PHEBUS FPT-1 SIMULATION, USING MELCOR: BLOCKAGE MODEL ANALYSIS

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ABSTRACT

Recently, MAAP and MELCOR research teams completed a set of accident simulations to reconstruct the Fukushima-Daiichi accident in order to better understand severe accident progression. One result from this work was that the predicted hydrogen generation in MELCOR is notably more than in MAAP. The fuel rod degradation process (i.e., debris formation and blockage models) may likely be responsible for this hydrogen generation difference and an opportunity exists to understand the key reasons for this difference. To examine this hypothesis, the PHEBUS FPT1 experiment is selected as a benchmark test, and MELCOR is used as the analysis tool. In the past, the core degradation process of PHEBUS tests was simulated with MELCOR for fission product release insights. In this work, our calculation results are compared to PHEBUS FPT1 data to verify our MELCOR calculation. Given this validation of a nominal MELCOR simulation of the FPT1 test, we start the second step to use the volume fractions of each component as a way to visualize the debris-blockage geometric arrangement for PHEBUS FPT1 as the fuel degradation event proceeds. These results could also provide a logical approach for improving the fuel degradation (i.e., debris formation and blockage models). Relevant research is still ongoing, and will be provided in the final paper.

KEYWORDS
MELCOR, PHEBUS FPT1, CORE DEGRADATION, BLOCKAGE MODEL

1. INTRODUCTION

MAAP and MELCOR [1] are well known integrated, engineering-level simulation tools for severe accident analysis. The simulation of the Fukushima accident has been separately conducted by each research group as well as a comparison between the two research groups [2]. The comparison result shows that both codes can model the Fukushima accident signature with consistent initial and boundary conditions and with appropriate modeling and parameter assumptions. The calculation results, such as pressure and temperature history, and certain early event timing match observations. However, certain key physical processes differ, e.g., prediction of the hydrogen generation in MELCOR is notably more than in MAAP. Opportunity exists to understand the key reasons for this difference. The fuel rod degradation and flow blockage processes, which involve clad oxidation, fuel-clad melting, candling and freezing, debris formation and heat transfer, may be responsible for the hydrogen generation difference.

Research on core blockage mechanisms in severe accident has been considered in the past. In 1978, the mechanism of partial flow blockage in a turbulent flow in a model nuclear fuel rod bundle was done by

Greer [3]. Then a blockage analysis on flow distribution in a PWR fuel rod bundle model was done by Ang [4, 5]. Two years later, the cross-flow between identical sub-channels caused by a severe blockage was studied by Gencay [6]. During this period, several experiments about core degradation, including blockage mechanism research were conducted one by one, such as CORA [7], QUENCH [8], and PHEBUS [9]. A model for melt blockage (slug) relocation under severe accident conditions was developed by Veshchunov [10]. In the same year, an improvement of core modeling in ICARE/CATHARE was done by Drai [11]. Later, a flow blockage analysis was done by Lu [12]. This topic was also studied in severe accident research in the core degradation area by Bottomley [13]. The research was still ongoing by Vaghetto in his study: debris-generated core blockage scenarios during loss of coolant accidents [14]. Recently, flow blockage results were reviewed again by Haste in his comparison of CORA, QUENCH and PHEBUS [15].

As a consequence, we chose the PHEBUS experiments as benchmark tests to better understand the fuel degradation and flow blockage process. Recently, a new version modeling of PHEBUS has been finished by Sandia Labs, and provided to us. Meanwhile, a calculation of old version MELCOR by Cho is also referenced by us [16]. We completed an initial core degradation simulation with MELCOR in our current work [17]. Past work simulated the power input and the mass flow rate of the steam entering at the core inlet, as presented in the PHEBUS FPT experiment report [9]. After that, average pressure, energy distribution, mass of core materials and melting materials, fuel and clad temperatures, hydrogen mass and hydrogen generation rate were calculated separately [17]. In addition, the average pressure, and several fuel temperatures are compared with PHEBUS FPT1 experiment data to verify our calculation [17]. Based on this former work, now a calculation on volume fractions of each component are provided in this paper. The blockage mechanism is an important part in the core degradation process. During this process, the melting materials may fall down. The melting materials will distribute un-linearly on the intact materials, and then take the position of the flow channel. Once the flow channel is 95% covered, this cell is expected to be blocked. Once it is blocked, the melting materials cannot move downward anymore (steam can still go up). The melting materials above the blockage crust turn to be melting pool materials. Thereby, the flow characteristics are important for blockage mechanism analysis. The time evolution of the different species volume fractions, as we provide in this paper, can give the analyst some insights into how the fuel degradation and blockage models affect the overall meltdown process. A parameters sensitivity analysis is prepared and this work is ongoing. A new candling model for flow blockage is being developed and is expected to provide an improved approach.

2. BRIEF INTRODUCTION TO THE PHEBUS FPT1 EXPERIMENT

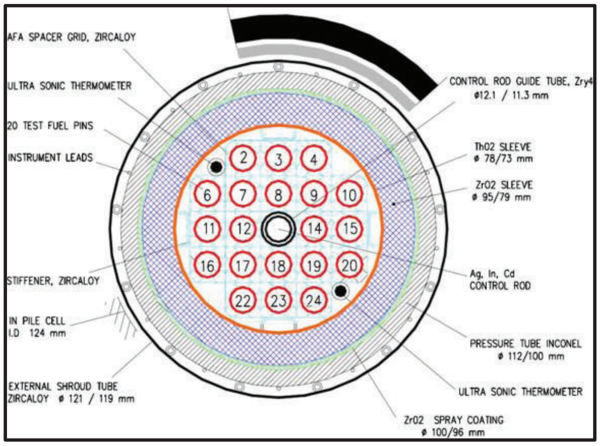


Figure1. Fuel Assemble Scheme of PHEBUS FPT1 [18]

The core degradation experiment PHEBUS was conducted by a French research team, to better understand fuel degradation and fission product release under prototypic conditions. It has been designated as an international standard problem by the CSNI (ISP-46). A postulated Loss of Coolant Accident was the accident scenario simulated in PHEBUS FPT1 in a steam-rich atmosphere. Fission-product release measurements were a key objective of PHEBUS FPT, and core degradation was observed and some details measured. The research of core blockage models in this paper relies on core degradation research of the PHEBUS FPT1 experiment.

As shown in Fig.1, the fuel assembly structure of PHEBUS is presented. Due to the experimental test volume constraints, only 21 fuel rods were used to simulate the core degradation process. As we can see in this figure, the control rod is in the center of the experiment facility. The structure and materials of this control rod are arranged as a typical PWR and it contains materials such as silver (Ag), indium (In), cadmium (Cd). The other 20 test fuel rods are arranged around the control rod in a square pitch lattice that could be modeled as annular rings. The test fuel bundles use uranium dioxide (UO2) as fuel and zircaloy as the clad material.

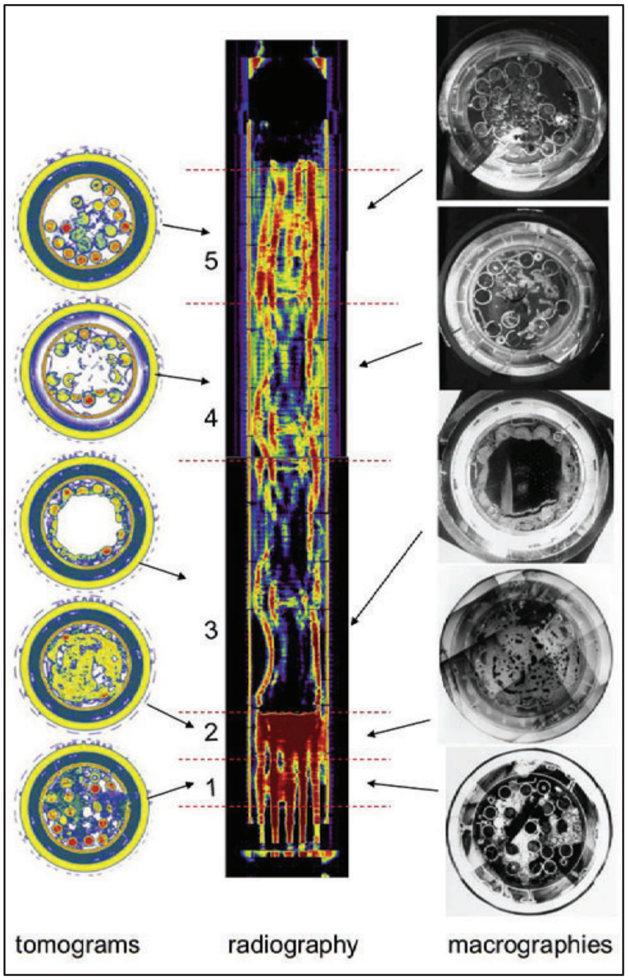


Figure 2. Radiography and Tomography of Test Bundles [19]

The PHEBUS FPT1 obtained temperature and pressure data from thermocouples, ultrasound thermometers and pressure sensors. X-ray technology is also used to get the cross-section image of its final state post-test assembly materials arrangement. Shown in Fig.2, the radiography and tomography of PHEBUS FPT1 testing bundles are obtained. These figures can show the core morphology after the core degradation process in the PHEBUS FPT1 experiment. As we can see in this figure, most of the fuel rod bundle is intact but highly distorted. There is fuel melting but the amount seems to be limited to local regions. The melting materials fall down along with the fuel rod and then finally accumulate at the bottom of the PHEBUS FPT1 facility. The core blockage and melting pool exist in Position 2 as shown in Fig.2. The real cases of how this evolves can be clearly exhibited by the calculation of volume fractions.

3. NODALIZATION OF PHEBUS FPT1

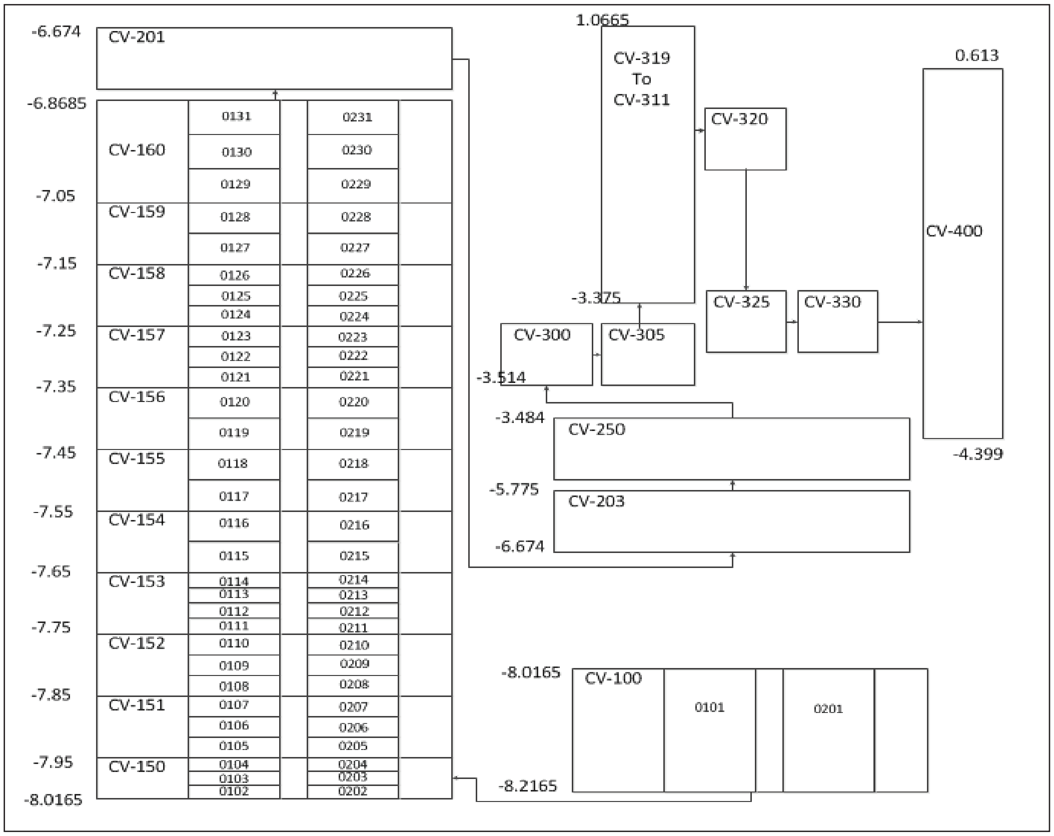


Figure 3. Nodalization of PHEBUS-FPT1 [17]

Our objective in reanalyzing PHEBUS FPT1 is to gain further insights into the fuel rod degradation process by looking at the effect of model parameters on the fuel melting, candling process, core debris next transfer and flow blockage [20]. Baseline MELCOR simulation is always a required first step of this research, as in our former work.17 We get a reasonable match of the pressure and temperatures that were measured and with this match we want to describe the evolution of the material motion. And then in later work, we will look at variations in the fuel degradation models and sensitivities to see key differences that affect hydrogen generation. It is the key parameter we are looking at to show blockage model differences. In this current work, we try to look for key parameters to vary blockage model parameters. The volume fraction is a key parameter to research the flow characteristics of PHEBUS FPT1. In Fig. 3 we depict the MELCOR nodalization that was used to simulate the test and note the core fuel bundle region is ‘expanded’ to explain the assumed geometry. Both the control volume nodalization and core cell nodalization are drawn in Fig.3. This makes this MELCOR PHEBUS model much easier to understand as a whole system. As one can see from this figure, in the radial direction, the rods have been separated into

2 rings. The control rod in the center occupies ring1 alone, and the surrounding fuel rods were arranged into ring2. In the axial direction, the bundles were separated into 31 core cells, and 12 control volumes, as shown in Fig.3.

4. EXTRA PRIMARY AND BOUNDARY CONDITIONS

In the former work, we provided the power input and the mass flow rate of the steam at the core inlet of PHEBUS FPT1 as the primary and boundary conditions [17]. Along with the progress of our work, more parameters are involved to support the research. As we can see in Fig.4, fuel materials distribute 40% in ring1 and 60% in ring2. The tendency of the primary clad is very similar to primary fuel mass in PHEBUS FPT1 as shown in Fig.5. However, the total mass of the clad is just about 25%of the fuel mass.

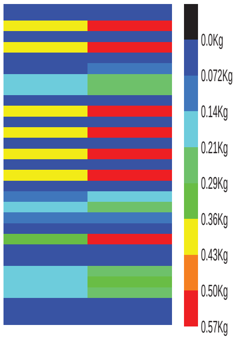


Figure 4. Primary Fuel Mass in PHEBUS

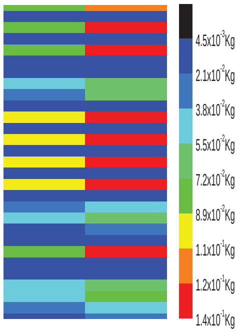


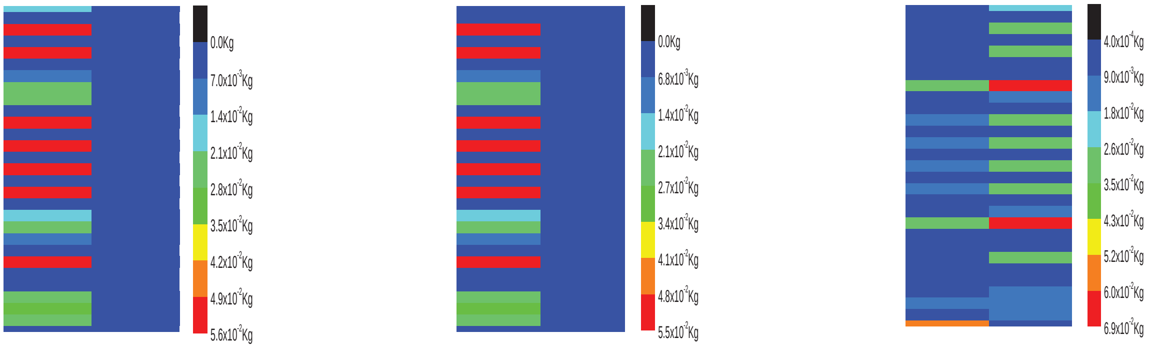
Figure 5. Primary Clad Mass in PHEBUS

There is nearly no supporting structure materials in the PHEBUS FPT1 experiment as shown in Fig.6. As shown in Fig.6 (a), there is only a little zircaloy in the bottom of ring1. And as shown in Fig.6 (b), there is just a little stainless steel in the bottom of ring2.

(a) Zricaloy **(b) Stainless Steel**

Figure 6. Primary Mass of Supporting Structure Materials

On the other hand, the non-supporting materials are abundant in the PHEBUS FPT1 experiment. As we can see in Fig.7 (a), the non-supporting material stainless steel mainly exists in ring1. This is because the control rod exists in ring1. The stainless steel is the main material for the control rod guide tube. For the same reason, the control poison is also in ring1 as we can see in Fig.7 (b). Meanwhile, the non-supporting zircaly exists in both ring1 and ring2. Ring 2 has more zircaloy for more fuel rods existing.



(a) Stainless Steel **(b) Control Poison** **(c) Zircaloy**

Figure 7. Primary Mass of Non-supporting Structure Materials

As shown in Fig.8, the primary flow area in ring2 is higher than in ring1, it is about 3 times different. Through this figure, we can also know the general flow situation of ring1 and ring2. As the setting of the MELCOR input, the primary core debris porosity are all 0.5, as shown in Fig.9.

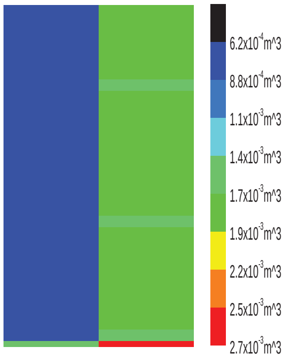


Figure 8. Primary Flow Area of Each Cell

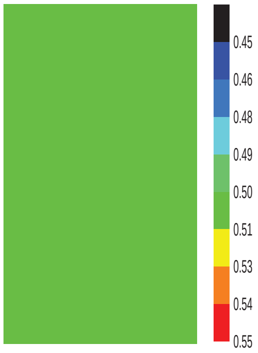
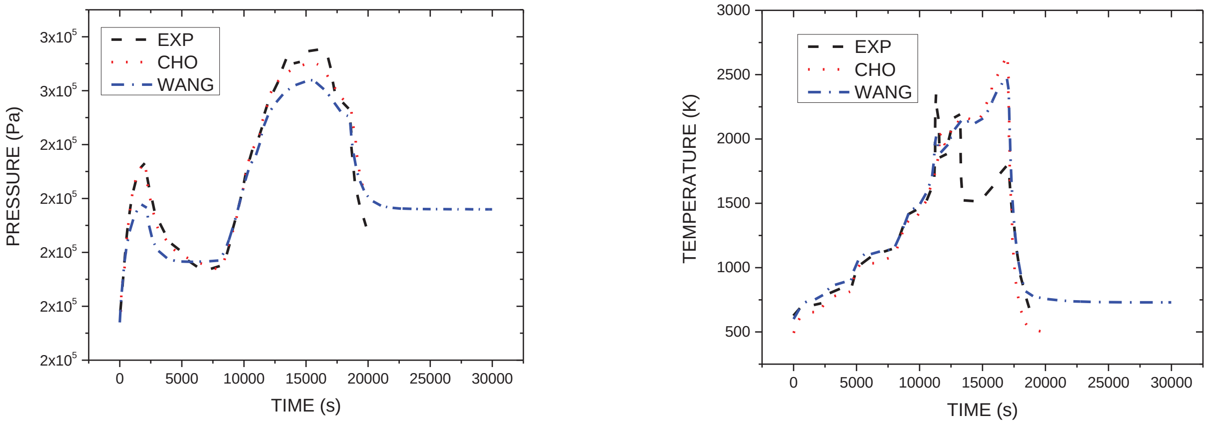


Figure 9. Primary Core Debris Porosity

5. VERIFICATION AND CALCULATION

As mentioned above, we completed an initial core degradation simulation with MELCOR in our current work [17]. The most important parameters were involved in the former work, including average pressure, energy distribution, mass of core materials and melting materials, fuel and clad temperatures, hydrogen mass and hydrogen generation rate. The average pressure, and fuel temperatures were compared with the PHEBUS FPT1 experiment and Cho's calculation to verify our work, as shown in Fig.10 [16, 17].



(a) Average Pressure of PHEBUS-FPT 1 Faculty (b) Fuel Bundle Temperature in 400mm

Figure 10. Comparison and Verification of Calculation [17]

A comparison of the hydrogen generation rate is made in Fig.11. We can see that the hydrogen generation rate in PHEBUS FPT1, Cho's calculation, and our calculation agree very well. [17] The behavior of the hydrogen generation rate is also a key parameter to see what happens during the fuel degradation and blockage process.

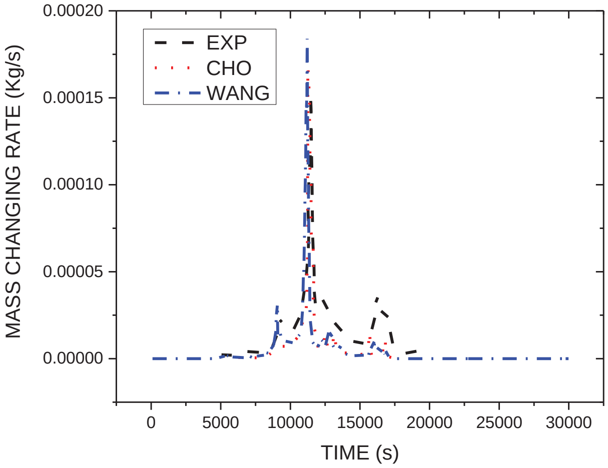
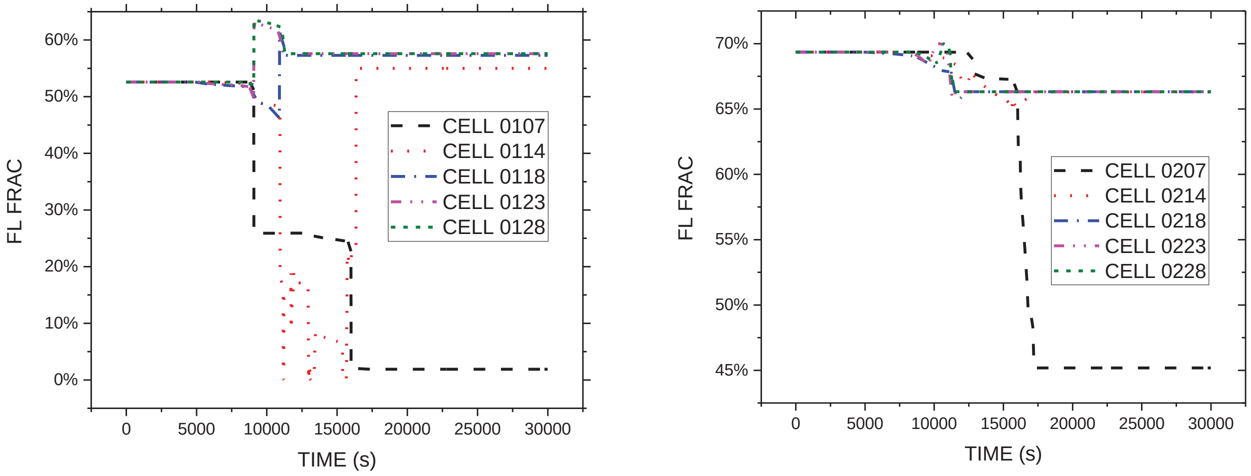


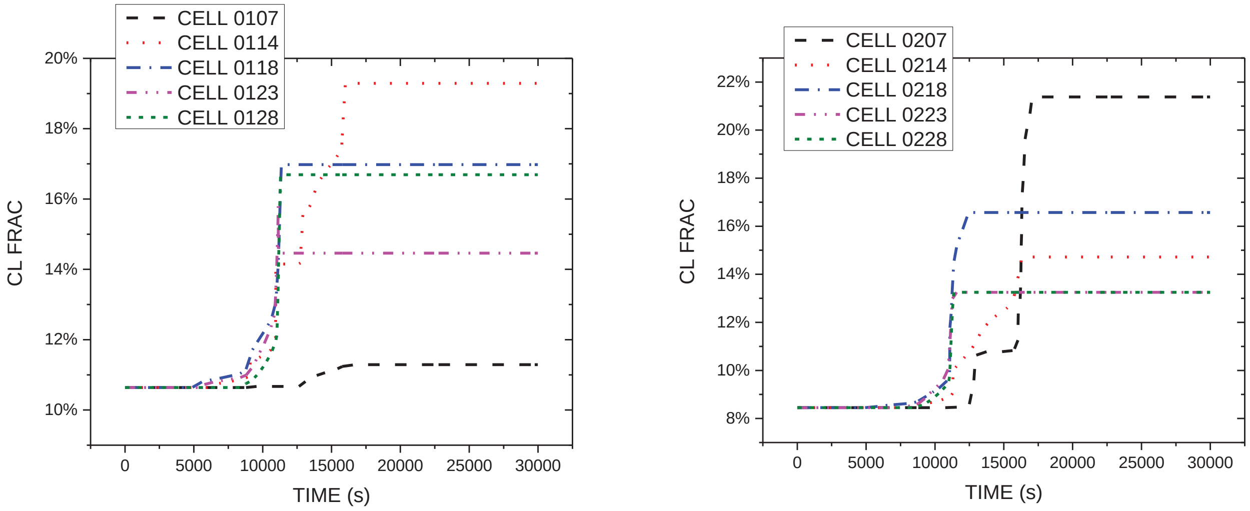
Figure 11. Comparison of Hydrogen Generation Rate [17]

The flow volume fraction of PHEBUS1 is shown in Fig.12. As we can see in Fig.12, the flow volume fractions in ring 1 vary greatly. High elevation cells, such as CELL 0123 and CELL 0128, are always unobstructed. Middle elevation cells show a mixed character: CELL 0118 fluctuates a little after 10000s before stagnating while CELL 0114 fluctuates significantly over a longer time span. And lower elevation cells, which receive molten material, are always monotonically decreasing smoothly. This situation can reflect the drastic change of flow volume in that region.



(a) (b)

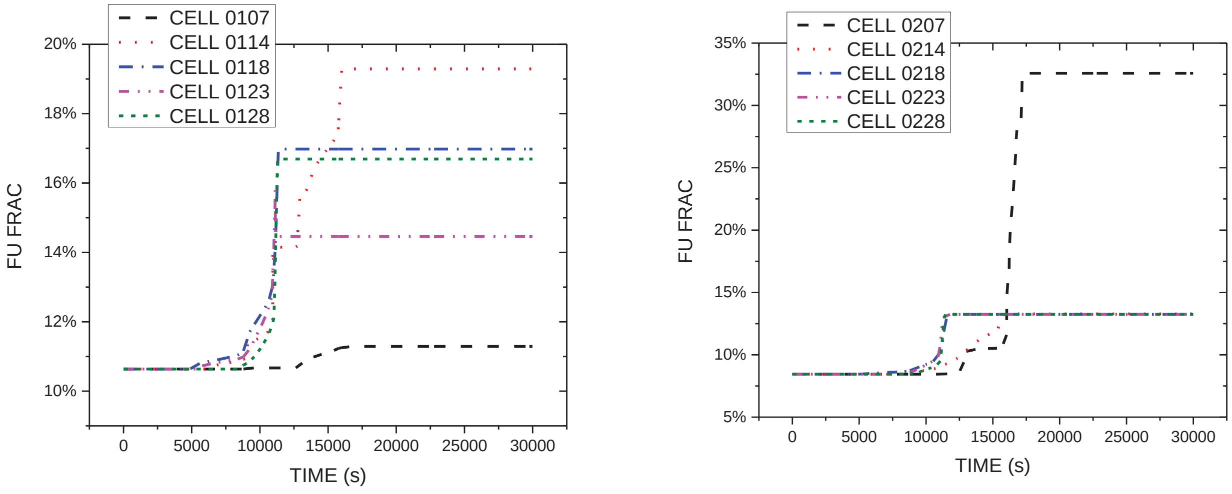
Figure 12. Flow Volume Fraction of PHEBUS1 in (a) Ring1 and (b) Ring2



(a) (b)

Figure 13. Cladding Volume Fraction of PHEBUS1 in (a) Ring1 and (b) Ring2

Despite the flow volume fraction, the core materials can be separated into intact and conglomerate parts. Clad materials and fuel materials are the main parts of intact materials. The change in flow volume fractions is tied to the relocation of clad and material during core degradation. As shown in Fig.13 (a), the cladding volume fractions in all cells increase along with the core degradation process. In Ring1, the cladding volume fraction in cell 0114 is the highest while the cladding volume fraction in cell 0107 is the lowest. In Ring2, the cladding volume fraction in cell 0207 is biggest while the above cells 0223 and 0228 are the lowest.

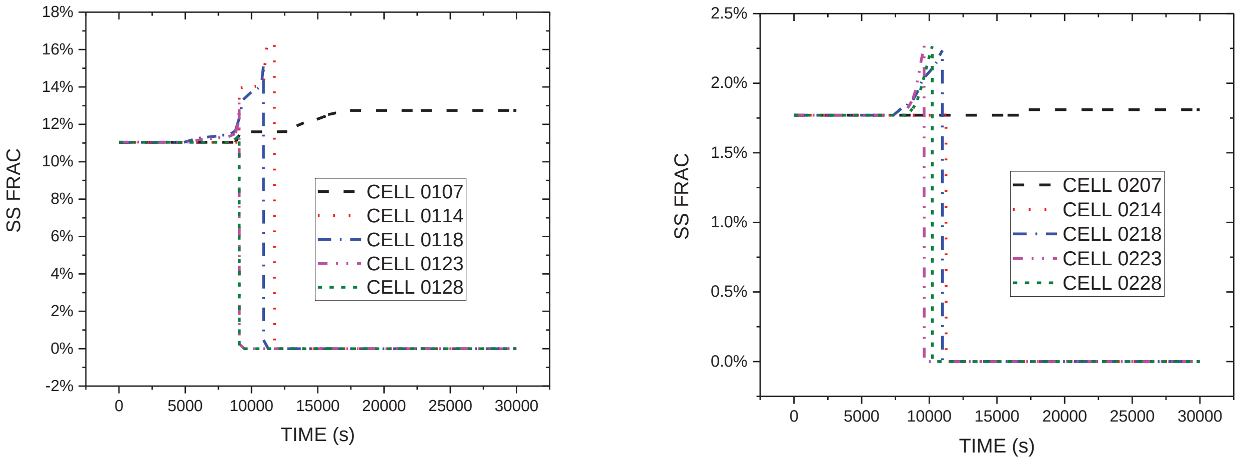


(a) (b)

Figure 14. Fuel Rod Volume Fraction of PHEBUS1 in (a) Ring1 and (b) Ring2

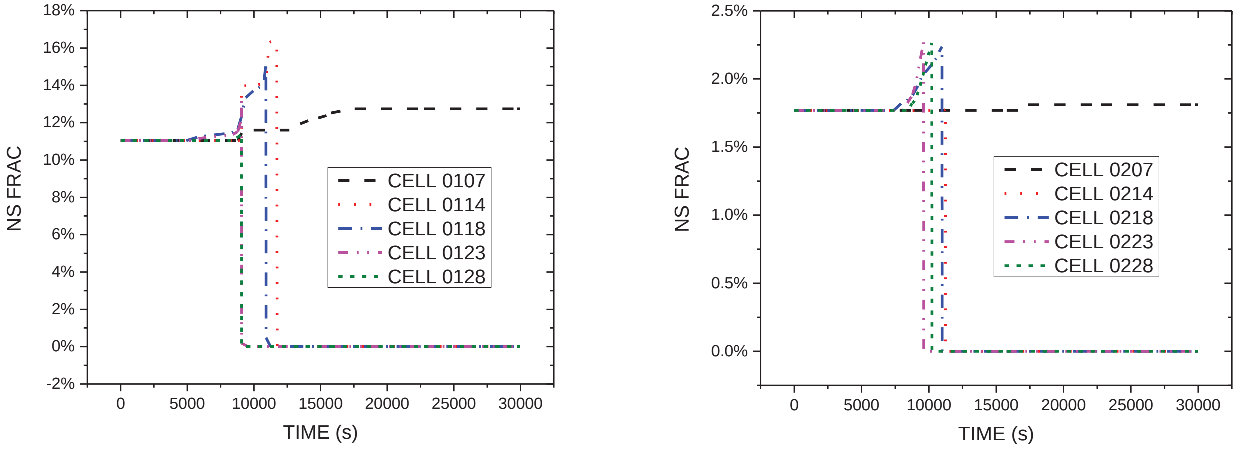
The fuel material volume fraction is shown in Fig.14. The trend of the fuel material in ring1 is similar to the distribution of cladding materials in ring1. However, in ring2, the fuel material in the bottom of PHEBUS, such as cell 0207, is significantly higher than in other positions. And in the above positions of PHEBUS, the fuel material volume fraction is all staying at around 15% after 12000s.

The volume fractions of supporting materials are shown in Fig.15. As we can see in Fig.15 (a), the volume fraction in cell 0107 and other lower cells increases only by a percentage point. However, in other positions, such as cell 0114, cell 0118, cell 0123, cell 0128, the volume fractions of supporting materials increase a little, and then turn to be 0% after 120000s. The situation of ring2 is similar to ring1.



(a) (b)

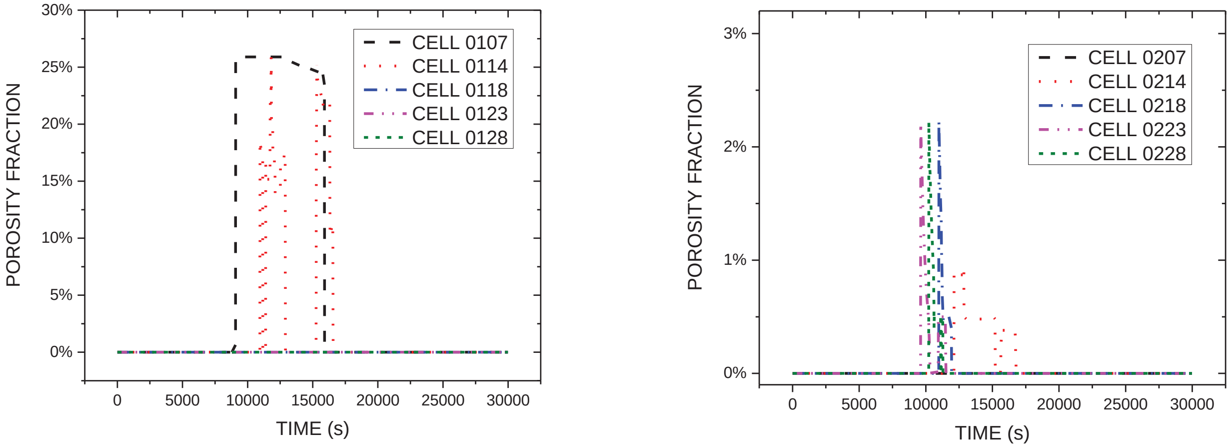
Figure 15. SS Volume Fraction of PHEBUS1 in (a) Ring1 and (b) Ring2



(a) (b)

Figure 16. NS Volume Fraction of PHEBUS1 in (a) Ring1 and (b) Ring2

The non-supporting material volume fractions are shown in Fig.16. The time evolution is very similar to that of the supporting material. In ring1 and ring2, the bottom space, cells 0107 and 0207, the non-supporting materials volume fractions are steady and increase a little. In the above space, the non-supporting materials volume fractions have some fluctuation between10000s to 12000s, and then rapidly decrease to around 0%.



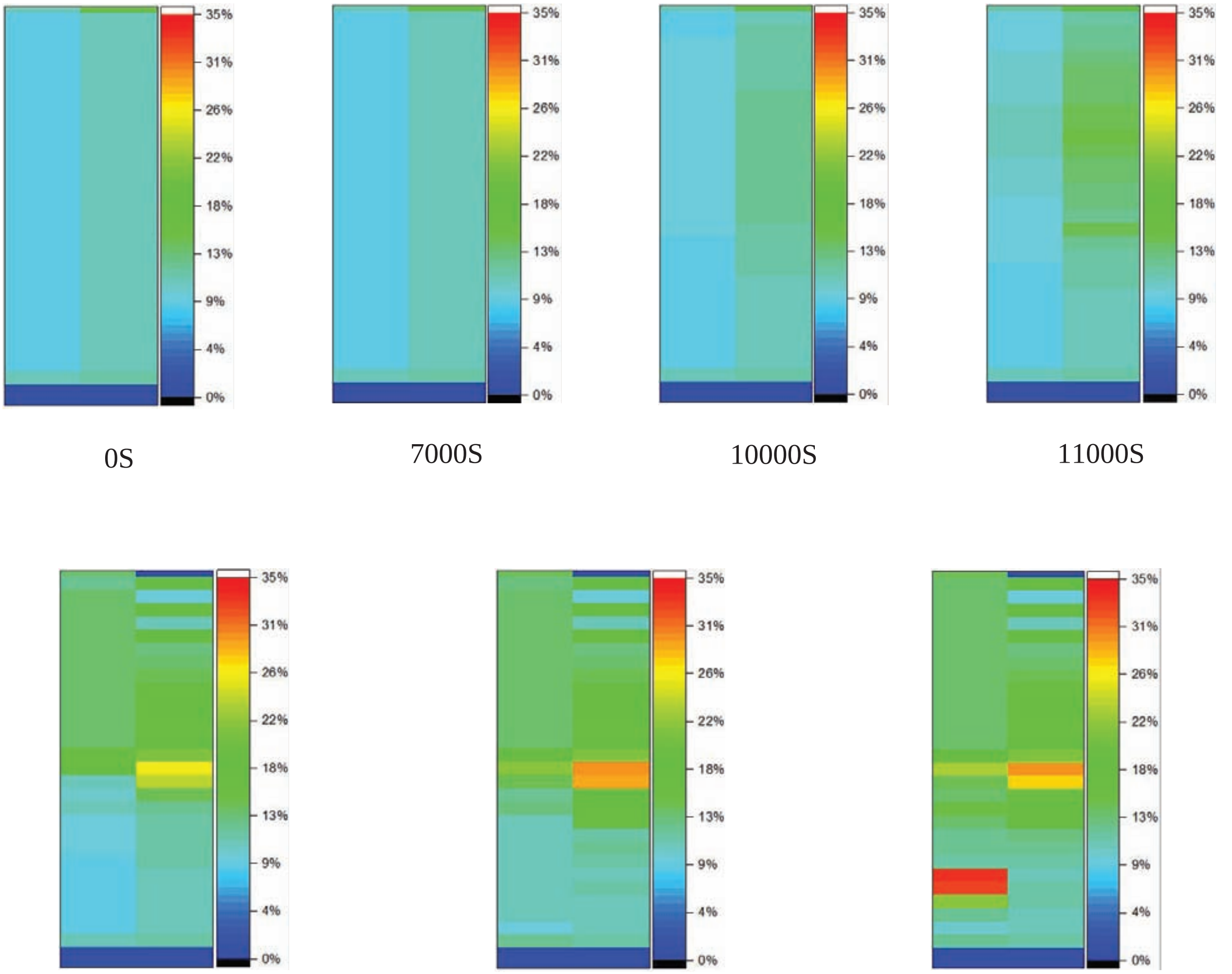
(a) (b)

Figure 17. Debris Bed Porosity Fraction of PHEBUS1 in (a) Ring1 and (b) Ring2

Debris bed porosity means the internal space of melting particles. This parameter greatly affects the flow characteristics of PHEBUS. By default in MELCOR, when the porosity falls below 5%, the flow is considered blocked. As we can see in Fig.17 (a), the debris bed porosity fraction changes a lot. In cell 0107, it stays at around 25% between 10000 s and 16000 s. During this time, in cell 0114, the porosity fraction spikes from 0% to 25% twice. And the debris bed porosity fractions in the higher regions of ring1 stays at 0% all the time. In ring2 the variation in debris bed porosity fractions is greatly reduced to a maximum of only 2% across all cells

6. CLOUD FIGURES OF FUEL RODS VOLUME FRACTION

As presented in Chapter.5, the direct output from MELCOR can only show the tendency of each cell along with the development of progress. As a consequence, a method presenting the space distribution better is in needed. The fuel rod volume fraction cloud figures can show visually how the fuel rod volume fraction weight changes during the process of core degradation. It is necessary for us to do such kind of work before making a model sensitivity analysis. The fuel rod volume fraction cloud figures are shown in Fig.18, and other parameters, such as clad, supporting structure, and non-supporting structure are ongoing.



0S 7000S 10000S 11000S

12000S 15000S 20000

Figure 18. Cloud Figure of Fuel Rods Volume Fraction

7. CONCLUSION

This work seeks to gain a better picture of the evolution of the fuel degradation and flow blockage process using the PHEBUS FPT1 experiment as a first benchmark. This work can also provide a research scheme that can be used for our separate and on-going fuel degradation and flow blockage model development. Given that we were able to match the key test data such as hydrogen generation, pressure history and certain temperature measurements, we then used the MELCOR model of the experiment to track the fuel degradation process, examining the time evolution of the various fuel materials to gain key insights.

Our current observations are summarized below:

- The flow channel is occupied by several kinds of core materials, such as: fuel, clad, and other materials (support, non-support). The fluid volume and particulate debris porosity can be viewed.
- The core degradation process mainly exists between 10000 s and 20000 s. The flow channels in the upper portion of the test fuel bundle are always available for steam flow even after core degradation begins, while the flow channels in the bottom part of the PHEBUS experiment are always completely blocked.
- Generally, the intact mass increases due to steam oxidation, as shown in Fig.7 and Fig.8.
- The support and non-support materials as defined in MELCOR mostly drop down into the bottom of PHEBUS.
- The particulate debris porosity changes significantly during the severe accident process. It is around 20% in ring 1 and 2% in ring 2.
- The presenting method of cloud figures can improve the visualization of the results.

As discussed above, the time evolution of the different species volume fractions, as we provide in this paper, can give the analyst some insights into how the fuel degradation and blockage models affect the overall meltdown process. This research provides the basic conditions of the following blockage model analysis. A parameters sensitivity analysis is prepared and this work is ongoing. A new candling model for flow blockage is being developed and is expected to provide an improved approach.

ACKNOWLEDGMENTS

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