Comparative Validation of Severe Accident System Codes Through TMI-2 Accident Modeling: Focus on Reflooding Phenomena

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1. Introduction

In-vessel injection (IVI), or reflooding, is a key severe accident management measure intended to restore coolant inventory, rewet degraded core regions, and enhance heat removal to limit further damage. However, reflooding under severe accident conditions is much harsher than in a standard LOCA reflood: the core may be deformed or compacted and coolant flow paths can be partially blocked by debris, which can limit coolant access to hot regions. Therefore, reflooding performance should be evaluated using energy-based metrics (e.g., core stored energy and core-to-RCS heat transfer), not only pressure and level indicators.

The TMI-2 accident is an important reference for severe accident analysis because it provides an integrated, plant-scale progression in which large portions of the core experienced high temperature and damage, followed by inventory recovery that ultimately avoided vessel failure. Previous benchmarks and code-comparison studies [1, 2] typically assessed code performance by accident phase, but late-phase predictions-especially during reflooding-often diverge because differences in code modeling assumptions and implementations can yield different degraded-core thermal-hydraulic and oxidation responses, and thus different estimates of effective post-reflood heat removal. Furthermore, many studies concentrated on early-phase behavior, and the reflooding phase was only weakly validated, particularly in terms of effective heat removal. Accordingly, the present study conducts a comparative analysis of MELCOR 2.2 [3] and MAAP 5.06 [4] for a TMI-2–based scenario and assesses reflooding performance using energy-based metrics (e.g., core stored energy and core-to-RCS heat transfer), in conjunction with conventional pressure and level indicators.

2. Modeling

The accident progression is structured into phases, as summarized in Table 1, to organize the modeling and interpretation. While early phases capture initial inventory loss and system response, the analysis here emphasizes the transition from core uncovery and damage progression (Phase 2) to reflooding recovery (Phase 3 and beyond), where the competition between heat removal, oxidation heating, and geometry-limited coolant access is expected to dominate code differences.

Table 1. Phase-based description of the accident progression

Phase	Time (s)	Simple description
1	0–6,000	Early transient: loss of heat removal and system depressurization (PORV stuck open).
2	6,000–10,440	Core uncovery and major core damage progression (rapid heat-up / hydrogen generation).
3	10,440–13,440	Recovery/reflooding: inventory recovery and core reflood.
4	13,440–14,100	Relocation to lower plenum (bypass relocation after baffle/crust damage).
5	14,100–18,000	Lower head heating period; vessel integrity maintained.

Figures 1 and 2 show the RCS nodalization for each code.

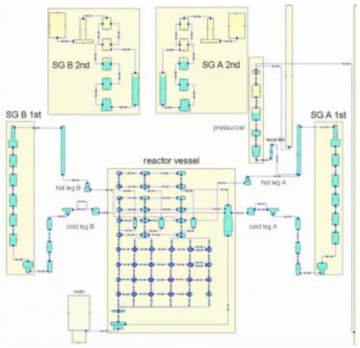

Figure 1. MELCOR RCS nodalization

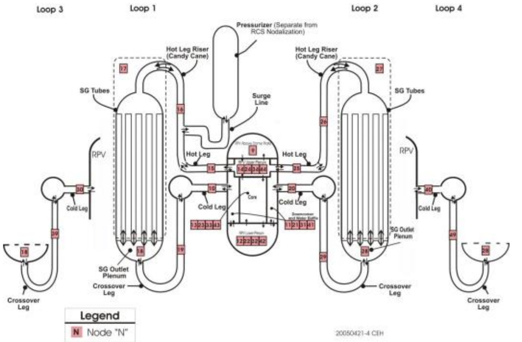

Figure 2. MAAP RCS nodalization

Reflooding injection (Fig. 3) is applied as time-dependent boundary conditions intended to reproduce the recovery of inventory. While each code applies injection to different node types (downcomer/cold-leg representations), the modeling aims to maintain consistent system-level injection history across the simulations. System discharge and letdown pathways are also modeled to reproduce the net inventory balance and its impact on pressure evolution.

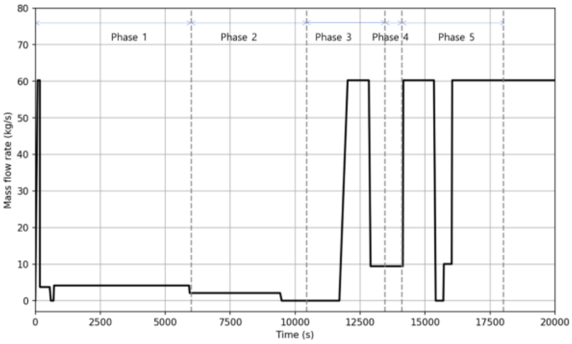

Figure 3. Mass flow rate for reflooding

Core degradation outcomes depend strongly on (i) how relocation is triggered and (ii) how oxidation kinetics are represented, particularly at intermediate temperatures where increased steam availability can cause rapid escalation. Liquefaction / eutectic-related criteria differ between codes:

- MELCOR includes the UO_2–ZrO_2 eutectic reaction at 2500 K as a key criterion influencing liquefaction/relocation behavior.
- MAAP includes α-Zr(O)/UO_2 eutectics at 2170 K (and also accounts for UO_2 melting at higher temperatures), enabling earlier relocation under certain thermal histories.

Oxidation modeling differs between the codes. In MAAP, the Zr–steam oxidation kinetics are represented by the Cathcart model for $T \leq 1850$ K and the Baker–Just model for $T > 1875$ K (with interpolation over 1850–1875 K), and the oxidation reaction is allowed to initiate at 800 K. In MELCOR, Zr oxidation is modeled using the Urbanic–Heidrich correlation with an oxidation start temperature of 1100 K (with the rate constant K(T) specified piecewise and interpolated over 1853–1873 K). These differences can contribute to an earlier onset and greater contribution of oxidation heating in MAAP relative to MELCOR under comparable thermal-hydraulic conditions.

Both codes apply boiling heat transfer correlations (e.g., Rohsenow-type nucleate boiling) while also applying limiting concepts such as CHF/dryout, especially when damaged-core morphology is represented as particulate or compacted beds. Importantly, debris-bed CHF/dryout restrictions and associated model inputs (bed thickness, porosity/permeability, effective particle size, etc.) can cap local heat transfer even when substantial injection is available. Thus, reflooding performance is better assessed using an integrated energy perspective than by relying solely on inventory recovery metrics.

3. Results

3.1. RCS pressure and core water level

Both codes reproduce the overall Phase 1–2 system response, showing similar trends in RCS pressure and collapsed water level (see Figs. 4 and 5). Differences become more pronounced as core uncovery and damage progression develop. However, similar pressure or level trends do not necessarily indicate similar in-core conditions. System-level responses may appear comparable even when core temperature distribution, oxidation state, and coolant access differ. The comparison is therefore made in terms of hydrogen generation, relocation mass, and core-to-RCS energy transfer.

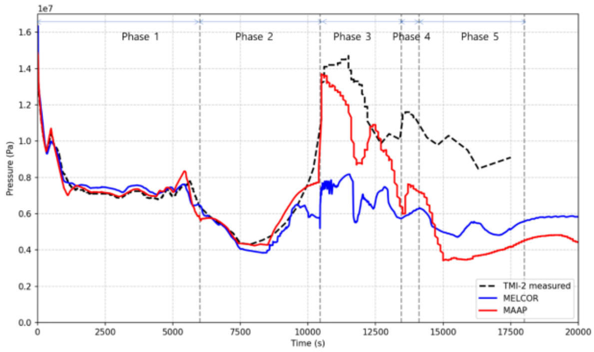

Figure 4. RCS pressure

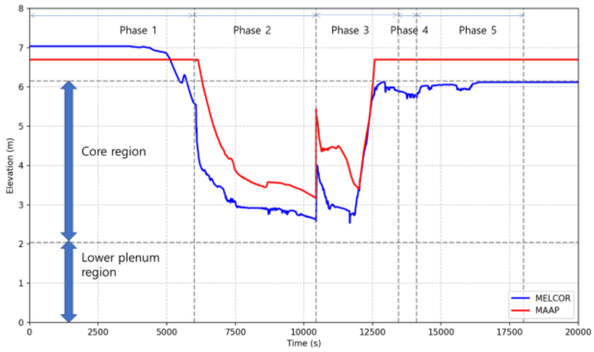

Figure 5. Core water level

3.2. Oxidation and hydrogen generation

During Phase 2 core uncovery, as shown in Fig. 6, MAAP predicts earlier oxidation initiation and larger oxidation-related responses than MELCOR, resulting in higher hydrogen generation during the damage escalation period. This behavior is consistent with differences in oxidation start temperature and kinetic formulation, as well as the positive feedback whereby oxidation heat increases temperature and further accelerates oxidation. As steam availability increases—particularly at the onset of reflooding—additional oxidation heat release may occur, implying that reflooding can enhance steam supply to hot zirconium surfaces and thereby intensify transient hydrogen generation, rather than solely reducing temperatures.

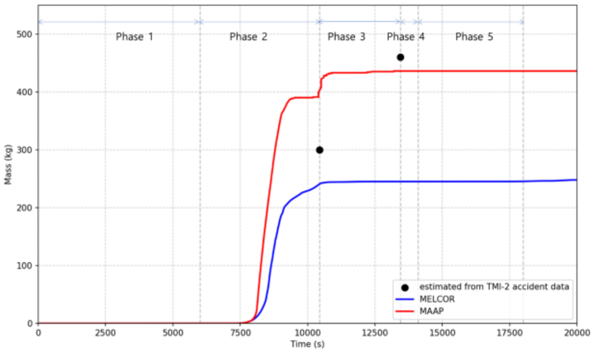

Figure 6. Cumulative mass of hydrogen generation

3.3. Core material relocation

Relocation behavior is assessed using the relocated UO_2 mass. In this analysis, MAAP predicts an earlier onset and a larger final relocation than MELCOR, with the final relocated mass being on the order of ~20% higher in MAAP, as shown in Fig. 7. This difference is consistent with code-to-code differences in oxidation heat release and liquefaction criteria (eutectic thresholds), which govern the onset of structural melting and downward relocation. The relocation difference is important not only for mass balance but also for post-damage geometry. Earlier and larger relocation can increase blockage and reduce permeability, limiting coolant access and boiling heat transfer during reflooding. Figures 8 and 9 show the relocated core material distributions predicted by each code.

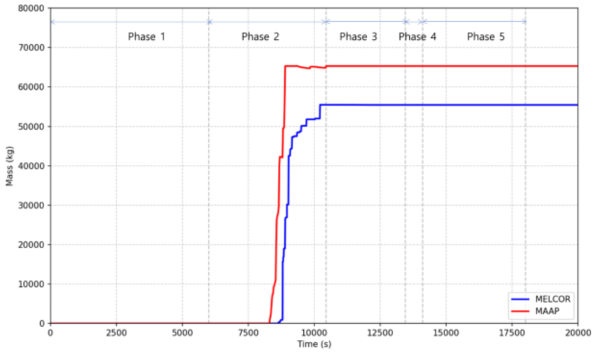

Figure 7. Mass of relocated UO_2

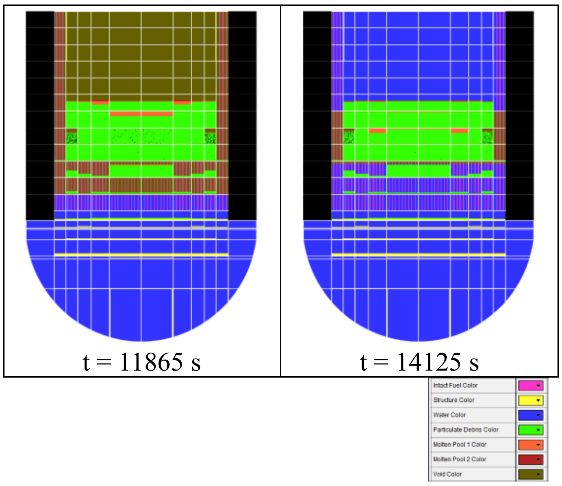
t = 11865 s
t = 14125 s

Figure 8. Relocated core material distribution (MELCOR)

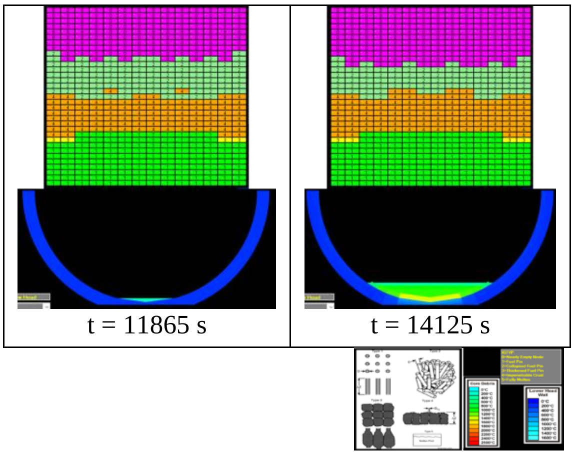
t = 11865 s
t = 14125 s

Figure 9. Relocated core material distribution (MAAP)

3.4 Reflooding recovery and energy-based cooling efficiency

Following Phase 3 reflooding, both codes show similar trends in coolant inventory recovery and do not predict substantial additional global relocation (see Fig. 10). An energy-based assessment indicates that the heat removed by boiling and transferred to the RCS after reflooding reaches only ~30% of the theoretical upper bound, defined by the case in which the injected water fully participates in phase change at the core. This suggests that reflooding performance is governed less by the nominal injection flow rate than by effective coolant access to dominant heat sources and the extent to which conditions support sustained nucleate boiling. Two-phase flow interactions, preferential bypassing, and CHF/dryout constraints in compacted regions can reduce the wetted area and suppress boiling heat transfer. Consequently, increasing injection alone does not necessarily yield a proportional increase in heat removal when permeability, flow redistribution, and two-phase behavior restrict coolant penetration.

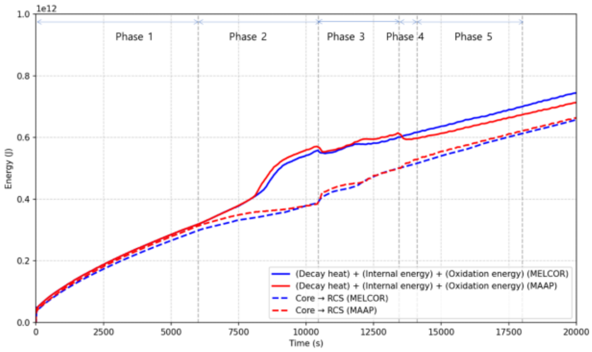

Figure 10. Cumulative energy transferred from core to RCS

4. Conclusion

Through a TMI-2–based comparison of MELCOR and MAAP, this work evaluates reflooding performance beyond conventional pressure/level indicators by adopting energy-based measures, thereby providing a clearer basis for interpreting code-to-code differences in degraded-core cooling. The main conclusions are summarized as follows:

- System-level response: Both codes reproduced similar system-level trends during Phases 1–2 (pressure/level behavior), while deviations became more apparent as core uncovery and damage progression developed in Phase 2, indicating increasing sensitivity to in-core modeling assumptions.

- Oxidation and hydrogen: In Phase 2, MAAP predicted earlier oxidation initiation and stronger oxidation-related responses (including higher hydrogen generation) than MELCOR, consistent with differences in oxidation activation and kinetic formulations.

- Core relocation: Relocation behavior differed; in this analysis, the final relocated UO_2 mass in MAAP was on the order of ~20% higher than in MELCOR. This implies different post-damage geometries that can modify blockage/permeability and thereby affect coolant access during reflooding.

- Reflooding effectiveness: After Phase 3 reflooding, both codes showed similar inventory recovery and no substantial additional global relocation. However, an energy-based assessment indicated that effective post-reflood boiling heat removal reached only ~30% of the theoretical upper bound, suggesting that permeability reduction and two-phase limitations can strongly constrain “effective” cooling even with sufficient injection.

To further quantify uncertainty in reflooding effectiveness and to better interpret code-to-code differences, subsequent work will conduct targeted sensitivity studies on injection conditions, degraded-core morphology/flow characteristics, debris cooling limits (dryout/CHF and film-boiling transition treatment), oxidation modeling assumptions, and eutectic-temperature criteria governing relocation onset.

Acknowledgements

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