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Simulation of OECD/NEA FIDES-II LOC-C-4 experiment practice by MERCURY V1.0

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1. Introduction

The NEA Second Framework for Irradiation Experiments (FIDES-II) addresses the experimental needs of nuclear safety regulators, technical support organizations, research institutions, and industry, while preserving experimental knowledge for future applications. FIDES-II coordinates a global network of research facilities to conduct high-priority experiments through Joint Experimental Programmes (JEEPs). The 2024–2027 FIDES-II programme includes nine JEEPs covering a broad spectrum of research topics. Among them, the Fast Power Transients programme (HERA and LOC-HBu) focuses on investigating fuel behavior under accident conditions at higher burnup levels [1].

Within the LOC-HBu programme, in-pile loss-of-coolant accident (LOCA) experiments will be conducted using the Transient Water Irradiation System for TREAT (TWIST) at the Transient Reactor Test (TREAT) facility of Idaho National Laboratory (INL). Prior to testing high-burnup (HBu) fuel specimens, a commissioning test series will be performed using fresh fuel. The primary objective of the Loss-of-Coolant Commissioning (LOC-C) test series is to qualify the TWIST device and its in-situ instrumentation and to validate the power coupling between TREAT and the TWIST fuel rod [2].

In the LOC-C scenario, where coolant in the core rapidly flashes to steam within the first few seconds following a pipe rupture, the stored thermal energy in the fuel undergoes rapid redistribution. This leads to a decrease in temperature in the central region of the fuel at rates on the order of ~100 K/s, while the cladding temperature simultaneously increases at a comparable rate. The LOCA experiments performed using the TWIST vehicle are intended to address existing data gaps by leveraging the extensive experimental database and accumulated knowledge. To support this objective, an integral LOCA test plan has been developed under the DOE Advanced Fuels Campaign (AFC) programme.

KAERI is participating in the LOC-C-4 practice code benchmark under the OECD/NEA FIDES-II framework. This study presents the simulation model and results for the LOC-C-4 scenario obtained using the MERCURY V1.0 code.

2. Modeling of LOC-C-4 experiment

In this section, simulation code and experiment model are introduced.

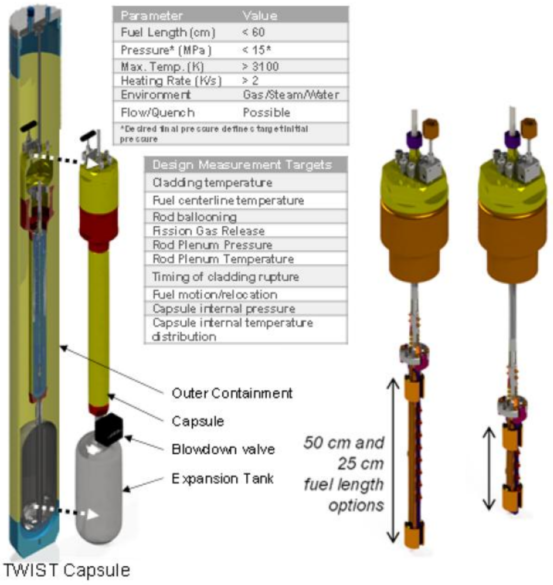
2.1 MERCURY V1.0

A multidimensional entire fuel rod analysis module (MERCURY) based on the finite element method has been developed to simulate multidimensional fuel behaviour. The MERCURY incorporated a transient thermal analysis model, a multidimensional gap conductance model, a nonlinear mechanical model, and a transient creep model as thermomechanical models. As fuel models, burnup-dependent material properties, an oxidation model at high temperature, a rod internal pressure model, and cladding burst criteria were incorporated [3]. Currently, a fully coupled MARS-KS and MERCURY code has been developed to conduct the safety evaluation of the reactor that considers fuel behaviours during accident condition. ATF models (coated cladding models, microcell pellet models, etc.) have been implemented in compliance with software quality assurance. The MERCURY code was validated through an out-of-pile test (EIGEN) and in-pile test (Studsvik-NRC192, IFA-650.5) [4]. The double ballooning behaviour observed in HRP-IFA650.9 experiment can be predicted by MERCURY [5]. Verification and validation (V&V) of the MERCURY code have been conducted against numerical benchmarks and experimental data, respectively. In June 2025, a MERCURY V1.0 user group training workshop and technical meeting were held to enhance the technical readiness level (TRL) and improve the accessibility of the code within Korea.

2.2 Modelling of LOC-C

The TWIST experiment vehicle consists of two capsules stacked vertically. The upper vessel is a pressurized static water capsule containing the nuclear fuel rod to be tested. The lower capsule is a low-pressure expansion tank. A controllable valve connects the upper capsule with the lower expansion tank. During a LOCA experiment, this valve is opened at a specified moment during the experiment, in coordination with reactor power, causing rapid depressurization and rapid water movement from the upper capsule into the expansion tank.

The upper capsule is designed to house a test specimen with a fueled length up to 50 cm and supports a wide variety of instrumentation connections. This allows for instrumentation packages to be configured on a per-experiment basis depending on specific experiment objectives. A schematic overview of the TWIST design is shown in Fig. 1.



Parameter	Value
Fuel Length (cm)	< 60
Pressure* (MPa)	< 15*
Max. Temp. (K)	> 3100
Heating Rate (K/s)	> 2
Environment	Gas/Steam/Water
Flow/Quench	Possible

*Desired final pressure defines target initial pressure

Design Measurement Targets
Cladding temperature
Fuel centerline temperature
Rod ballooning
Fission Gas Release
Rod Plenum Pressure
Rod Plenum Temperature
Timing of cladding rupture
Fuel motion/relocation
Capsule internal pressure
Capsule internal temperature distribution

Fig. 1. Schematic overview and key specifications of the TWIST LOCA device [6]

To develop the fuel performance model for the LOC-C experiment, the geometrical dimensions of the fuel pellet and cladding were explicitly modeled. Detailed design information for the test specimen was provided by INL. For accident simulations, thermal-hydraulic boundary conditions are critical parameters governing fuel behavior. INL developed a dedicated thermal-hydraulic model and simulated the LOC-C transient using the TRACE code. The TRACE results were adopted as boundary conditions for the fuel performance analysis.

The LOC-C-4 experiment is the fourth fresh fuel commissioning test to be performed in TWIST. While previous commissioning tests focused on the characterization of specific behaviors (thermal hydraulic performance, fuel rod power, etc.), the goal of the LOC-C-4 test is to perform the full TWIST LOCA experiment evolution and drive the test fuel rod to balloon and burst. This experiment will contain a pre-pressurized fuel rod with an active fuel height of ~24 cm and a plenum volume of ~15 cm3. TREAT will be brought up to and held at a constant power to generate a radial temperature profile consistent with an LWR at operating conditions. Upon opening of the valve, the redistribution of stored energy will drive the pellet periphery and cladding temperature up rapidly.

The thermal-hydraulic boundary conditions, the axial power shape and power history were provided by INL and applied to the fuel rod simulation. Figure 2 presents the MERCURY modeling results for the LOC-C-4 test.

The LOC-C-4 specimen comprises fresh Zircaloy-4 (Zr-4) cladding and unirradiated UO_2 fuel pellets, with the rod internally pressurized using helium gas. In the MERCURY code, the Norton–Bailey creep model was employed to describe the high-temperature deformation behavior of the Zr-4 cladding, and a strain-based failure criterion was implemented to predict cladding burst. To minimize uncertainties in plenum pressure estimation, the plenum temperature provided by INL was directly imposed rather than being calculated within the code.

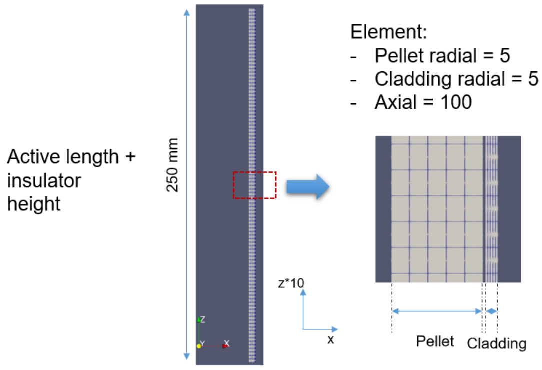


Fig. 2. MERCURY model for LOC-C-4 experiment

3. Simulation result

In this simulation, Table I shows the matrix of the condition to demonstrate the rod free volume and rod internal pressure effect in terms of fuel performance.

Table I: Test matrix of LOC-C-4 practice

CASE #	Rod free volume (cm^3)	Rod internal pressure (MPa)	Note
1	15.9	10	Nominal rod pressure
2	15.9	10	Nominal rod pressure
3	15.9	5	Lower rod pressure
4	15.9	15	Higher rod pressure
5	10	10	Reduced plenum vol.
6	5	10	Reduced plenum vol.

Figure 3 presents the time evolution of the maximum fuel centerline temperature. As expected under a nominal LOCA scenario, the peak centerline temperature occurs prior to the blowdown phase. Following blowdown, the fuel rod power decreases; however, the centerline temperature rises again to approximately 1400 K. This increase is attributed to the reduced heat transfer capability under degraded cooling conditions and the additional heat generated by cladding oxidation during the reflood phase.

Figure 4 shows the deformation history of all cladding surface nodes. When the internal pressure remains significant and the cladding temperature exceeds approximately 1000 K, ballooning deformation is initiated, eventually leading to cladding burst. The upper surface temperature is higher than that of the lower surface due to thermal-hydraulic effects and non-uniform heat losses within the test rig. The elevated local temperature promotes accelerated creep deformation, thereby inducing cladding ballooning and subsequent burst.

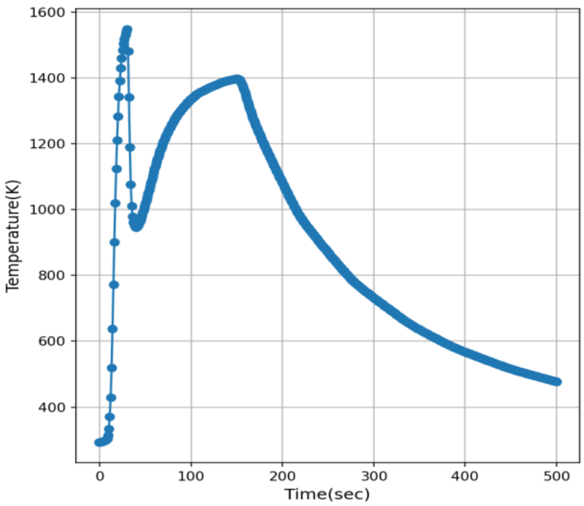


Fig. 3. Maximum fuel centerline temperature along time (CASE 4)

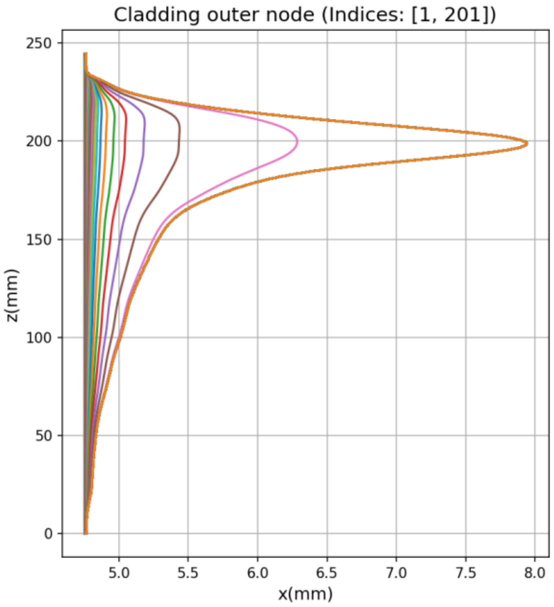


Fig. 4. Radial deformation history as function of time (CASE 4)

Figure 5 presents the evolution of cladding oxide thickness during the experiment. Because oxide growth is strongly governed by surface temperature, the upper axial region—where higher temperatures are observed—exhibits greater oxide thickness compared to the lower region. Overall, the oxide distribution along the axial direction follows the corresponding temperature profile. In this simulation, surface temperatures were treated as boundary conditions. From a practical perspective, the oxide thickness in the ballooned region may decrease due to gap widening. This behavior can be more accurately represented using a fully coupled MARS/MERCURY code.

In contrast, the deformation behavior shows additional mechanical effects beyond the thermal profile alone. Localized cladding deformation leads to stress concentration, which further accelerates creep strain accumulation and promotes enhanced ballooning in the affected region.

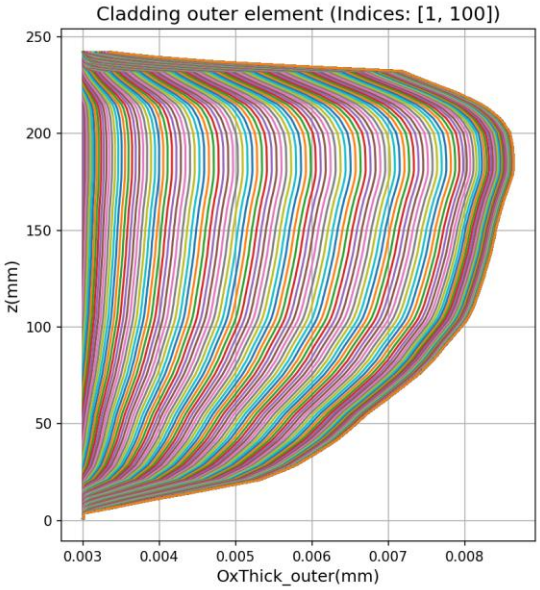


Fig. 5. Oxidation thickness behavior as function of time (CASE 4)

A code benchmark study was conducted among fuel performance codes, including BISON and DRACCAR, focusing on fuel centerline temperature and deformation. The results calculated by MERCURY show good agreement with those from other fuel performance codes. These results will be released by INL.

4. Conclusions

Within the framework of the OECD/NEA FIDES-II programme, the LOC-C-4 experiment will be prepared and conducted at the TREAT reactor facility at INL to improve the practical understanding of fuel behavior under LOCA conditions, including cladding ballooning, burst, and fuel fragmentation, relocation, and dispersal (FFRD) phenomena in high-burnup fuel.

As a contribution to the code benchmark activities, KAERI performed simulations of the LOC-C-4 scenario to analyze fuel rod behavior. A dedicated MERCURY V1.0 model for the LOC-C-4 test was developed, and the simulation results provide key fuel performance parameters, including fuel centerline temperature, cladding deformation, and oxide thickness. The results were compared with those obtained from other participating codes within the benchmark framework.

For future work, KAERI plans to develop a thermal-hydraulic model of the LOC-C-4 scenario using the MARS-KS code. The MARS-KS results will be compared against the reference calculations performed by INL using TRACE. After validation of the MARS-KS model against the reference solution, a coupled MARS-KS/MERCURY analysis will be conducted to enable an integrated assessment of thermal-hydraulic and fuel performance behavior for LOC-C-4.

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