TEST IRRADIATION OF ENHANCED NUCLEAR FUEL AND CLADDING

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ABSTRACT: The nuclear power industry sees an increasing demand for enhanced fuel types that can be regarded as safer, more reliable and more durable than the uranium oxide fuel currently used. In response to this, several actors work to develop such fuels, and to test them under reactor conditions. A test rig has been introduced in the Halden Research Reactor in Norway, comprising two microcell fuel types and a set of different thorium enhanced uranium fuel, as well as and two novel cladding coatings. The rods are instrumented for on-line measurement of fuel and cladding elongation, fuel rod pressure and fuel centerline temperature. The information generated by this test irradiation is intended to support the introduction of test rods of the studied fuel types in commercial reactors. The irradiation is scheduled to continue for several years, and the flexibility of the rig design and the Halden Research Reactor makes it possible to introduce further innovative fuel and cladding types in the rig as development efforts continue in the industry and in academia, aiming for safer and more sustainable nuclear power. Preliminary irradiation results are available and show that the microcell structures and, in some cases, the addition of thorium lower fuel centerline temperatures. All other investigated aspects of the fuel behaviors correspond to expectations.

KEYWORDS: Test Irradiation, Microcell Fuel, Thorium, Coated Cladding, Halden Research Reactor.

I. INTRODUCTION

The nuclear power industry sees an increasing demand for enhanced fuel types that can be regarded as safer, more reliable and more durable than the uranium oxide fuel currently used. Not only the fuel material itself, but also the cladding is subject to scrutiny and increasing demands. In response to this, several actors work to develop such fuels and claddings, and to test them under conditions similar to those present in the reactors in which they are designed to operate. This testing is not only intended to confirm that they fulfill expectations on improved performance, but also to build the basis for simulations of the materials, necessary for predicting their behavior under varying circumstances.

In December 2015, The Norwegian company Thor Energy and a consortium of interested parties introduced a test rig in the Halden Research Reactor in Norway. The information generated by this test irradiation is intended to support the introduction of test rods of the studied fuel types in commercial reactors, and to support development of fuel performance simulation codes. The test rig and the data that can be acquired during its irradiation are thoroughly described in this paper. Currently, three different types of enhanced fuel and two cladding coatings are being tested, along with reference material – standard uranium oxide fuel and zirconium alloy cladding. The test is designed such that some of the currently irradiated fuel rods may be switched for new rods later in the irradiation. This allows for extended collaborations in experimental fuel investigations. Preliminary irradiation results are available and show that the microcell structures and, in some cases, the addition of thorium lower fuel centerline temperatures.
II. FUEL AND CLADDING TEST IRRADIATION

I.A. The Halden research reactor

The Halden research reactor is the world’s only heavy boiling water reactor (HBWR), and is located in the town of Halden, Norway. The HBWR has operated since 1958 and has hosted hundreds of successful test irradiations of fuels and other nuclear materials. The flexibility of the core loading pattern and operating scheme makes it possible to tune the operating power of the rig as desired. In addition, the operators of the HBWR, the Norwegian Institute for Energy Technology (IFE) have long experience and great expertise in instrumentation of test materials for acquisition of on-line irradiation data. The instrumentation of the rig described in this paper, IFA-790, is described in detail in the following section.

The reactor operates at a thermal power of about 18-20 MW, producing process steam for a nearby papermill. The operating pressure is 34 bar. The reactor normally operates approximately 180-200 days per year, divided upon two operating cycles. Interim shutdowns may also occur. During downtime, maintenance and exchange of driver fuel is carried out, as well as inspection, exchange and handling of the approximately 20-30 experimental test rigs present in the core.

Data is regularly logged at 5 s intervals, but is in general only stored at 15 minute intervals, since most parameters do not change significantly during such time span. More frequent storage is however in principle possible. An exception is made during fast transients such as reactor scram, which will automatically increase the logging frequency to once every 0.5 s for five minutes. This data is useful for interpretation of the transient behavior of the tested materials.

I.B. The fuel test rig and instrumentation

The operating conditions of the rig are closely monitored, which is essential for the correct interpretation of the irradiation data. The neutron flux is monitored by means of neutron detectors located as shown in Fig. 1. As can be seen, detectors are placed at two axial locations for each cluster of six rods, thus making it possible to quantify the axial power gradient over the rig. In addition, three neutron detectors in the axial plane of each cluster gives the flux tilt over the rig. In general, the flux will be a few percent higher on the side directed towards the core center, but movement of control rods and other test rigs in the vicinity of IFA-790 may cause other flux variations which are captured by the neutron detectors.

The rig is enclosed in a shroud as shown in Fig. 1, and the coolant temperature is measured by thermocouples at the in- and outlet of the rig channel. Note that Fig. 1 shows only a schematic drawing, which is compressed in the axial direction in order to show all instrumentation – the distance from the active fuel section to the inlet and the outlet are approximately 50 cm and 90 cm respectively. The active length of each fuel rod is 25 cm. The coolant flow (about 0.5 m/s) ensures that the axial increase in coolant temperature over the test rig does not exceed 2°C. In general, the coolant temperature in the HBWR is close to 235°C.

The coolant flow is measured at the shroud inlet by means of a turbine flowmeter. The flow data combined with the temperature increase over the test rig, measured by the inlet and outlet coolant thermocouples, is used for power calibration during the first startup with the rig. Using this data, the total rig power can be determined. The power of each pin relative to the other pins in the rig is given by the aforementioned neutron detector readings and neutronic simulations of the test rig giving the power distribution between the pins.

The twelve rods in the rig are instrumented for on-line measurement of fuel and cladding elongation, fuel rod pressure and fuel centerline temperature. The placement of the instrumentation in the rig is also shown in Fig. 1, and each instrument is briefly described below.

- Fuel thermocouples: The centerline temperature of the fuel pellets is measured by means of a thermocouple inserted into a hole drilled through a few pellets at the top or bottom of the fuel stack.
- Cladding extensometers: Elongation of the cladding is measured by means of a magnetic rod mounted on the cladding, extending through a magnetic coil picking up its longitudinal movements.
• Fuel extensometers: Elongation of the fuel is measured by means of a magnetic rod which is kept in contact with the fuel stack by a spring. The rod extends through a magnetic coil picking up its longitudinal movements.
• Pressure transducers: The internal gas pressure of a fuel rod is measured by means of a pressure bellows within the fuel rod that communicates with a sensitive transformer mounted on the rod exterior. Due to the desire to mount also cladding and/or fuel extensometers on the rods in the current rig, the rod interior is connected with the pressure bellows by means of a pipe extending around the extensometer.

Fig. 1. Schematic drawing of the test rig IFA-790.

I.C. The tested materials
The rig comprises two microcell fuel types manufactured by the Korean Atomic Energy Research Institute (KAERI) and a set of three uranium fuel types with different amounts of thorium dioxide added to the fuel matrix, as well as a uranium reference fuel manufactured by the Norwegian Institute for Energy Technology (IFE). In addition, two novel cladding coatings, also invented and manufactured by KAERI, are being tested. The enrichment of the uranium in the different fuel rods is tuned to give an approximately equal power in all rods throughout the irradiation. The basic features of fuel materials are described in Tab. I. The microcell fuel types are designed and manufactured so that the additive (Cr or SiO$_2$/TiO$_2$ mixture) forms a microcell network within the fuel matrix. The Cr network aims to improve the thermal conductivity of the fuel material, whereas the SiO$_2$/TiO$_2$ network has the purpose of trapping volatile fission products. These fuel types are more thoroughly described in Ref. 1. The purpose of adding ThO$_2$ to the UO$_2$ fuel matrix in the concentrations listed in Tab. I is mainly motivated by neutronic considerations described in Refs. 2, 3 and 4.

The uranium reference fuel rods have two different diameters; a larger one corresponding to a normal BWR fuel rod diameter and equal to that of the thorium containing test fuel rods, and a smaller one with the same diameter as the microcell fuels manufactured by KAERI. The small diameter reference rods are foreseen to be exchanged for new test rods within the life time of the irradiation rig. Therefore, one is only instrumented with a thermocouple for comparison with the temperatures of the microcell test rods, and one is completely un-instrumented. However, Linear Variable Displacement Transducers (LVDTs) are mounted in the corresponding positions in the rig for later use with instrumentation on new test rods, and in-core connectors are available for connection of further instrumentation, such as thermocouples.

| TABLE I. Basic characteristics of the fuel types being irradiated in the IFA-790 test rig in the Halden Research reactor. Compositions are given as weight percentages. Densities are the average of values obtained by geometric and immersion methods. |
|-----------------|-------|--------|--------|--------|-----------------|-----------------|
| Fuel type       | UO$_2$| Th$_{0.07}$U$_{0.93}$O$_2$ | Th$_{0.25}$U$_{0.75}$O$_2$ | Th$_{0.40}$U$_{0.60}$O$_2$ | Metallic microcell UO$_2$ | Ceramic microcell UO$_2$ |
| UO$_2$ content [%] | 100  | 93    | 75    | 60    | 97             | 99             |
| Additive        | -    | ThO$_2$ | ThO$_2$ | ThO$_2$ | Cr             | SiO$_2$/TiO$_2$ mix |
| Additive content [%] | -    | 7     | 25    | 40    | 3.34           | 0.6           |
| U enrichment [%] | 4.5  | 4.96  | 6     | 7.6   | 4.5            | 4.5            |
| Diameter [mm]   | 8.19/8.48 | 8.48  | 8.48  | 8.48  | 8.19           | 8.19           |
| Density [% of TD] | 95  | 94.8  | 94.8  | 95.0  | 97.0           | 96.5           |
| Cladding inner ø [mm] | 8.63/8.36 | 8.63  | 8.63  | 8.63  | 8.36           | 8.36           |
| Cladding outer ø [mm] | 9.84/9.50 | 9.84  | 9.84  | 9.84  | 9.50           | 9.50           |

The fuel rods containing the microcell fuel types also feature new advanced chromium-based cladding coatings. These coatings are expected to improve the corrosion resistance of zirconium cladding at high temperatures. In addition, the cladding’s resistance to hoop stress and compressive stress is enhanced. The two different chromium based alloys that are being tested are (Fe,Cr,Al) and (Cr,Al).

III. RESULTS AND DISCUSSION

Preliminary irradiation results are available and show that the instrumentation is working well and giving the expected output. Irradiation data from the first 100 days of irradiation is presented below.

III.A. Fuel centerline temperatures

The microcell fuel rods have significantly lower fuel centerline temperatures than the corresponding uranium reference fuel rods, as shown in Fig. 1. For the Cr microcell fuel, this is expected since the network of highly conductive Cr should increase the bulk thermal conductivity of the fuel. For the oxide microcell fuel, the lower temperature can likely be explained by increased swelling of the fuel, resulting in direct contact between the fuel and the cladding and thus a better conductance.
between the fuel and the coolant. This hypothesis is supported by the cladding elongation data shown in Fig. 3. Also, the addition of thorium seems to lower the fuel centerline temperature in some cases, as shown in Fig. 2. This is unexpected, given that introduction of an impurity in the UO₂ lattice should decrease the conductivity of the fuel, and possible causes for this unexpected measurement are being investigated.

Fig. 1. Fuel centerline temperatures for the microcell fuel rods and the instrumented pure UO₂ rod of the same diameter, normalized to a linear heat rate of 30 kW/m.

Fig. 2. Fuel centerline temperatures for the ThₓU₁₋ₓO₂ fuels (x = 0, 7, 25 and 40) located in the upper cluster in rods 7, 9, 12 and 10 respectively. The temperatures are normalized to a linear heat rate of 30 kW/m.

III.B. Cladding elongation

The cladding elongation measurements are shown in Fig. 3. For rod 8, a normal growth rate of ~0.01 mm/(MWd/kgOx) is observed between the shutdown periods. For rod 11, an elongation rate similar to the expected axial fuel swelling rate is observed, indicating that there is indeed contact between the fuel and the cladding as suggested by the temperature data.
Fig. 3. Cladding elongation of rods 8 and 11 and a line representing a growth rate of 0.01 mm per MWd/kgOx.

III.C. Fuel elongation

The elongation data displays the expected fuel behavior, i.e. a slow swelling rate, initially counteracted by rapid shrinkage due to in-pile resintering. This can be seen in Fig. 4 where fuel elongation data is plotted for the same rods as the temperatures in Fig. 1. Some exceptions to this behavior occur early in the irradiation and during a period around 40 irradiation days, and correspond to periods when the reactor was operated at lower than nominal power, resulting in lower fuel temperatures and correspondingly smaller thermal expansion of the fuel.

Fig. 4. Fuel elongation for the Th₄U₁₋ₓO₂ fuels (x = 0, 7, 25 and 40) located in the upper cluster in rods 7, 9, 12 and 10 respectively.

III.D. Fuel rod pressures

Fuel rod pressure data is plotted in Fig. 5, again for rods 7, 9, 10 and 12. In this early stage of the irradiation, no fission gas release is observed, but instead, the pressure corresponds to the dimensional changes of the fuel discussed above. Since this data is normalized with respect to the power, the low-power operation periods do not affect the plotted values.
IV. CONCLUSIONS

At this stage, no showstoppers have been identified that indicate that test rods of the irradiated fuel types cannot be introduced in commercial reactors. The lower temperature observed in the metallic microcell fuel shows that the additive works as expected. The irradiation is scheduled to continue for several years, during which fission gas release and gap closure is expected to occur in most of the fuel rods, which will yield additional information on the fuel’s in-core performance. The irradiation campaign will be followed up by extensive post-irradiation examination, showing among other things how well the ceramic microcell structure has served its purpose of trapping fission products.

Through the continued operation of this test rig, further information will be gained on the usefulness of the fuel and cladding types described herein, and possibly also on other fuel types which may be introduced in the rig at a later stage. In this manner, the described experiment will contribute greatly to the continued development and validation of new, better fuel types.

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REFERENCES