In-pile Creep Studies of ATF Claddings
Joint project proposal for OECD/NEA Framework

Project acronym: INCA

Operating Agent: CVR

Project proposed by: CVR, UJV, VTT, CEA, Alvel

Foreword / Context
In the wake of the Fukushima-Daichi event, significant effort was invested worldwide in development of the Enhanced Accident Tolerant Fuels (EATF’s). In fact, the improvements of not only fuel but also other in-core components such as control rods and channel boxes are investigated. These materials, in comparison with standard UO$_2$-Zirconium alloy system currently used by the nuclear industry, promise longer grace times in the case of severe accident scenarios. On the other hand, the design and manufacturing of the current materials has reached mature state with excellent reliability in-pile and very good economics. Therefore, for the new material solutions it is necessary not only to show the improvements in the design extension conditions, but also to understand the behavior of new material in normal operation and design basis events including the long term storage of irradiated fuel.

While 1st lead test assemblies (LTA) with the EATFs are already loaded into the commercial power reactors, the experience with the development of the Zr-alloys show, that the prompt feedback between the optimization in the manufacturing process and in-pile operation experience is mandatory to reach the required level of the technological maturity in an economically viable timeframe. This feedback can be gained only in a material test reactor. The primary objective of the proposal is to address one specific topic – namely irradiation induced creep of the cladding materials – aiming at providing data of sufficient quality and quantity in timely manner in order to allow for optimization and qualification of new solutions (both EATFs and optimized Zr-alloys) with credible or even direct comparison to the “standard” materials behavior.

One of the key issues for the process of the implementation of new fuels and materials into operation, especially for the utilities and regulators, is the consistency and continuity of experimental plan/testing. Halden Reactor Project (HRP) used its unique reactor (HWBR) to fulfill most of these needs. After HBWR closure it was found, that the repeatability of these tests, or their transfer to other current material test reactors are impossible, or it can take decades to implement. Therefore, new approaches for fuel and cladding material testing need to be developed. However, this development needs to have its continuation in the future. The secondary objective of the proposal is therefore to provide such devices and approaches, which will allow continuity, transfer and extension of the research also in the forthcoming Jules Horowitz Reactor (JHR), which in the long term will become the strategic tool for extensive fuel and material irradiations on a worldwide scale.
**Objectives**

The intended proposal focuses on the assessment of a key fuel cladding property that is the cladding creep behavior during operation. Irradiation induced creep of the cladding has a significant impact on the fuel rod performance, and must be well understood in order not to endanger the safety and reliability of fuel rod operation:

- Cladding creep has a direct impact on the fuel – cladding heat transfer dynamics and hence on:
  - Fuel performance related phenomena such as fission product release and fuel swelling
  - Core neutronics behavior through the thermal feedback
- Cladding creep sets limits to fuel operation domain:
  - Ductile materials (e.g. Zr-alloys) result in early gap closure. Knowledge of creep/stress relaxation properties enables to avoid failures in closed gap conditions.
  - More brittle materials (SiC/SiC) or the materials susceptible to stress corrosion cracking can reach “hard” fuel – cladding contact. Therefore, we have to assess capabilities to accommodate flexible operation also at high burn up, and the creep rate of the cladding must be known to derive such limits.
- Further, a very important objective, will be to develop advanced methods, equipment and instrumentation for in-pile creep studies of new cladding and guide tube materials, and to set up their transfer for the future use at other facilities, e.g. in JHR.

The main objective of the proposed project is therefore to provide data needed to understand the impact and model the creep behavior of several candidate ATF cladding materials as well as the reference Zr alloys. This will be achieved not only by the in – pile creep (and irradiation induced growth) experiments in the LVR-15 material test reactor, but also by supplementary studies of the evolution of the cladding microstructure and the mechanical properties with the irradiation.

The irradiation induced creep of the coated Zr claddings was not so far directly investigated in any international research project (Halden IFA-796 experiment was focusing primarily on the corrosion and was terminated only few months after it has started). Only limited set of results was obtained in the ORNL tests in Halden with small tensile samples of SiC and FeCrAl ([3.]).

**Value for the Industry/Regulators/Science**

For industry, the project will provide direct comparison between the creep of the current cladding materials and ATFs facilitating the implementation of the ATFs into the NPP reactor cores. In addition, a platform for testing evolutionary materials will be established, as well.

The regulators will benefit from the results allowing the independent assessment of the proposed fuel rod design changes.

The scientific community will be able to profit especially from the detailed post-irradiation examinations focusing on such aspects as the irradiation and strain effects on the interface layer of the coated alloys through the multi-scale modelling.
Facilities

Material Test Reactor LVR-15

The irradiation will take place in the LVR-15 material test reactor that is located in the Research Centre Řež Ltd. The reactor is a light-water moderated and cooled pool type nuclear reactor with light water or beryllium reflector operated at maximum power of 10 MW (Fig.1).

The reactor is operated in 21 day irradiation cycles, with 9 - 10 cycles per year. The fuel assembly consists of 6 or 8 concentric square cross section tubes made of UO$_2$-Al alloy enriched to 19.75 %. Reactor core consists of 80 cells, each with the square geometry 71.5x71.5 mm$^2$. In the basic operation configuration, 28-32 cells contain fuel elements, 2-4 the fuel cells are dedicated to channels for experimental probes.

LVR-15 high-dpa creep irradiation rig

To achieve maximum fast neutron flux the high-dpa rig placed in the center of the fuel assembly will be used (Fig.2). The rig contains up to 16 pressurized cladding samples in inert atmosphere at PWR/BWR relevant temperatures (350°C is foreseen for 1st test). Cladding temperature and fluence will be monitored. Temperature can be modified before the test by optimizing the heating and gas insulation. Cladding dimensional changes will be measured during the interim inspections.
MELODIE II

To provide the on-line measurements of the irradiation creep of LWR claddings under biaxial stress, MELODIE device, originally developed by VTT and CEA for testing in CEA’s Osiris reactor [2.], will be implemented for LVR-15 reactor as a next generation version MELODIE-II. The experiment is based on a mechanical device with pneumatic controls, i.e. the biaxial load is induced by independent control of both the internal pressure and the bellows pressure to induce variable hoop and axial stress on the pressurized tube specimen. The axial creep strain is measured continuously during the experiment by using a fixed LVDT sensor, and the diametral strain is measured periodically along the specimen surface by a moving Diameter Gauge (DG). The movement of the DG is driven by a pneumatic mover and controlled by another LVDT sensor.

Post-Irradiation Evaluation (PIE)

For studying the effect of neutron radiation on the mechanical and microstructural properties of ATF claddings, proper PIE will be provided by CVR’s hot laboratories. Detailed test parameters will be defined by the project participants.
- Visual control and geometry measurement
- Mechanical testing
  - Axial tensile test and Ring tensile test
  - Creep or stress relaxation test
- Microstructural studies
  - SEM
  - HR-STEM
  - Micro and nanoindentation

Reference Zr-Nb samples irradiated at NPP
In 2012, the Czech company Alvel, started in cooperation with Bochvar Institut from Russia and other Czech companies, such as Czech utility CEZ, Skoda JS, UJV and CVR, a long term project for irradiation of standard as well as advanced Zr-Nb based alloys up to fluence exceeding the current operation limits. Samples are irradiated in Temelin NPP core (VVER-1000) and their post-irradiation evaluation will be performed in CVR with the first results already available in spring 2020. The results from these tests will be used as a reference in this proposed work.

Scope
To study the phenomena of the cladding materials creep (standard as well as optimized and ATF), irradiation in LVR-15 will be provided with use of high-dpa in-pile creep rig and the Melodie-II device. Due to complexity of this project, it will be divided into two Phases. Phase 1 is dedicated to study the creep phenomena of standard and coated Zr claddings in slightly instrumented in-pile creep rig and to prepare the Melodie-II device for Phase 2, where samples will be studied in detail.

Phase 1 – Impact of coating on Zr-alloys on creep rate

Samples
1st set of the experiments is foreseen with the reference Zr-alloys and with the coated Zr-alloys.

The burst tests performed at LOCA conditions have shown that even thin Cr based coating reduces the strain rate. Therefore, the purpose of the study in Phase 1 will be to investigate the impact of the coating on the in-pile creep rate in the normal operating conditions. This goal will be achieved by direct comparisons of the reference and coated samples to reduce the experimental uncertainties as much as possible. The first set of samples will use reference base alloy with well-known creep properties – for this purpose Zry-4 was chosen. A modern Nb containing alloy will be used as the second base material, in this case alloy E110 (identical to material used in reference Temelin VVER-1000 irradiation) is proposed.

Several variants of Cr-based coating are proposed for the first experiment, with different compositions, thickness and fabrication processes. Two levels of pressure will be used (both will be specified by the core group). 10 MPa overpressure will result in the effective stress corresponding to the PWR conditions.

In PWR, the coolant pressure is greater than the rod pressure, in the experiment, the rod will be pressurized. However, the aim is to achieve equivalent effective stress. Also, with the pressurized rod, the impact of the cladding ovality will be suppressed.
Since the first phase is focusing on the comparison, only single level exposure is proposed, corresponding to about 8-10 MW/kgU.

**Pre-test characterization**
Initial state of the microstructure and mechanical (tensile) properties will be determined as specified above.

**In-pile creep testing**
Irradiation of the pressurized cladding samples in high-dpa rig placed in LVR-15 core. The proposed conditions for Phase 1 are:

- The fast neutron flux 6.7E13 cm$^{-2}$s$^{-1}$ (E>1.0MeV), with target fluence of 1.7E21 cm$^{-2}$
- 4 irradiation strings, each containing up to 4 pressurized tubes, totally up to 16 tubes, each 8-10 cm long

The proposed first loading contains two well-known alloys E110 and Zry-4, without and with specific coatings, pressurized on two levels of inner pressure.

Small unpressurised reference samples will be irradiated in the same rig in order to provide direct evaluation of the impact of the irradiation induced growth. After achieving the final fluence, final PIE will be included.

**Post-test characterizations**
The impact of the irradiation on the microstructure and the mechanical properties will be evaluated in the hot cells. The PIE will be valuable especially from the scientific point of view, as it will allow the development of general predictive models for the mechanical behavior of the coated claddings based on the multi-scale approach.

**Comparison to reference samples irradiated in VVER-1000**
The fluence foreseen in Phase 1 corresponds to approx. 8-10 MWd/kgU burnup. In order to see if the samples have already reached saturation of the radiation damage from the mechanical properties point of view the results can be compared to creep measurement, tensile tests and microstructural studies performed on a Zr-1%Nb cladding samples irradiated in VVER-1000 for 1-3 cycles. The current budget proposal considers TEM and tensile testing only. Other measurements may be added depending on future discussions between the project partners.

**Preparation of Melodie-II**
Due to uniqueness of the Melodie device design, originally developed for the Osiris research reactor aiming at future use in JHR, the middle step needs to be done: testing in LVR-15 reactor to prove the functionality of the loading system using NaK as medium for stabilizing the temperature. In the tests in Osiris it was found that the current Melodie design is too sensitive for the disturbances coming from the environment. Therefore, the design needs to be more robust and for that improvement the tests in LVR-15 are needed. However, the transfer of such a complicated device from reactor to reactor is not an easy process, therefore, detailed design of Melodie-II device will be finished, manufactured and tested out-of-pile during Phase 1. The main goal is to have Melodie-II device prepared for irradiation experiments within Phase 2.
Phase 2 – “Revolutionary” ATF material studies

In-pile creep testing in high-dpa rig
To continue the studies of creep behavior of ATF cladding materials, the new material matrix will be set up by the project participants. This matrix will include the long-term deployment materials like SiC/SiC or FeCrAl. To achieve the continuation of this type of studies in the future, the detailed design for the use in JHR conditions will be prepared too.

In-pile creep testing in Melodie-II
This device allows on-line in-pile measurements of the diameter of the cladding sample under bi-axial load, but at reduced neutron flux and with limited sample capacity compared to the irradiation in high-dpa rig. In the second phase of the project it will be used to investigate the creep behavior of the selected samples in detail.

Comparison to reference samples irradiated in VVER-1000
As written above, six batches of standard Zr-1Nb samples are irradiated at Temelin NPP under VVER-1000 conditions. Each batch will be studied every year, to study the effect of neutron damage on this alloy. The target fluence of the sixth batch correspond to the equivalent burnup of ~85 GWd/tHM. Correlation between real operating conditions in VVER-1000 and in the material test reactor (LVR-15) will be established using these samples.

References
[3.] K. A. Terrani, T. M. Karlsen, Y. Yamamoto: Input Correlations for Irradiation Creep of FeCrAl and SiC Based on In-Pile Halden Test Results, ORNL/TM-2016/191