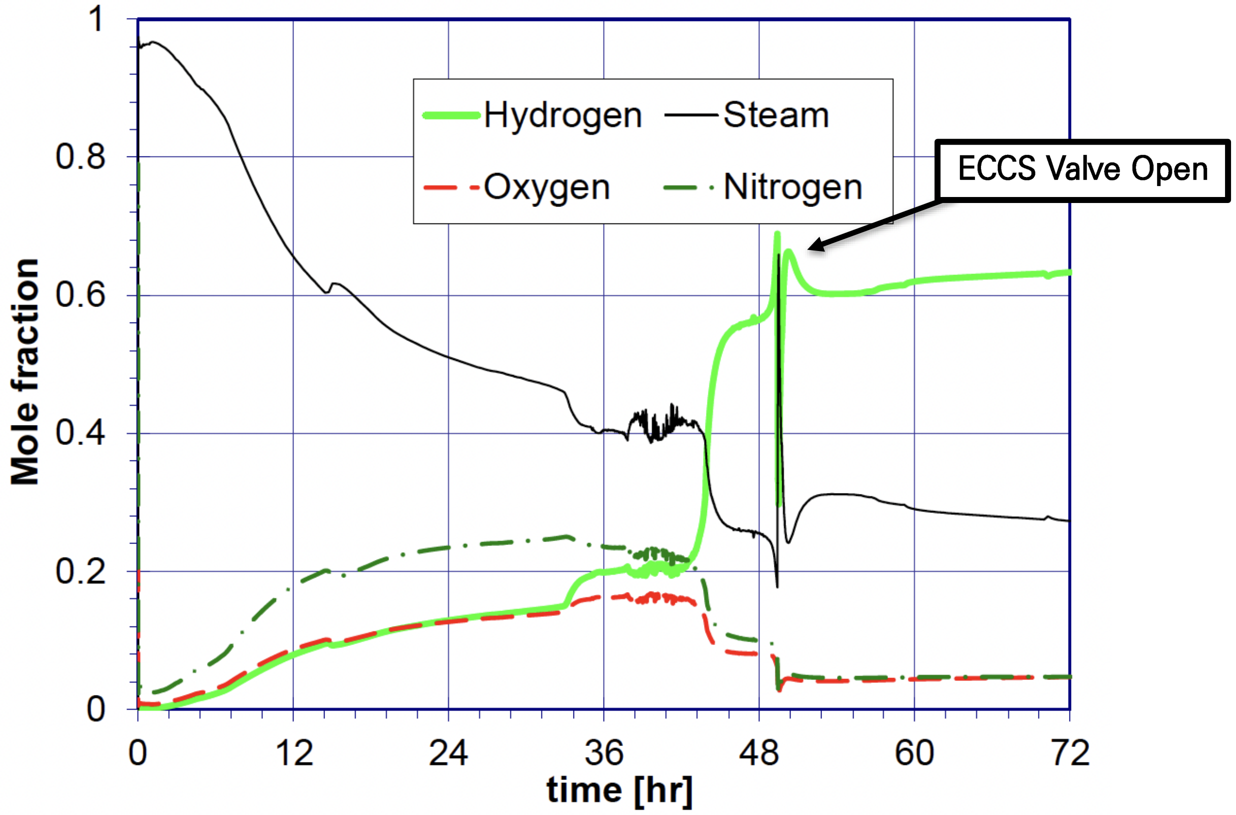
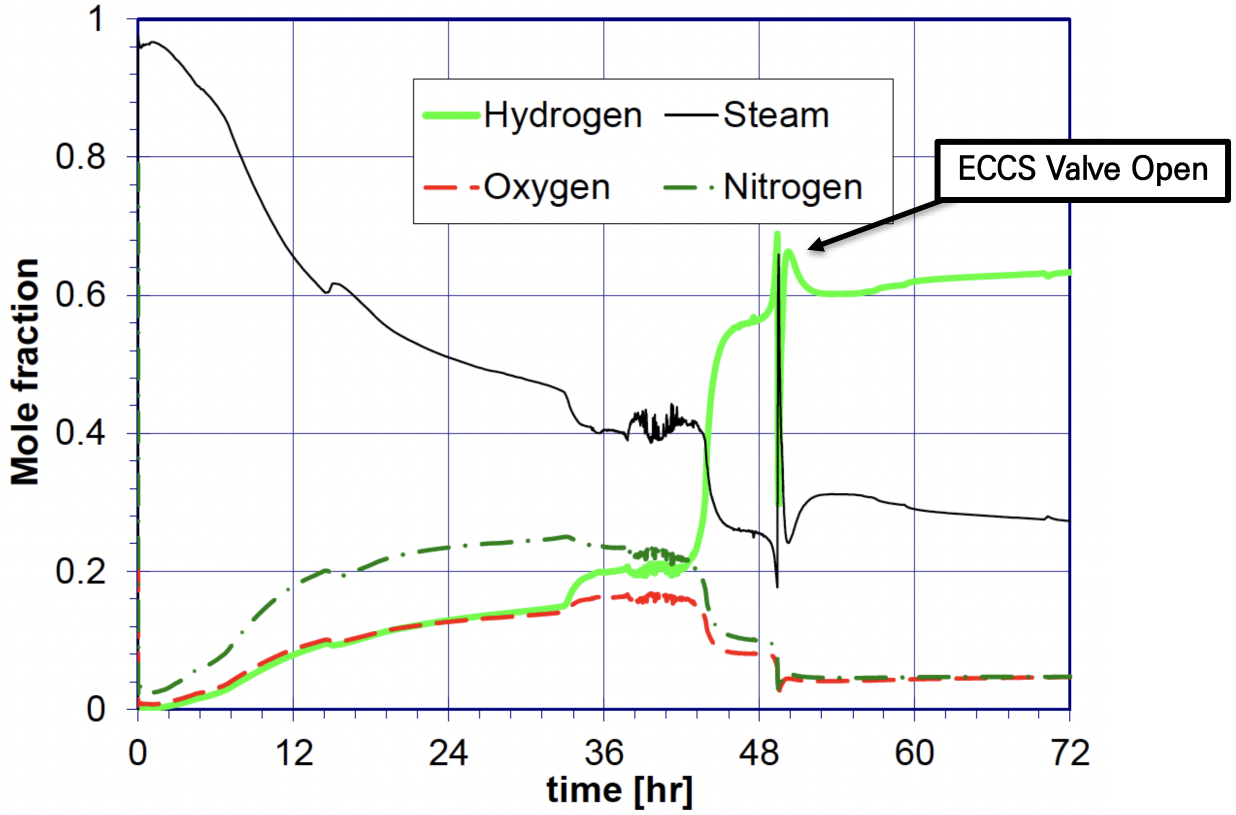
Result



Hour	H_2O (%)	H_2 (%)	O_2 (%)	N_2 (%)	P (Pa)
44	31.42	44.98	10.43	13.63	113044
46	26.13	55.20	8.25	10.52	161535
48	25.38	56.54	8.11	10.01	168244
50	24.41	66.30	4.44	5.04	300857
54	31.19	60.17	4.11	4.58	343244
60	29.01	62.02	4.34	4.76	333842
66	27.98	62.77	4.58	4.76	330569
72	27.37	63.28	4.67	4.86	328967

[1] *Assessment of Hydrogen Combustion During Severe Accidents in a NuScale Plant Module*, ERI/NRC 18-202, 2019

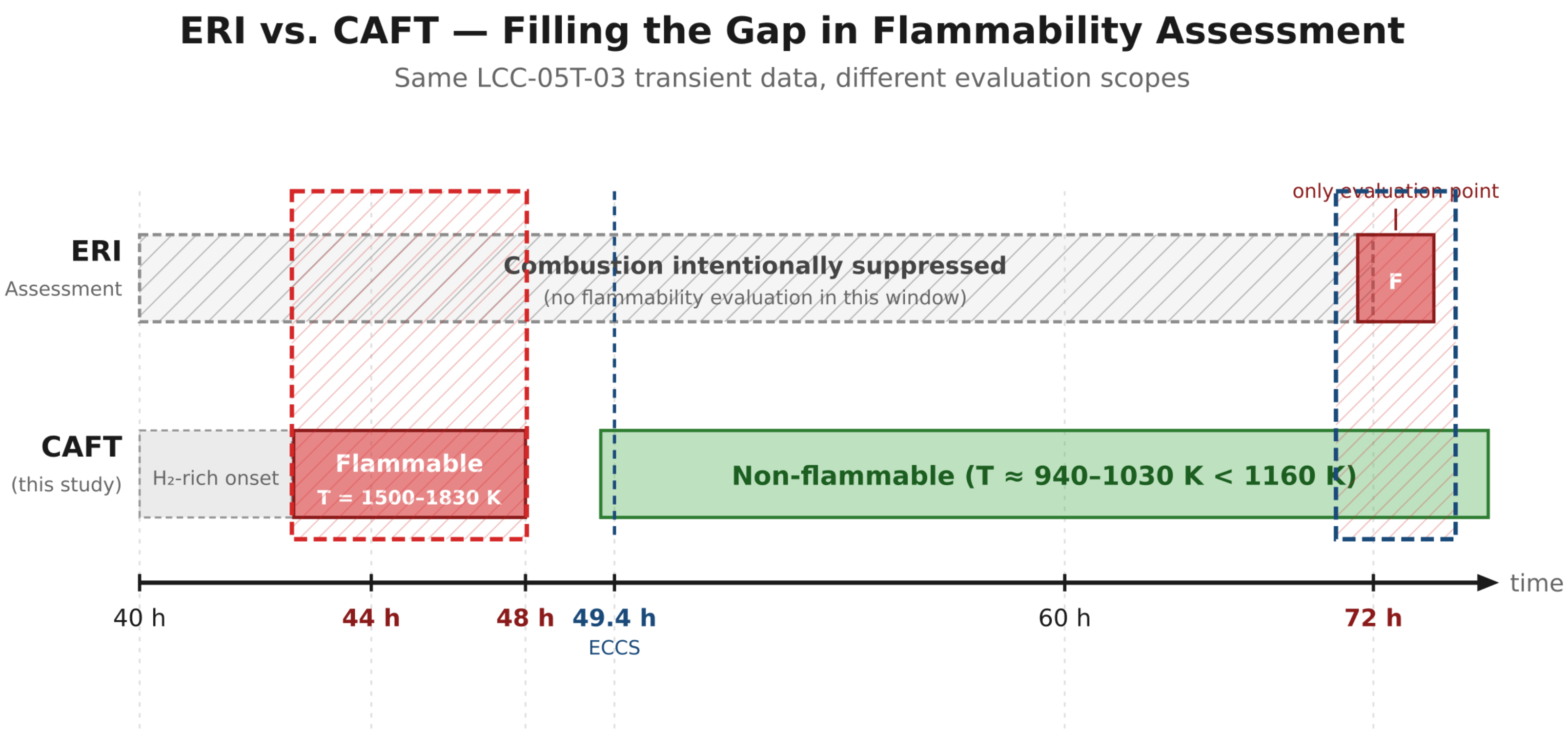
Result



Hour	Flame Temperature(K)	Flammability
44	1834.52	O
46	1552.52	O
48	1536.48	O
50	1006.03	X
54	943.93	X
60	981.62	X
66	1017.81	X
72	1032.57	X

[1] *Assessment of Hydrogen Combustion During Severe Accidents in a NuScale Plant Module*, ERI/NRC 18-202, 2019

Result



★ Newly identified window
ERI: not evaluated (suppressed)
CAFT: **flammable** ($O_2 \approx 8\%$, low steam)

◆ Reassessment of 72 h
ERI: flammable ($O_2 = 5\%$, direct calc)
CAFT: **non-flammable** (steam dilution)

Key Insights

- ERI's own MELCOR transient shows $O_2 \approx 8$ mol% at 44–48h, but combustion in this window was intentionally suppressed and never evaluated
- CAFT applied to the same MELCOR data identifies 44–48h as **the actual high-risk window** — while the 72 h "worst case" lacks combustion energy due to post-ECCS steam dilution

Note

The 44–48 h window already exceeds ERI's own 5 mol% O_2 threshold. Its omission from the ERI assessment likely reflects the scenario framing.

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Conclusion

- **Hydrogen-rich flammable window identified** At **t = 44–48 h**: The CAFT-predicted flame temperature exceeds **1500 K** — well above the 1160 K threshold. This window lies outside ERI's evaluation scope.
- **Reassessment of the 72 h "worst-case"**: Post-ECCS steam dilution lowers flame temperature to ~1030 K at 72 h, falling below the combustion threshold despite O_2 reaching 5 mol%.
- **Methodological implication**: Single-concentration criteria ($O_2 \geq 5\%$) may **underestimate transient risk** and **overestimate steady-state risk.** The CAFT model provides a thermodynamically rigorous, energy-based framework for SMR hydrogen risk assessment.
- Future work
  - CFD analysis of ECCS-induced gas mixing
  - Heat loss consideration at the UFL
  - Extension to i-SMR

Acknowledgment

This work was supported by the Regulatory Research Management Agency for SMRs (RMAS) and the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea(Nos. RS-2024-00509653, RS-2024-00403364).

원자력안전위원회

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Numerical Investigation for Nature & Energy Lab.

Thank You.
Any Questions?

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