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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Development of MELCOR v2.2 Input for the simulation of QUENCH-06 experiment

TESI MAGISTRALE IN NUCLEAR ENGINEERING – INGEGNERIA NUCLEARE

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1. Introduction

International guidelines for the licensing of nuclear power plants require that safety assessment is performed on a variety of system states, involving also Severe Accidents (SA). In order to predict complex phenomena occurring during SA, deterministic codes have been developed, like ASTEC and MELCOR. Nevertheless, their application is not straightforward on accidental prototypical systems or reactor studies, but proper validation procedure must be conduct prior to the use to assess the implemented models performance. This thesis work is devoted to conducting an independent user validation campaign on MELCOR v2.2 code employing the experimental dataset provided as outcome of QUENCH-06 test. The expected result of the current work consists in the accuracy evaluation of Core Heat up, Oxidation and Degradation models embedded in MELCOR.

The document is organized as follows. In Chapter 2 QUENCH-06 facility, geometry and test procedure will be briefly introduced. Chapter 3 delivers the description of MELCOR code and target phenomena it is able to describe. Chapter 4 provides the overview on the nodalization schemes of QUENCH-06 Input and on the sensitivity analysis using different zircaloy oxidation correlations. Main Figures Of Merit (FOM) trend and comparisons with experimental data will be the object of Chapter 5. Conclusion and future developments are postponed to the last chapter.

2. QUENCH-06 Test

QUENCH-06 is a scaled down, separate test effect experiment conducted at Karlsruhe Institut fur Technologie (KIT) for the simulation of a hot uncovered core of a generic Light Water Reactor (LWR) in Design Basis Accident condition suddenly cooled down by water and steam.

Main goals of the test are:

- Evaluation of hydrogen build-up arising from zircaloy oxidation in various stages of the simulated accidental sequence;
- Suppression of initial core degradation by reflooding (**quenching**).

2.1. Test Facility

QUENCH [1] facility consists of a heated bundle, a thermal insulator and external devices as water circuits components, argon tanks and hydrogen detection instruments.
Test bundle is composed of 20 fuel rods simulators (FRS) electrically heated by 1024 mm length tungsten wires, arranged in two rings connected to the two power supply units of 35 kW of gross capacity each. Tungsten wires are surrounded by ZrO_2 annular pellets. FRSs are sheathed by prototypical 0.725 mm thick Zircaloy-4 cladding. In the upper and lower heads of the FRSs, molybdenum and copper electrodes substitute the tungsten heater. Center of the test section is occupied by a dummy rod, composed just by zircaloy cladding and a zirconia pellet stack without any power source. Four solid zircaloy corner rods are located in the four corners of the bundle. Rods structures are held in position by five spacer grids placed at different altitudes, made of zircaloy and Inconel. The cooling chamber is radially surrounded by a 2.36 mm thick zircaloy shroud.
Radial overview of QUENCH-06 bundle is presented in Figure 2.1.

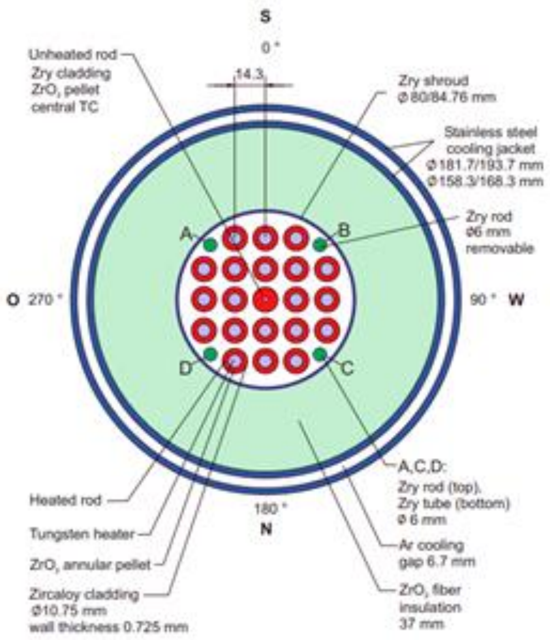

Figure 2.1: Bundle radial view [1]

Test section is separated from the environment by means of an insulator, composed of 37 mm thick zirconia fiber layer, placed in correspondence of the bundle active region, stagnant argon filled volume and double-walled stainless steel cooling jacket.
Figure 2.2 shows the axial structure of the QUENCH-06 test section.

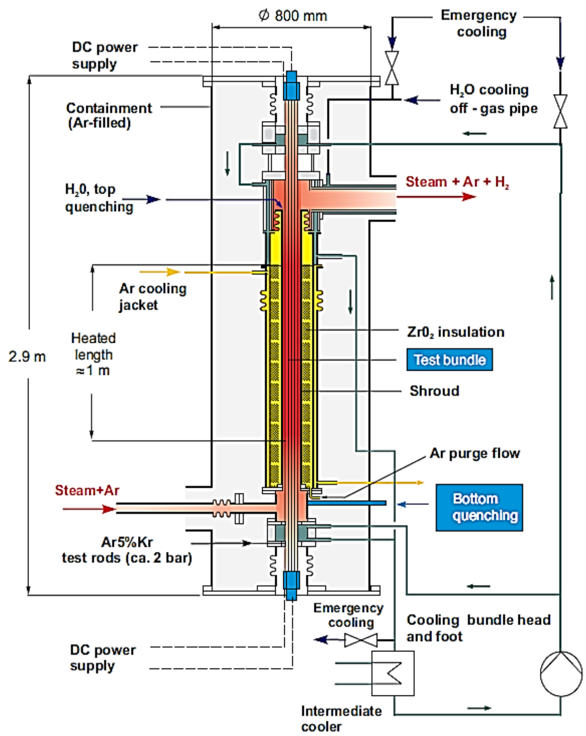

Figure 2.2: Bundle axial view [1]

External water circuit, connected to bundle lower plenum, is composed of a main loop, which supplies superheated steam and subcooled water depending on the test phase, and a 6 bar Fast Water Injection (FWI) system, designed to insert into the system 4 l of subcooled water in 5 s.
Test bundle and thermal insultation system are equipped with large set of sensors, detecting surface temperature, pressure, and mass flow rates.

2.2. Test Procedure

Bundle [1], which is initially at room temperature, is stabilized at 873 K by a stepwise increase in electrical power, while crossed by a flowing atmosphere of 3 g/s of steam and 3 g/s of argon. At the end of the stabilization period, power fed into the bundle is enhanced from 4kW up to 11 kW and then kept constant for 4046 s. This stage, called **preoxidation**, is characterized by a rather constant temperature, high enough to trigger the oxidation reaction on the zircaloy structures. Coolant mixture is still made of 3g/s of steam and 3g/s of argon, entering the bundle from the bottom section at a bulk temperature of 640 K. At the end of preoxidation phase, power is steeply ramped up to 18 kW, boosting oxidation and hydrogen production until *quenching condition* is reached, namely:

1. Three rod thermocouples should have reached 1973 K;
2. Central rod thermocouple, located at 950 mm, should have reported at least 1873 K.

Once reflooding term is fulfilled, steam injection is turned off, argon flow rate is switched to bundle upper head and FWI is activated to promptly cool down the test section. Concurrently, power supply is decreased to 4 kW to simulate decay heat source in nuclear fuel. With 30 s of delay, main water loop pumps in subcooled water at a rate of 42 g/s for 255 s. Once reflooding procedures are ended, power is set to zero and the bundle rests for 3500 s, terminating the experiment.
In Table 2.1, QUENCH-06 sequence of events is reported.

Time [s]	Event	Flowing mixture
0	Test starts, heat up from 873 K to 1473 K	3 g/s steam 3 g/s argon
1965	Preoxidation stage onset, power at 11 kW	''
6011	Power ramping	''
6620	Corner rod B withdrawal for metallographic analysis	''
7179.5	Reflood on-set	0.78 g/s FWI 3 g/s argon in bundle head
7184.5	FWI ends	3 g/s argon in bundle head
7215	Main quench, power to 4 kW	42 g/s water 3 g/s argon in bundle head
7431	Power shutoff, quenching ended	3 g/s argon in bundle head
11420	Test termination	-

Table 2.1: QUENCH-06 events

3. MELCOR code

MELCOR [2] (*Methods for Estimation of Leakages and Consequences of Release*) is a fully integrated, engineering level computer code developed at Sandia National Laboratory (SNL) for the US Nuclear Regulatory Commission (USNRC) for the simulation of stationary operations and accidental conditions in LWR, spent nuclear fuel pools, and gas reactors.
MELCOR is able to simulate interacting events, both in in-vessel and ex-vessel regions, as:

- single phase and two phase thermal hydraulics in primary circuits (advection, flashing, condensation, flow boiling, film boiling) and in containment;
- core degradation processes (zircaloy oxidation, ballooning, candling, molten pool relocation, corium formation) and hydrogen build up estimation;
- core-concrete interaction on the lower head, jet ejection;
- fission products release, aerosol behavior, direct containment heating…

MELCOR architecture adopts a unified structure, composed of several packages [2], each one devoted to the description of specific phenomenology, characterized by mainly 1-D calculational frameworks.
MELCOR code has undergone several validation studies to ensure that internal models and implemented correlations provide accurate results.

4. QUENCH-06 MELCOR Input

The developed MELCOR Input embodies QUENCH-06 lower plenum, lower molybdenum electrode zone, active region, and the whole upper plenum where off-gas pipe is located. Radially it includes test bundle and the insulator until stainless steel inner cooling jacket.
Thermal-hydraulics of QUENCH-06 test section is described through **Control Volume Hydrodynamics** (CVH) and **Flow Path (FL)** packages. Space available for the passage of flowing mixtures is subdivided in 12 Test Control Volumes (TCVs) linked by means of 12 flow paths. TCVs are all *active*, meaning their temperature, pressure and energy are allowed to change in time, and only *pressure equilibrium* between the liquid and gaseous phase is set. TCVs are summarized as follows. CVH_01 describes fluid inventory in

correspondence of copper lower electrode. It contains the sources of superheated steam, argon, and quenching water as tabular function of mass flow rate and temperature in time. CVH_02 models the free volume in correspondence of the lower molybdenum electrode region. The thermal-hydraulic behavior in the active region is modeled by means of TCVS for CVH_31 to CVH_38. CVH_04 includes fluid space between end of the active region and elevation 1300 mm. Lastly, CVH_05 is entitled to represent QUENCH-06 upper plenum. It contains source of argon for the post quenching argon flow rate in bundle head.
In addition, also 10 additional control volumes (ACVs) are specified for the description of FWI system, mass sink as off gas pipe and bypass volumes required by COR Shroud. In Figure 4.1 outline of control volumes network developed for QUENCH-06 input is presented.

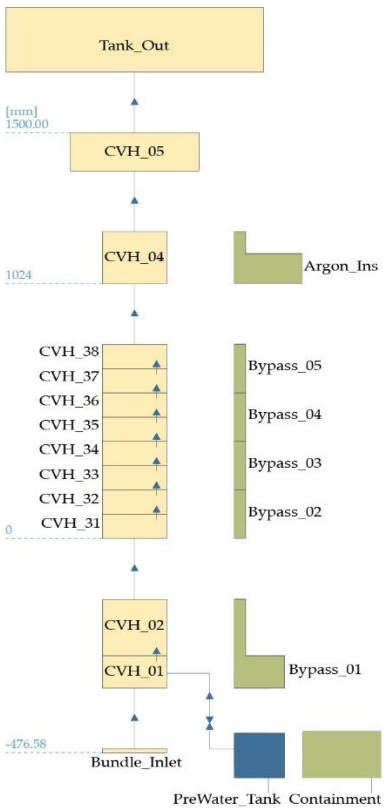

Figure 4.1: QUENCH.06 hydraulic nodalization

All rods structures, grid spacers and zircaloy shroud are modeled as **COR** package component to account for their oxidation and degradation. The bundle is axially subdivided into *42 COR levels*: Level 1 is a dummy level for COR lower head. Level 2: contains COR supporting plate. Level 3 and 4 incorporate solid structures in correspondence of copper electrode. Level 5 to 9 include items in correspondence of molybdenum lower electrode. Level 10 to 33 contain shroud and rods in active region. Level 34 to 38 are occupied by structure located between elevation 1024 mm and 1300 mm. Level 39 to 42 embrace upper plenum components.
Test section is radially divided in *4 COR rings*. Ring 1 encloses the central unheated rod. In ring 2 the eight FRSs are located, while the twelve remaining are located in ring 3. The outermost rings contains the four corner rods and the shroud, which is specified as Shroud (SH) component. All cladding structure with the exception of the shroud are defined as cladding, the zirconia pellet stack as Supporting ZrO_2 and the electrodes and tungsten heater by means of **COR_ELHEAT** card. The five grid spacers are shared by the 4 rings as Supporting items. **Heat Structure** (HS) package models the 1-D heat conduction across the intact, solid thermal insulator. Its nodalization reflects COR scheme. Zirconia fiber layer properties are user specified by means of **Material Properties** (MP) package, while for the stainless steel of the cooling jacket default material is adopted. Left surface (zirconia fiber inner surface) of each HS exchanges heat with the TCV at the same altitude, while the right surface (cooling jacket outer surface) has temperature imposed as boundary condition. Power, mass sources and the boundary conditions are set by the users as time vectors through **Tabular Function** (TF) packages.
QUENCH-06 results are firstly evaluated by applying the default Zircaloy-Steam oxidation correlation embedded in MELCOR (*Reference* input), which is the Urbanich-Heidrich [2][3]. Its application is then extended to include a sensitivity analysis adopting different formulations [4], with kinetics covering both low and high temperature regimes. Table 4.1 reports the 6 different case studies.

Input	$T_{surface}$<1800 K	$T_{surface}$ >1900 K
Reference	Urbanich-Heidrich	
CP-V	Cathcart-Pawel	Volchek
L-V	Leistikow-Schanz	Volchek
CP-Pr	Cathcart-Pawel	Prater-Courtiright
L-Pr	Leistikow-Schanz	Prater-Courtiright
Baker	Baker-Just	

Table 4.1: QUENCH-06 Input sensitivity analysis

5. QUENCH-06 MELCOR Results

5.1. *Reference* Input Results

As it will be presented in the following figures, MELCOR Input is qualitatively judged to be able to simulate the main thermal-hydraulic and oxidation phenomena. The response of the system to changes in power supplied, and to the different boundary conditions is overall well predicted in terms FRS surface temperature (*Ref FRS* label) evolution [Figure 5.1].

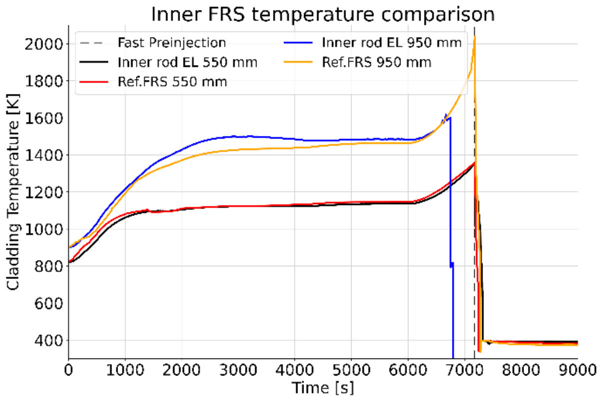

Figure 5.1: FRS temperature

Since the fluid mixture flows upwards, it reaches its peak temperature in correspondence of elevation 950 mm, inducing in this altitude the hottest cladding temperature. The mismatch for the trend shown in Figure 5.1 at 950 mm is due to failure of the thermocouples. Hydrogen generation from Zircaloy-Steam oxidation is evaluated correctly for what concern the preoxidation phase, as shown in Figure 5.2.

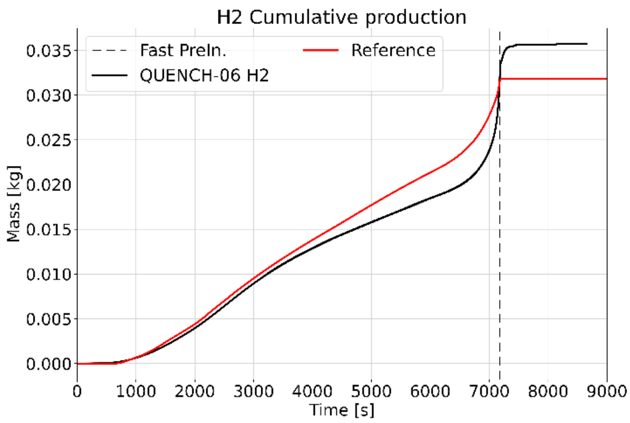

Figure 5.2: Hydrogen source term

Unfortunately, hydrogen 4 g produced between the FWI and main quenching is not predicted by the input deck, mainly because it is not able to represent the sudden evaporation of the water that takes place in the test section, induced by simulated decay heat. The steam generated lowers the heat transfer coefficient, causing a further rod heating up post FWI. This physical aspect is clearly not simulated by *Reference* by observing the two divergent trends in Figure 5.2 on the bottom.

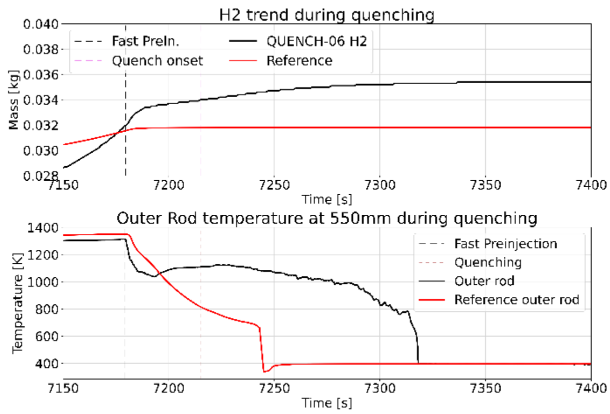

Figure 5.3: Hydrogen production during quenching and re-evaporation

Surface temperature of the outermost ring structures, namely corners rods (*Ref.CROD* label) and shroud, are characterized by a trend in general lower than the experimental, as plotted in Figure 5.4.

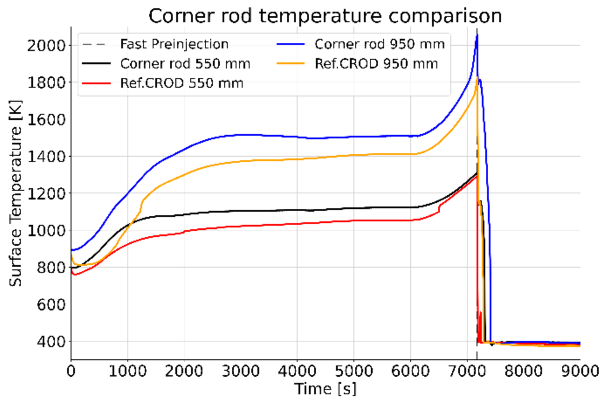

Figure 5.4: Corner rod temperature

Regarding the oxidation profile, the predicted oxide layer on corner rods is sufficiently in agreement with the metallographic analysis performed at t = 6620 s on Corner Rod B (*CROD-B* label) [Figure 5.5 on the left]. Given that post FWI evaporation is not modeled in the simulation, the final oxide thickness on Corner Rod A (*CROD-A* label), and generally on all zircaloy structures, is underestimated, as plotted on Figure 5.5 on the right.

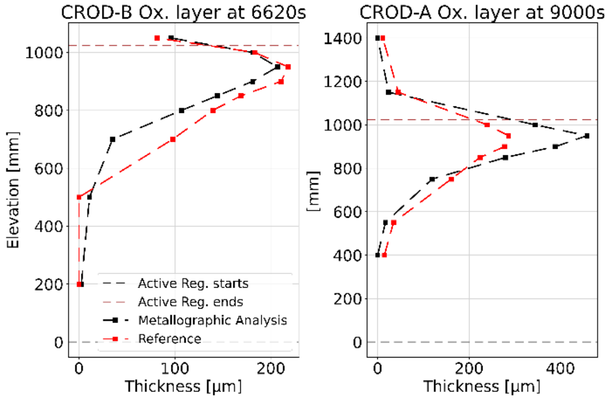

Figure 5.5: CRODs oxide layers

5.2. Sensitivity analysis

Reference input architecture is tested adopting different parabolic Zircaloy-Steam oxidation correlation, covering low cladding temperature domain (T<1800K) and high temperature regime (T>1900K). All reaction rates K implemented are Arrhenius-type. In the temperature frame between 1800 K and 1900 K, MELCOR code linearly interpolates the two boundary values of K(T).
In Figure 5.6 hydrogen cumulative mass profiles predicted by the different correlations are plotted.

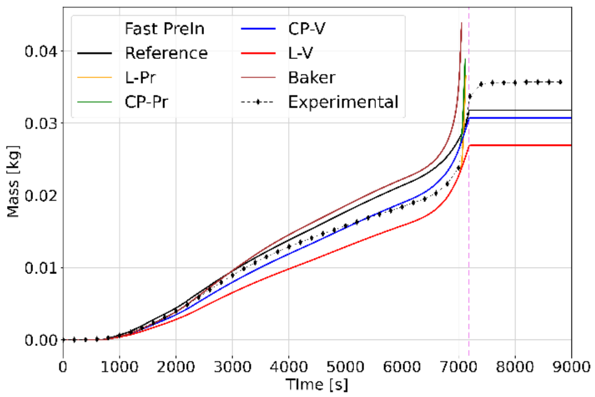

Figure 5.6: Hydrogen source in sensitivity analysis

During preoxidation, stage in which bundle does not exceed 1473 K, the formulation that provides the trend closer to the experimental hydrogen build-up is the *Cathcart-Pawel*, while the *Leistikow* underestimates the oxidation rate and hydrogen production. In power ramping phase, *Baker* and *Prater-Courtright* correlations are responsible for a significant overestimation of the oxidation reaction, and hence of the hydrogen production and of the temperature trend, leading to shroud melting and relocation. Given the fine nodalization, calculation for these two input decks becomes too burdensome, time step drops and so in these analyses it is not possible to evaluate the final hydrogen mass produced. In this phase, the trend closest to experimental production is provided by *Volchek*.

6. Conclusions

The developed MELCOR v2.2 Input successfully predicts the main phenomenologies occurring in all QUENCH-06 test phases. By considering the FRS cladding surface temperature and the hydrogen build-up during preoxidation, the reconstruction capability is satisfactory, but further studies involving features as COR-HTR and COR-BCP are foreseen to address the underestimation in Ring 4 structure temperatures. Post FWI evaporation is thought to be too challenging for this input deck, and hence upcoming efforts will adapt the nodalization to account for this process.
It is recommended that future studies adopting this Input will use the CP-V scheme for Zircaloy-Steam oxidation, which has been proved best performing during the sensitivity analysis.

References

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