# Assessment of CINEMA code with PBF-SFD experiment

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## 1. Introduction

Assessment of early-phase core degradation is important to dealt with the reaction between zircaloy and high temperature steam because it is directly coupled with management of the hydrogen during severe accident. CINEMA code is improving with respect to the model in the in-vessel module, COMPASS and has been analyzing the assessment problem including PHEBUS-FPT[1], CORA[2], QUENCH[3], ACRR-ST[4], and LOFT-LP-FP2 [5]. Present study reports the main result by CINEMA code about Power Burst Facility-Severe Fuel Damage (PBF-SFD) tests.

## 2. Methods and Results

PBF-SFD of Idaho National Lab is in-pile boil-away experiment under high pressure (~7 MPa) with 32 fuel rods and 0.914 m active core length, which belongs to international research program initiated by US NRC [6]. As the core power is increased, the water level is gradually decreased, and exposed fuel rods undergo the heat-up, oxidation and relocation during the test. Present study covers three cases of the PBF-SFD experiments: ST (Scoping Test), Test 1-1 and 1-4.

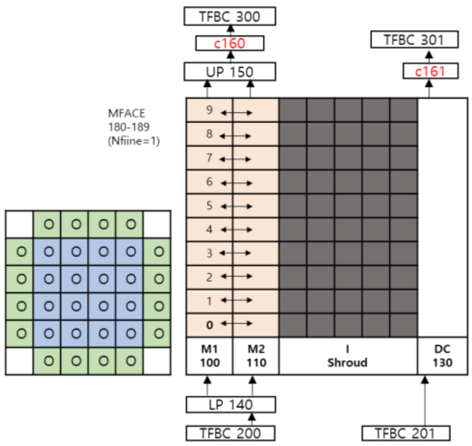


Fig. 1. Core modeling of PBF-SFD test

### *2.1 CINEMA Model*

CINEMA code is the integral system code for severe accident and is consisted of modules: SPACE, COMPASS, SIRIUS, SACAP and MASTER [7,8]. Present study uses the SPACE and COMPASS, so called CSPACE. Core of 32 fuel rods (0.914 m for the active core length) in the PBF-SFD test are simulated with the 2 radial and 10 axial nodes. Multi-layered shroud is interacted between the core and the bypass channel. CINEMA code also considers inner liner (Zircaloy) of shroud to simulate its heat-up and oxidation leading to hydrogen generation. Inlet and outlet boundary condition are simulated by the TFBC (Table I). PBF-SFD-ST and TEST 1-1 do not have any control rods in the core, while the TEST 1-4 contains four control rods (Ag-In-Cd) with stainless steel clad.

Table. I. Boundary condition of PBF-SFD tests

| | ST | 1-1 | 1-4 |
|---|---|---|---|
| Number of fuel clad [-] | 32 | 32 | 28 |
| Number of control rod [-] | 0 | 0 | 4 |
| Inlet coolant temp. [K] | 518 | 531 | 532 |
| Inlet bypass temp. [K] | 518 | 531 | 520 |
| Inlet coolant flow rate [kg/s] | 0.016 | 0.0006 | 0.0006 |
| Sweep gas during transient | X | X | O |
| Inlet bypass flow rate [kg/s] | 2.10 | 2.05 | 2.10 |
| Peak core power [kW] | 93 | 36 | 27 |
| Initial water level [m] | ~ 0.5 | ~ 0.1 | ~ 0.2 |
| System pressure [MPa] | 6.65 | 6.8 | 6.95 |
| Calculation time [s] | 15000 | 3000 | 4000 |
| Rx shutdown time [s] | 12347 | 3900 | 4740 |
| Reflood time [s] | 12600 | 3645 | 3475 |
| Core cool-down method | Reflood | Gas + Reflood | Gas |

### *2.2 PBF-SFD: scoping test (ST)*

Scoping test (ST) is conducted under steam-rich environment with constant flow rate and temperature of liquid coolant. Coolant level is gradually decreased until 210 min and the reflooding is initiated by increasing the coolant flow rate. Sensitivity study of the RELAP/SCDAP showed that parameters strongly influenced by the coolant level and clad temperature are the axial power peaking factor and inlet subcooling [9]. CINEMA code uses the best-fitted boundary condition of the RELAP/SCDAP in the present study. CINEMA shows good capability to predict the coolant level compared to the experiment or other codes [9-11]. Clad temperature is quite overpredicted the CINEMA code at lower elevation (from 0.35 to 0.5 m with high power peaking factor), however, peak temperature and time for uncovering of them show good agreement, compared to the REALP/SCDAP [9]. Temperature difference of bypass flow is nearly identical between the experiment and CINEMA (below maximum 5 K).

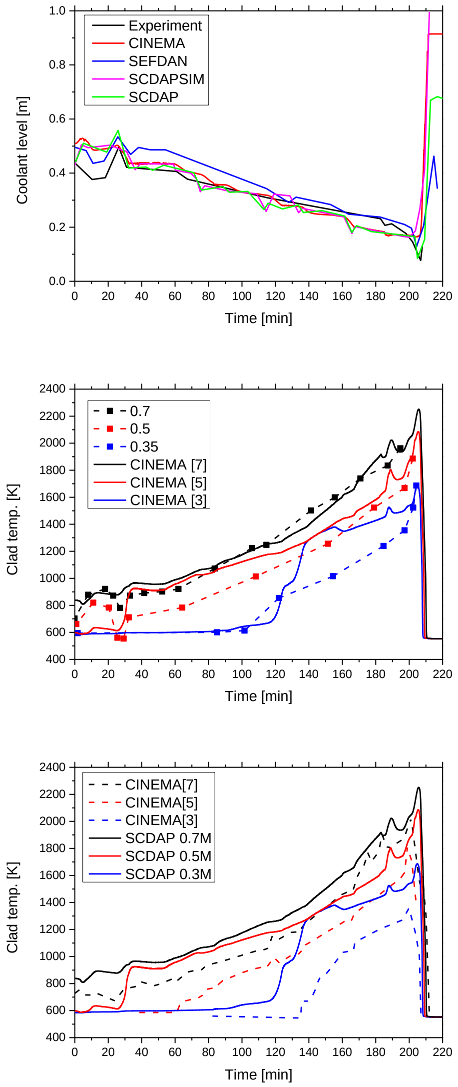


Fig. 2. Level and clad temperature of PBF-SFD-ST

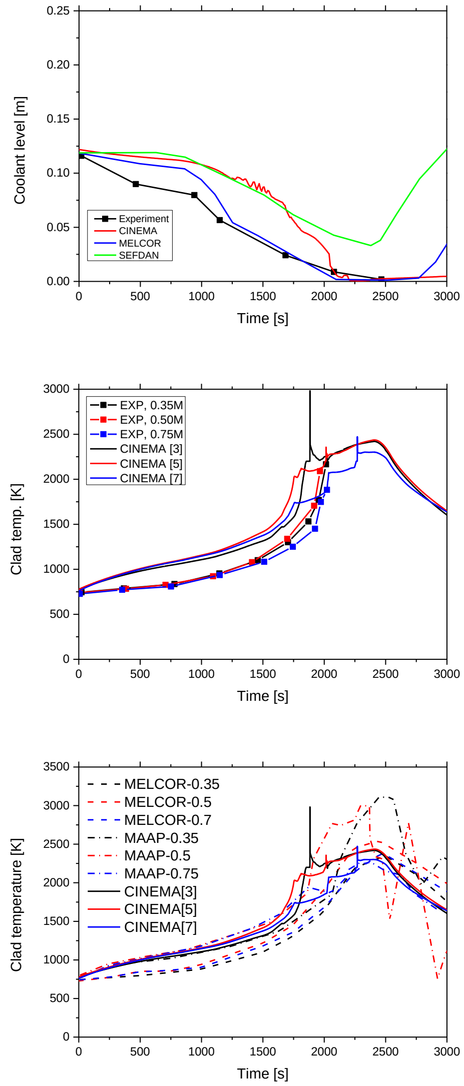


Fig. 3. Level and clad temperature of PBF-SFD-TEST 1-1

### *2.3 PBF-SFD: TEST 1-1*

TEST 1-1 has different boundary condition compared to the scoping test with same core configuration. After lower power stage (4 kW) at 3180s, the flushing gas (argon) at 3200s and reflood of 17 g/s at 3645s make the cooldown of the cores in the experiment [12]. Present study covers the analysis until 3000s before the cooldown stage. Calculated coolant level is quite distributed among codes [13-16]. CINEMA code shows an intermediate value of the coolant level and clad temperature between MELCOR and MAAP code. Clad temperature is overpredicted by CINEMA code at the position (Fig. 2) where the core is uncovered and this is due to the uncertainty of the power peaking factor and power time-table at boilaway test. MELCOR (or SCDAP) uses the effective core power by considering the heat loss from refluxing condensate from upper plenum and present study uses the bundle power time-table between the experiment and the MELCOR [12,13].

### *2.3 PBF-SFD: TEST 1-4*

TEST 1-4 has different boundary condition of inlet flow. Sweep gas (argon) is introduced from the lower plenum to the fuel bundles during the high temperature transient to stabilize the bundle pressure and to transport the fission product through the sampling system [17]. Also, long term exposure under high temperature steam environment (~ 2000K) leads to an increased mass of relocated core at lower elevation of the core. CINEMA code well predicts the coolant level, clad temperature and shroud temperature, compared with the other codes or experimental data [18,19]. Compared to the scoping test, TEST 1-4 has small core power and inlet coolant flow rate and it leads to steam-starvation environment like TEST 1-1. In particular, relocation time and temperature of control rod is nearly identical to the experiment. Lower melting temperature of control rod (Ag-In-Cd for 1123 K and steel for 1709K) than fuel-clad leads to an earlier relocation during transient.

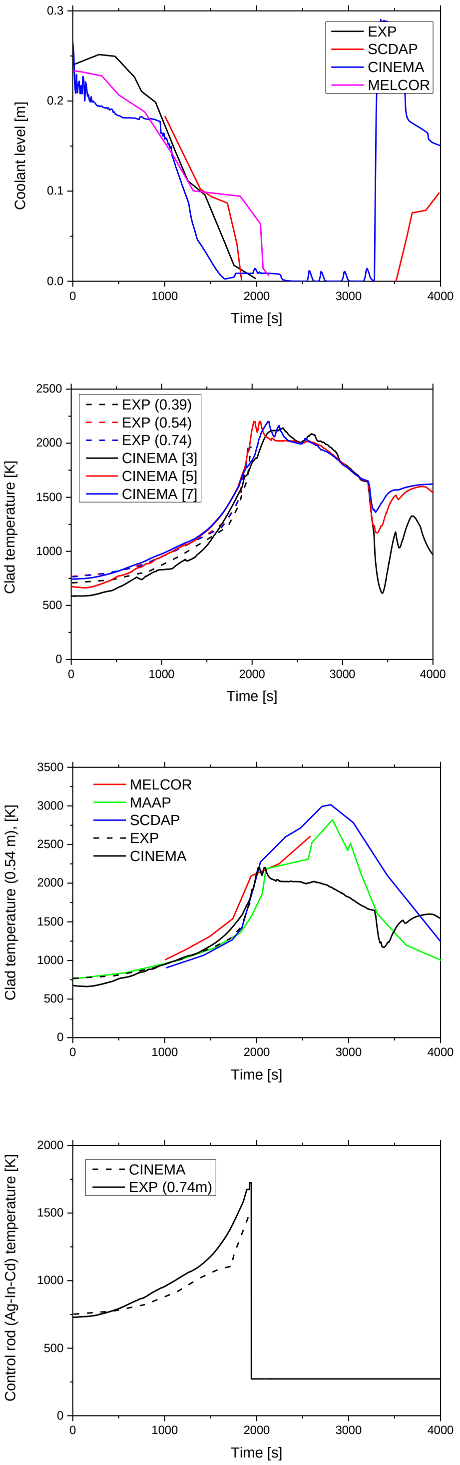


Fig. 4. Level and clad temperature of PBF-SFD-TEST 1-4

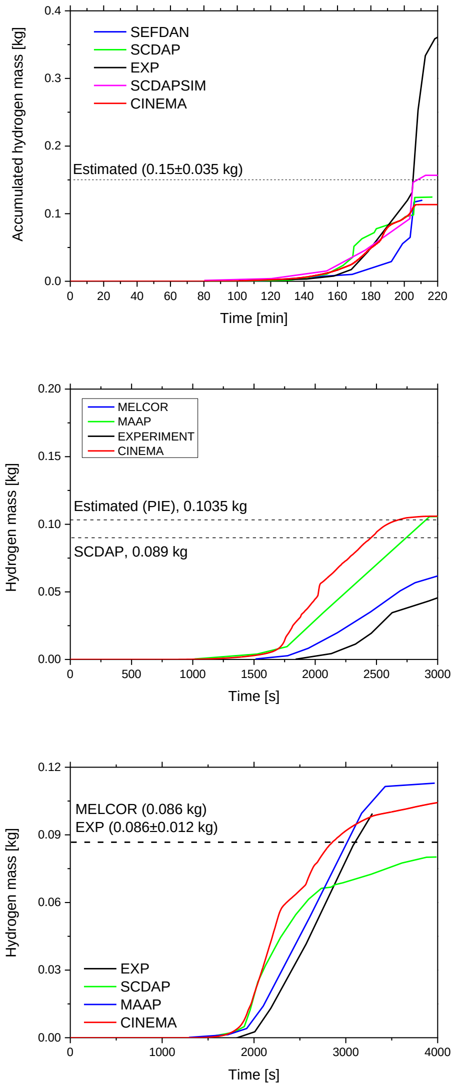


Fig. 5. Accumulated hydrogen mass of PBF-SFD test: ST (top), TEST 1-1 (middle), TEST 1-4 (bottom)

### *2.5 Hydrogen by zircaloy oxidation*

Accumulated mass of the hydrogen gas is major parameter to evaluate the early-phase core degradation. This is function of the coolant level, temperature of the core and mass distribution by relocation and oxidation. Source of hydrogen is the zircaloy of the cladding and of the shroud inner liner.

In case of scoping test, generated mass of hydrogen is more after reflooding than before at the test and this behavior is nearly identical to LOFT LP-FP2 experiment [5]. At reflooding under high temperature, protective oxide shell on zircaloy clad is easy to be failed because of its brittleness and inner surface of zircaloy clad can be oxidized [20]. Also, relatively low coolant flow rate during reflooding is not sufficient to quench the core and to prevent the rapid oxidation caused by steam-rich condition [21,22]. Even though most of the system code do not evaluate the hydrogen generation after reflooding, accumulated H2 mass obtained from CINEMA and other codes show similar behavior prior to the reflooding, compared to the experimental data. In case of TEST 1-1, the hydrogen mass seems to be overestimated by MAAP and CINEMA, compared to the experimental and MELCOR. But, measured mass by several methods shows wide range from 64±7 g (collection tank) to 104 g (postirradiated estimation). TEST 1-4 also shows that CINEMA well predicts the hydrogen generation compared to the test data, which is similar to other codes.

*2.6 Lesson learned from the assessment*

Boilaway test like the PBF-SFD has a number of experimental uncertainties such as inlet subcooling, axial power peaking factor, input power history during the transient, and axial heat loss from the lower plenum. Present study is based on the sensitivity analysis of RELAP/SCADP in each test and the best-fitted boundary condition is applied in the CINEMA code. The most sensitive variable influenced by the boundary condition is the coolant level. Slight difference of coolant level directly impacts the heat-up rate of the clad, timing of core uncovering and heat transfer between the core and shroud. Also, oxidation model during reflood is required to simulate the explosive generation of hydrogen in CINEMA code as discussion 2.5. RELAP/SCDAP considers the model of oxide shell failure under reflooding condition [20] and it can be the reference for code improvement in the future.

## 3. Conclusions

CINEMA code shows good capability to predict the coolant level and temperature of core components with the PBF-SFD tests. Accumulated mass of the hydrogen gas is well predicted to the test data and its value is comparable with other codes. Based on the present study, releasing behavior of the fission product is going to be investigated for PBF-SFD TEST 1-4 and this approach will be a part of the assessment of source term module, SIRIUS, in the CINEMA code.

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