Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 30-31, 2025

MELCOR Analysis of the QUENCH-10 Experiment under Air Ingression Conditions

Hyoung Tae Kim [a*] and Sang Ho Kim [a]
Intelligent Accident Mitigation Research Division, KAERI, Daeduk-daero 989-111, Daejeon, Korea
[*]Corresponding author: kht@kaeri.re.kr

Keywords : QUENCH-10, reflood, severe accident, MELCOR, air ingression

1. Introduction

The QUENCH-10 experiment [1], performed at the Karlsruhe Institute of Technology (KIT), investigated the behavior of Zircaloy cladding during reflooding under air ingress conditions. The presence of nitrogen and oxygen significantly affects oxidation kinetics, hydrogen production, and embrittlement of the fuel rod simulators. This study presents a numerical analysis of QUENCH-10 using the MELCOR 1.8.6 [2] severe accident analysis code. While MELCOR reproduces the general thermal behavior, the code has notable limitations in representing air oxidation and nitridation phenomena. In particular, the simplified treatment of nitrogen interaction and the absence of a mechanistic breakaway oxidation model lead to discrepancies with experimental results. Therefore, improvements are recommended, including the incorporation of mechanistic ZrN formation kinetics and refined temperature-dependent correlations for high-temperature oxidation.

2. Methodology

2.1 The QUENCH-10 experiment

Severe accident research has highlighted the importance of air ingress accidents, which can occur during high-temperature transients such as loss-of-coolant accidents (LOCAs) or delayed reflooding scenarios. Unlike steam oxidation, the ingress of air introduces oxygen and nitrogen that accelerate cladding degradation through combined oxidation and nitridation processes. The resulting enhanced embrittlement can lead to cladding failure, hydrogen generation, and subsequent risk of exothermic reactions during quenching.

The QUENCH-10 experiment at KIT was designed to specifically examine fuel rod bundle behavior under air ingress conditions followed by reflooding. The test provided high-quality data for code validation, including temperature distributions, hydrogen release, and post-test examinations of cladding microstructure. To support model validation, the MELCOR severe accident code has been applied to simulate the QUENCH-10 experiment.

The QUENCH facility simulates the fuel rods with the out of pile bundle. This bundle consists of a 5 × 5 structure made up of 21 fuel simulator rods and 4 corner rods fixed by five grid spacers (Fig. 1). This bundle includes 20 heated rods, one unheated central rod that can be used for measurement devices or as a control rod, and four corner rods. The overall length of the rods is approximately 2.5 m, and the heating length is about 1 m. The cladding is a zirconium alloy Zircaloy-4 with an outer diameter of 10.75 mm and a wall thickness of 0.725 mm. A tungsten heater at the center of each heated rod has an outside diameter of 6 mm. ZrO_2 pellets surround the tungsten heaters of the heated rods, whereas the unheated central rod is totally filled with ZrO_2 pellets without the heater.

The bundle is surrounded by a shroud of three layers. The first one is made of Zircaloy at the inner side (outer diameter: ~85 mm), followed by a central ZrO_2 fiber insulation layer and an annular stainless steel cooling jacket.at the outer side, to provide the encasement of the bundle.

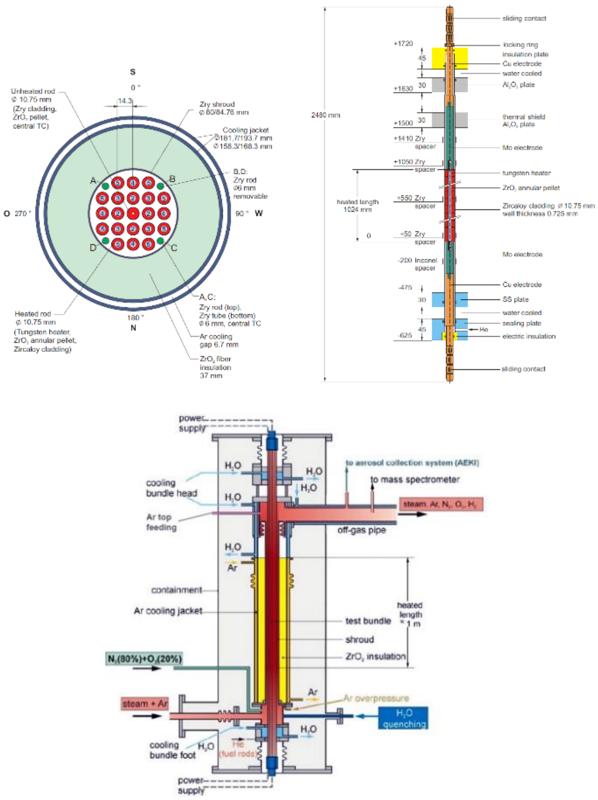

Fig. 1. Fuel rod simulator bundle including rod type indications of the QUENCH test facility [1].

The main test phases of the QUENCH-10 experiment are summarized in Table 1.

It should be noted that the gas composition transitions in the MELCOR model were implemented in a simplified manner compared with the detailed stepwise procedures of the QUENCH-10 experiment (Table 1). For instance, the model assumes an idealized switch between steam and air phases, while in the actual test overlapping transients and mixed atmospheres were present. This simplification may contribute to discrepancies in oxidation kinetics and hydrogen generation predictions. A more refined nodalization that directly reflects the phase-by-phase boundary conditions of the experiment would likely improve agreement with the experimental data.

Table 1: Sequence of events and phases of the QUENCH-10 experiment

Phase	Test procedures
Phase I	Stabilization at ~873 K. Facility checks
Phase II	Heatup with ~0.3-0.6 K/s to ~1620 K for ~32 min (first transient)
Phase III	Pre-oxidation in a flow of 3 g/s of superheated steam and 3 g/s argon for ~113 min at relatively constant temperature of ~1620-1690 K.
Phase IV	Intermediate cooling from ~1690 to 1190 K in a flow of 3 g/s of superheated steam and 3 g/s argon for ~38 min.
Phase V	Air ingress and transient heatup from ~1190 K to 2200 K with an initial heating rate of ~0.3 K/s in a flow of 1 g/s of air for ~30 min (superheated steam flow turned off)
Phase VI	Quenching of the bundle by a flow of 50 g/s of water from the bottom

Figure 2 shows the temperature measurement of the rod and the electric power for test phases.

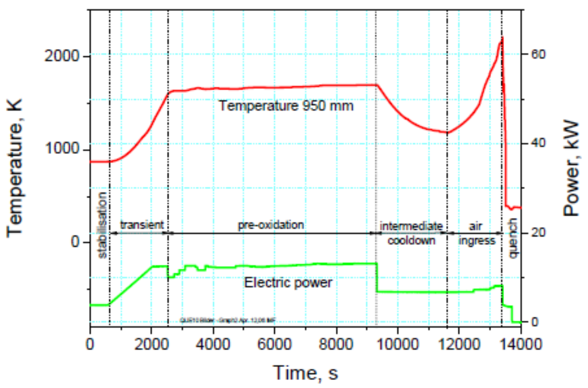

Fig. 2. Temperature at the 950 mm level (TIT A/13) and electric power vs. time together with an indication of the QUENCH-10 test [1].

2.2 MELCOR nodalization for QUENCH-10 experiment

The QUENCH-10 experiment at KIT was simulated in MELCOR 1.8.6 using the COR package (core degradation module). Because MELCOR is essentially a 1-D lumped-parameter severe accident code, the QUENCH facility (which is a single fuel bundle experiment) is represented by a simplified, nodalized structure as shown in Fig. 3.

1) Radial representation

Fuel bundle homogenization: The 21 Zircaloy-4 rod simulators in the QUENCH-10 test bundle are represented in MELCOR as a single average channel. Fuel rod is divided into radial rings: cladding (Zr-alloy), oxide/nitride layers, and internal heater (as fuel surrogate).

Since QUENCH used electrically heated rods, the MELCOR “fuel” node simply acts as a heat source, not an actual UO_2 fuel pellet.

Control rods are not present in QUENCH-10, so no radial representation of absorber materials is included.

Fig. 3. Nodalization scheme of QUENCH -10 facility for MELCOR 1.8.6 model.

2) Axial nodalization

MELCOR divides the rod length (~2.5m of total rod including ~1.0m of heated length in QUENCH-10) into 10–15 axial nodes.

Each node includes cladding, oxide layer, and coolant channel. Independent calculation of temperature, oxidation, hydrogen production, and degradation. Finer axial nodalization is usually applied in upper bundle regions, where oxidation and air ingress effects are strongest.

3) Coolant / atmosphere nodalization

The QUENCH test bundle is represented as a single fluid control volume surrounding the rods.

Gas composition transitions are imposed:
- Air ingress (steam-air mixture introduced at controlled flow).
- Initial steam phase (pure steam atmosphere).

- Air ingress (steam-air mixture introduced at controlled flow).
- Reflooding (liquid water injection from the bottom, modeled as quench front rise).

4) Boundary Conditions

- Power input:

In experiments, rods were heated electrically with programmed power. In MELCOR, the heater power curve is imposed as an external input to fuel nodes (instead of decay heat).

- Reflood injection: It is modelled as a boundary water source at the lowest coolant node. Quench propagation is calculated by MELCOR's thermal-hydraulic package.
- Pressure and venting: Boundary pressure is kept close to atmospheric (slightly above), consistent with experiment.

5) Oxidation / air Ingress model in MELCOR

- MELCOR adopts a parabolic model for air oxidation. Various correlations were reviewed [3, 4] from which a single correlation known as NUREG-B was chosen as default in MELCOR in order to provide a conservative upper bound on the oxidation rate.
- Air oxidation handled by an extended correlation: Oxygen reaction rate enhanced relative to steam
- Nitrogen effect simplified: MELCOR includes a lumped nitridation factor but does not mechanistically track ZrN growth.

6) Post-test analysis representation

MELCOR predictions per axial node are compared to experimental measurements:

- Temperature profiles at selected elevations (thermocouples)
- Hydrogen generation (integrated per node).

Nodalization is thus a 1-D axial average, but sufficient to capture bundle-scale integral behavior for code validation.

This nodalization approach captures integral bundle behavior but lacks the ability to model local effects (nitride penetration, breakaway oxidation, corner rod flow paths) seen in experiments.

3. Code Calculation Results

3.1 Temperature profiles at selected elevations

The QUENCH-10 test investigated air ingress following steam pre-oxidation of a Zircaloy-4 rod bundle, with subsequent reflooding. The rod temperature evolution is one of the main metrics compared between MELCOR simulations and experiment.

Figures from 4 to 6 show QUENCH-10 measured and calculated temperatures by MELCOR on the different heights of 350 mm, 550 mm, and 950 mm, respectively.

There is good agreement between the temperature trends predicted by MELCOR and the experimental data during the heat-up phase. As the temperature rise owing to the heat release from oxidation in air, the temperature escalation begins to dominate at the top of the bundle (at 950 mm height in Fig. 6). During the reflood phase, the temperature evolution is reasonably well reproduced compared with the experimental measurements.

The predicted maximum cladding temperature reached approximately 2000 K just before reflood, showing reasonable agreement with the thermocouple data (though sometimes underpredicting local peaks >2300 K).

These results indicate that MELCOR is capable of capturing bundle-scale thermal behavior; however, the code systematically underpredicts peak cladding temperatures and overpredicts quench cooling rates. This discrepancy highlights MELCOR's lumped-parameter approach, which cannot capture localized breakaway oxidation or delayed quenching effects observed in the experiment. Such limitations reduce the applicability of MELCOR for detailed material degradation studies, though it remains adequate for integral safety evaluations.

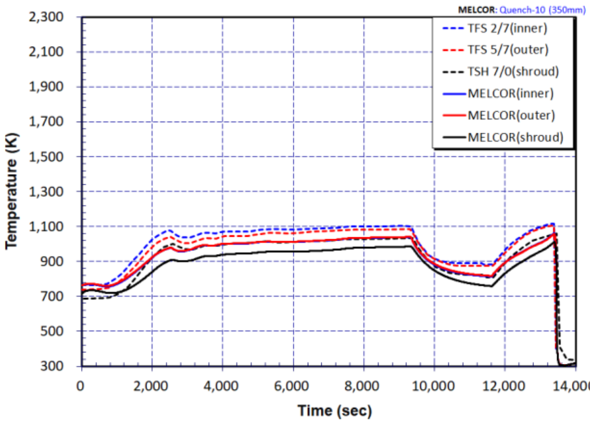

Fig. 4. QUENCH-10 measured and calculated temperatures by MELCOR on 350 mm bundle height.

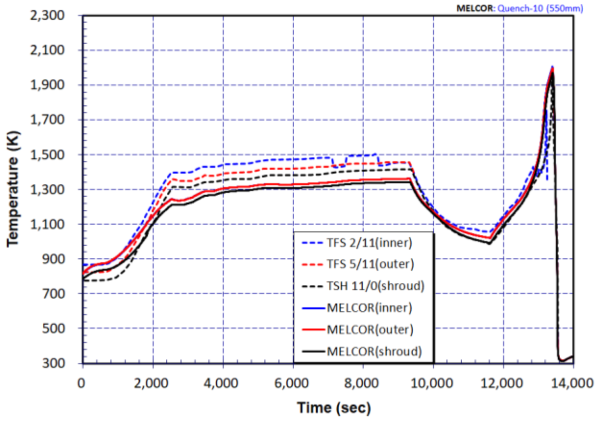

Fig. 5. QUENCH-10 measured and calculated temperatures by MELCOR on 550 mm bundle height.

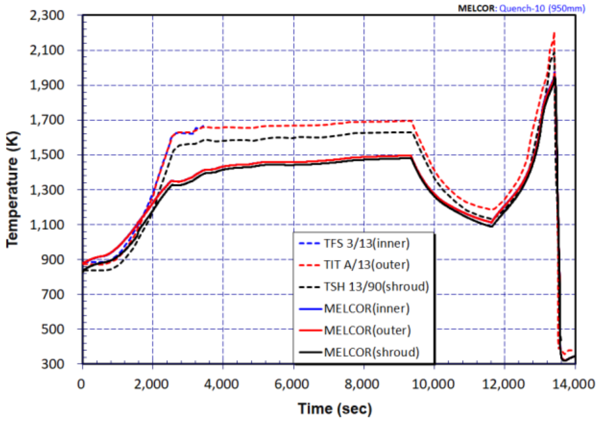

Fig. 6. QUENCH-10 measured and calculated temperatures by MELCOR on 950 mm bundle height.

3.2 Hydrogen generation

Figure 7 shows a total hydrogen generation. The calculations provided a reasonably accurate prediction of the onset time of hydrogen generation (during the heat-up phase) compared with experimental data. Hydrogen generation in MELCOR follows a sequence of processes: during the air ingress phase, enhanced oxidation occurs; once oxygen becomes depleted, an oxygen starvation phase temporarily stabilizes the protective oxide layer; upon reflooding, rapid steam oxidation resumes, resulting in an overprediction of hydrogen release in the MELCOR simulation. This overestimation reflects MELCOR's simplified treatment of oxygen depletion and oxide layer behavior, which differs from the experimentally observed kinetics [5].

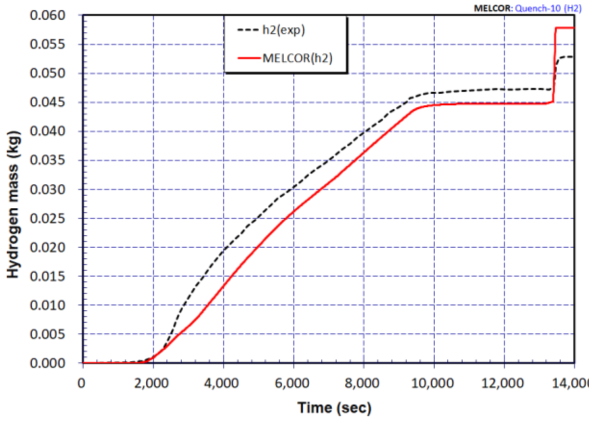

Fig. 7. QUENCH-10 calculated hydrogen generation by MELCOR versus experimental data.

3. Conclusions

MELCOR's predictions of the heater rod temperatures in QUENCH-10 show good agreement in overall trends but miss certain localized phenomena, such as breakaway oxidation spikes and delayed upper-bundle quenching. The discrepancies highlight the limitations of lumped-parameter models in capturing fine-scale thermal-hydraulic and oxidation interactions.

ACKNOWLEDGMENTS

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government (MSIT) (No. RS-2023-00259516).

REFERENCES

[1] G. Schanz, et. al, Results of the QUENCH-10 Experiment on Air Ingress, Report FZKA 7087, Karlsruhe, Germany, 2006.
[2] R.O. Gauntt et. al., MELCOR Computer Code Manuals, Version 1.8.6, Users Guide and Reference Manual, NUREG/CR-6119, SAND2005-5713, U.S. Nuclear Regulatory Commission, 2005.
[3] C. Bals, et. al., Modelling of Accelerated Cladding Degradation in Air for Severe Accident Codes, 2008.
[4] A.S. Benjamin, D.J. McCloskey, D.A. Powers and S.A. Dupree, Spent Fuel Heatup Following Loss of Water during Storage, NUREG/CR-0649, 1979.
[5] P. Vryashkova, New Zircaloy oxidation correlations of the computer code MELCOR 2.1 analysed on the base of QUENCH-10 test data. 12th International conference on WWER fuel performance, modelling and experimental support, 16-23 Sep. 2017, Nesebar, Bulgaria.