Proceedings of the Korean Nuclear Society Autumn Meeting
Seoul, Korea, October 2001

Irradiation Test of MOX Fuel in the Halden Reactor During the First Cycle and Its Analysis with a Computer Code COSMOS

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ABSTRACT

Two MOX fuel rods (MOX-ATT-TF and MOX-ATT-ET), which were fabricated in PSI by attrition milling method, are being irradiated in the Halden Boiling Water Reactor (HBWR) together with a MOX fuel provided by BNFL. The two MOX fuels have been successfully irradiated during the first irradiation cycle of June to October 2000, during which the average linear heating rate was 200-250 W/cm and the burnup reached ~5 MWd/kgHM. The irradiation test will continue up to a burnup of about 50 MWd/kgHM. MOX-ATT-TF rod is instrumented with TF while MOX-ATT-ET has ET at the top end. Both rods have PF at the bottom end. In addition, MOX-ATT-TF fuel is instrumented with EF at the top of the fuel stack. The densification is ~2% for MOX-ATT-TF and ~1% for MOX-ATT-ET, respectively. On the other hand, the densification estimated by EF measurement is ~0.2%, which is much lower than the one from PF. This is because PF is sensitive to the change in the volume of the entire fuel stack, whereas EF reflects the change at the edge of the pellet dish. This difference means that the significant densification occurs in the hot-dished region. For the analysis of irradiation results, a computer code COSMOS was used and its capability was verified. The predicted thermal behaviour and rod internal pressure show good agreement with the measured data.

1. INTRODUCTION

There are presently large stockpiles of plutonium worldwide which, in the current political climate, are of concern from the viewpoint of non-proliferation. To reduce these stockpiles, the plutonium can be disposed of as waste or transmuted, but there are many problems with this route and the energy potential of the plutonium is lost. Alternatively, the plutonium can be burned as fuel in commercial nuclear reactors. The latter option can be achieved by incorporating the plutonium into MOX fuel [1].

Three MOX fuel rods were loaded into the Halden Boiling Water Reactor (HBWR) with a rig IFA-651.1 in the middle of 2000. The primary aim of the in-pile experiment of MOX fuel is to prove its fuel performance. Of particular interest are the following:

- fuel thermal conductivity and its degradation with burnup
- fission gas release
- fuel densification and swelling.

The test will be performed under HBWR conditions for approximately five calendar years to a target burnup of ~50 MWd/kgHM. The present paper briefly describes the results during the first cycle irradiation of MOX fuels. Analysis of the measured data is performed with a fuel performance code COSMOS developed by KAERI.

2. DESCRIPTION OF IN-PILE TESTING

Figure 1 shows a schematic of the rig, IFA-651 and Halden boiling water reactor (HBWR).

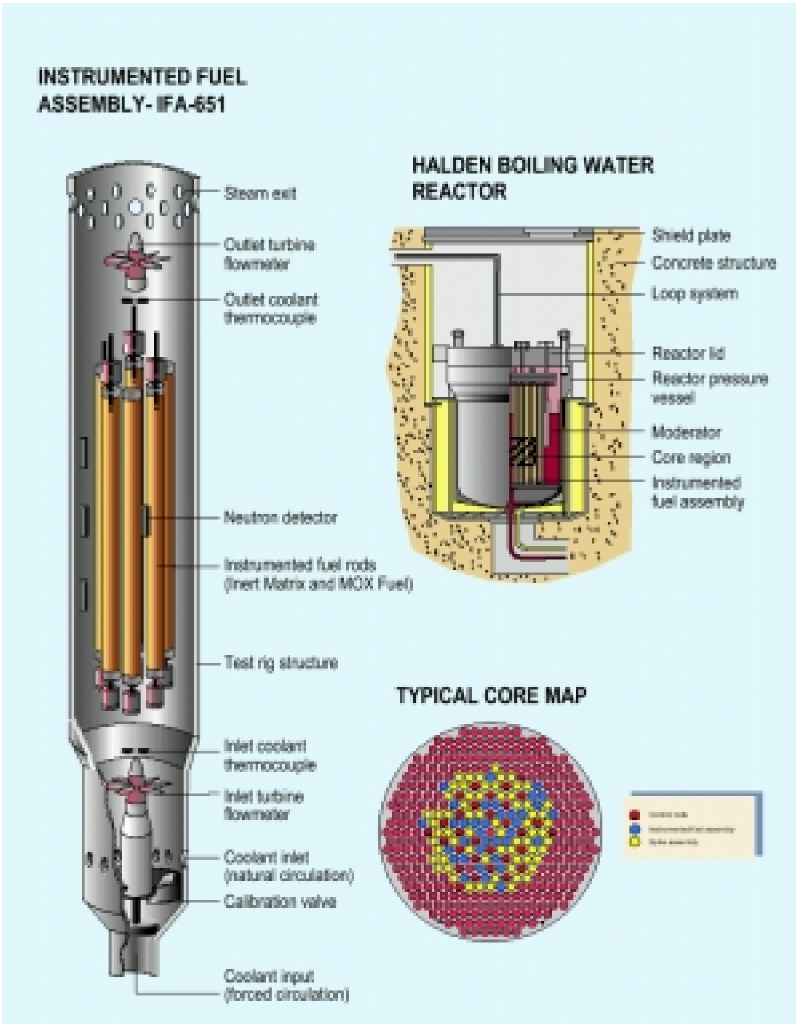

Figure 1. Schematic of IFA-651 rig and Halden Boiling Water Reactor

The IFA-651.1 rig contains six rods in one cluster - three MOX and three IMF (Inert Matrix Fuel) rods. The two MOX rods contain fuel manufactured in PSI using a dry milling process [2], whereas the other MOX fuel was provided by BNFL. The fuel compositions were determined so that all rods have comparable linear ratings. The fabrication and instrumentation of the three MOX fuel rods are summarized in Table 1.

Table 1. Summay of three MOX fuel rods.

Fuel designation	Fabrication method	Instrumentation
MOX-SBR	SBR	TF, PF
MOX-ATT-TF	ATT	TF, PF, EF
MOX-ATT-ET	ATT	ET, PF

SBR : Short binderless route / ATT : Attritoin milling
TF : Fuel thermocouple / ET : Expansion thermometer
PF : Pressure transducer / EF : Fuel extensometer

MOX-ATT-TF and MOX-SBR rods are instrumented with a thermocouple while the other MOX-ATT-ET have a expansion thermometer. All rods have pressure transducers at the bottom end. MOX-ATT-TF is also instrumented with a stack elongation detector at the top of the fuel stack.

To obtain an accurate axial flux distribution, the rig is instrumented with three co-linear neutron detectors at three different elevations. The radial flux distribution is measured by three axisymmetric neutron detectors, which are placed at the central elevation corresponding to the fuel stack midpoint.

The first cycle irradiation of IFA-651.1 commenced at the end of June 2000 and finished at the end of October 2000. The average burnup accumulation for the three MOX fuel rods was ~5 MWd/kgHM. The burnup and linear heating rate histories during the first cycle are illustrated in Figure 2. After the first several days of operation, the rod average ratings were maintained at an approximately constant level of 200 to 250 W/cm for the remaining cycle.

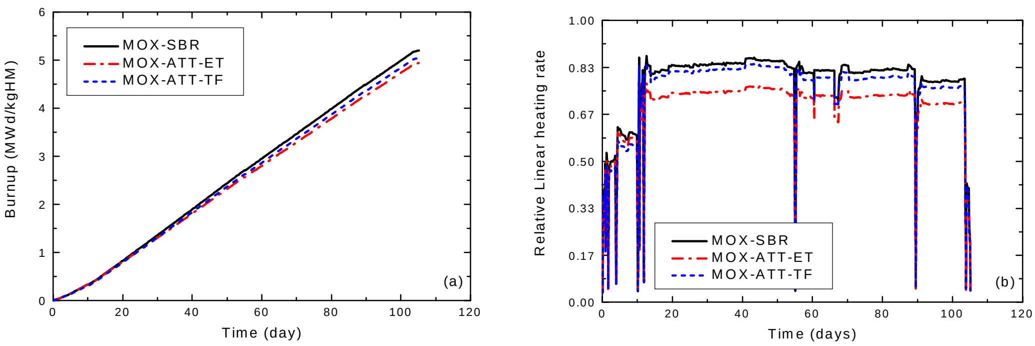

Figure 2. Burnup and linear heating rate history during the first cycle irradiation.

3. IN-PILE BEHAVIOUR

The in-pile behaviour of the two MOX-ATT fuel rods in IFA-651.1 is described in terms of thermal performance, rod internal pressure and fuel stack length change [1].

3.1 Thermal Performance

The measured fuel temperatures over the first cycle of irradiation are illustrated in Figure 3. It can be seen that the temperatures in the MOX rods show a very similar trend. To compare thermal behaviour based on the same condition, the temperature was normalized to 250 W/cm for steady state data with a coolant temperature of 235°C. A linear dependence of the difference between measured fuel temperature and coolant temperature on a linear heating rate was assumed. The normalized fuel temperatures for the three MOX fuel rods show very similar thermal behaviour since the fuel enrichments and densities and the rod dimensions are all very similar. The densification in all MOX fuels is reflected by a slight increase in the normalized fuel temperatures with burnup.

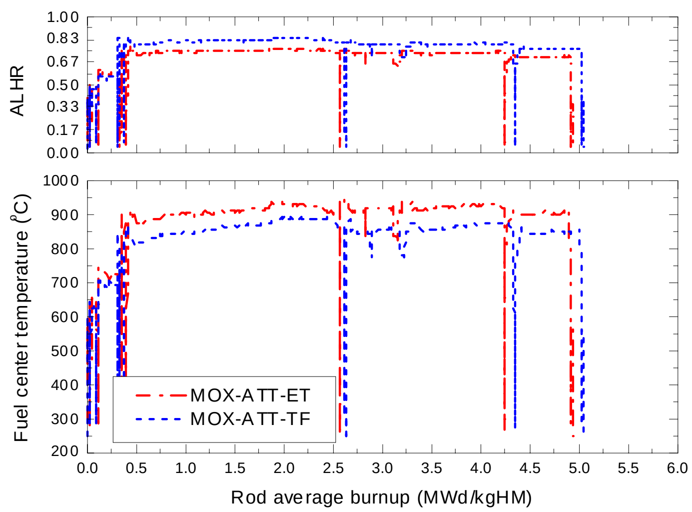

Figure 3. Measured fuel centerline temperature

3.2 Rod Internal Pressure

The two MOX rods were initially filled with helium at 10 bar at room temperature. The measured pressures for the two rods are plotted in Figure 4 together with the relative rod average linear heating rate. The normalized pressures were obtained using the Halden Project pf-norm program, which assumes ideal gas behaviour and a fuel temperature that is linearly dependent on the linear heating rate [3]. The measured pressure is normalized to hot stand-by (HSB) conditions (zero power and a constant coolant temperature of 235 °C). The initial normalized pressure increases at BOL to ~ 18 bar in all rods, are consistent with the temperature increases from room temperature (~ 20 °C) to 235 °C with ideal gas assumptions.

The normalized pressures initially dropped slightly (by ~ 0.5 bar), then rapidly stabilized. This is consistent with fuel temperatures lower than the threshold for fission gas release and slight fuel densification.

While MOX-ATT-TF showed ~ 2 vol% densification by the end of the cycle, MOX-ATT-ET displayed ~ 1 vol % densification. Since both the MOX-ATT fuel rods were fabricated by the same manufacturing route and the same campaign, the differences in densification are not likely to be due to these factors. It is thought that the differences are due to the lower linear heat rates

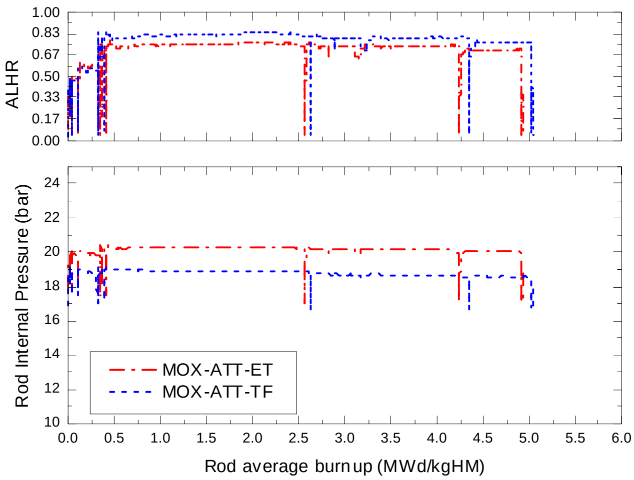

Figure 4. Variation of measured rod internal pressure.

in MOX-ATT-ET than in MOX-ATT-TF. The rod average linear heat rates for MOX-ATT-ET in the first cycle were consistently ~ 30 W/cm lower than those in MOX-ATT-TF. Previous experiments [4] have shown that the degree of densification in MOX fuel appears to be proportional to linear heat rate.

3.3 Fuel Stack Elongation

Fuel stack elongation has been measured for the MOX-ATT-TF equipped with EF. The at-power and hot stand-by measurements are plotted in Figure 5. From the elongation data at HSB, it can be seen that the permanent change in stack length at the end of the cycle is only ~ 0.2 mm.

The fuel volume changes at HSB, as inferred from the EF measurements, are estimated by assuming isotropic densification. The densification at the end of cycle derived from the EF

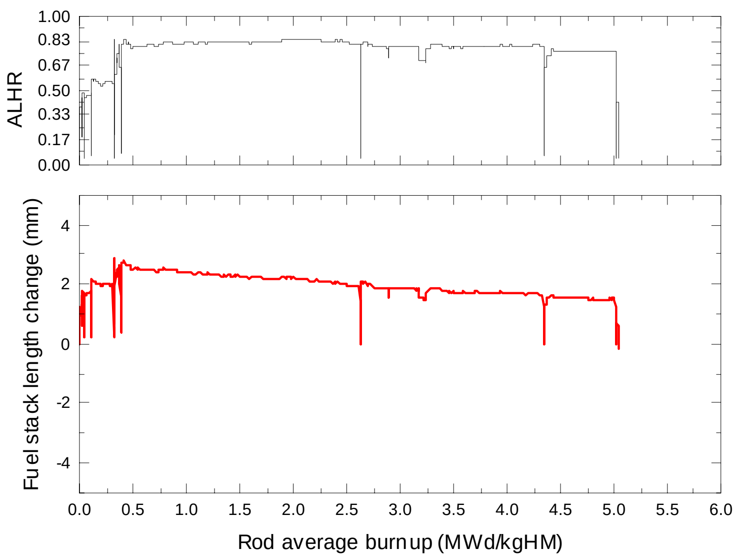

Figure 5. Measured stack elongation for MOX-ATT-TF.

measurements is ~0.2 vol% for MOX-ATT-TF. This compares to ~1.6 vol% for the densifications inferred from the PF measurements.

The trends for the fuel volume change obtained from the EF measurements are similar to those obtained from the PF measurements, but with significantly smaller volume changes in the first 0.5 MWd/kgHM of irradiation. It is thought that the differences between the densifications deduced from the EF and PF measurements are due to the pellet geometry. The densification (or in-pile sintering) is associated with the progressive disappearance of the fine pores which are introduced during the fabrication process. The pressure measurements are sensitive to the decrease in volume of the entire fuel stack. On the other hand, since the pellets are dished and chamfered, the EFs are measuring the densification at the edge of the pellet dish [5]. This is smaller than the rod average densification, since a significant fraction of the densification occurs in the hot dished region of the pellets and is accommodated by pellet deformation.

4. VERIFICATION OF COSMOS

4.1 COSMOS code

LWR MOX fuel is different from typical UO_2 fuel in that it contains about up to 10 wt% of Pu from the beginning. Due to a difference in microstructure arising from the addition of Pu, the following features should be considered when analyzing MOX fuel with performance models for UO_2 fuel: 1) change in thermo-mechanical properties such as thermal conductivity and thermal expansion coefficient, 2) change in radial power depression in a fuel rod as a function of Pu fissile content, 3) change in the mechanism of fission gas release resulting from the heterogeneous microstructure of MOX fuel depending on manufacturing method, and 4) high burnup phenomena of fuel such as rim formation and thermal conductivity degradation.

Considering the above features of MOX fuel and high burnup characteristics, a computer code COSMOS has been developed for the analysis of both MOX and UO_2 fuel during steady-state and transient operating conditions [6]. The followings are the main characteristics of the COSMOS:

- A mechanistic thermal conductivity model has been developed by using the concept of a two-phase thermal conductivity model [7], which considers the heterogeneous microstructure of MOX fuel. It is assumed that MOX fuel consists of Pu-rich particles and UO_2 matrix including PuO_2 in solid solution. The proposed model estimates that the MOX thermal conductivity is about 10% less than that of UO_2 fuel, which is in the range of the MOX thermal conductivity available in the open literature.

- A new fission gas release model, which takes into account the effect of the microstructure of MOX fuel, uses the concept of an equivalent spherical cell composed of an equivalent spherical particle and the surrounding UO_2 matrix [8]. The difference in fission densities in the two regions is one of the dominant factors that would cause different gas release behavior in MOX and UO_2 fuel. Figure 6 shows how the gas release is affected depending on the size distribution of Pu-rich particles. Furthermore, a mechanistic fission gas release model [9] was developed with emphasis on the effect of external restraint on the behavior of gas bubbles at grain boundaries. The model was compared with the measured data obtained from commercial reactors, Risϕ-III Project, isothermal irradiation and post irradiation annealing experiments. It is shown that the model predicts well the fractional fission gas release as well as

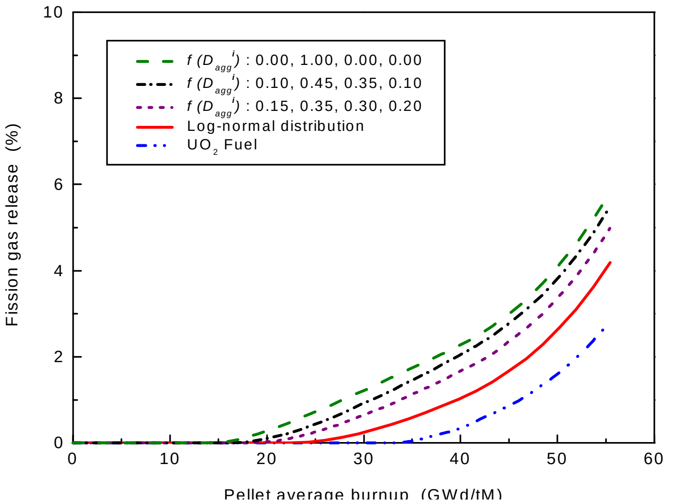

Figure 6. Effect of the size distribution of Pu-rich particles f ($D_{agg}{}^{i}$) on fission gas release in a MOX pellet with 4 groups of Pu-rich particles.
(Nagg : 0.5×10^{13}, f_{Pu}: 0.3, $D_{agg}{}^{i}$: 15, 30, 45, 60 μm)

the radial distribution of Xe gas across the fuel pellet under various operating conditions (Figure 7).

• Based on the measured rim characteristics of high burnup UO_2 fuel, the pressure of rim pores (Figure 8) and additional pellet swelling due to rim formation have been modeled as a function of temperature, pellet average burnup and pore radius [10]. This information could be used to analyze fuel behavior under RIA conditions during which pores with high pressure could cause crack propagation along subgrain boundaries resulting in the ventilation of gas atoms retained in the pores. In addition, thermal conductivity degradation due to porous rim formation is considered [11].

• Another important feature of the COSMOS is that it can analyze fuel segments re-fabricated from base-irradiated fuel rods. This makes it possible to utilize the database obtained from international projects such as HALDEN and RISO, many of which were collected from refabricated fuel segments.

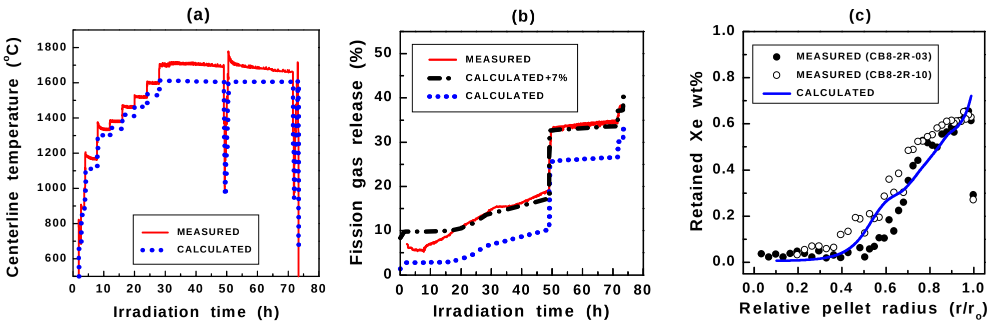

Figure 7. Analysis results for the Risϕ-III's AN3 test: (a) centerline temperature, (b) fission gas release and (c) radial distribution of Xe.

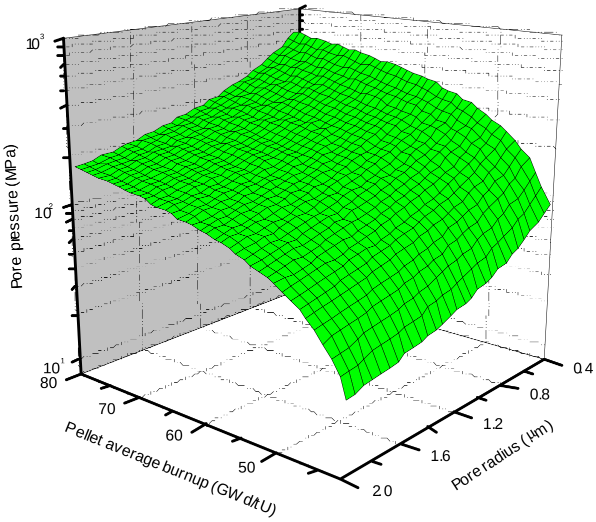

Figure 8. Calculated pore pressure in the rim as a function of pellet average burnup and pore radius.

The COSMOS has been tested with a number of experimental results obtained from some international fuel irradiation programs. It is found that calculated results of the COSMOS show good agreement with measured data.

4.2 Verification

The in-pile testing results during first cycle irradiation of MOX-ATT fuel rods were used for COSMOS code verification. The COMSOS code has been mainly focused on the thermal analysis since the irradiation temperature was below the threshold for fission gas release.

The COSMOS input is made directly from OECD HRP's TFDB (test fuel databank). To estimate the fuel centreline temperature of MOX fuel rods equipped with TF, the COSMOS code has been improved to simulate the hole for thermocouple.

The main input parameters are as follows:

- Coolant: HBWR conditions
- Maximum volume reduction: 2.0 vol % for MOX-ATT-TF and
  1.0 vol % for MOX-ATT-ET
- Matrix swelling rate: 0.53 vol % / (10 MWd/kgHM) (generally recommend value)

The linear heat rate from TFDB is redefined at 5 axial nodes to simulate the thermocouple.

The fuel thermal behaviour is influenced by the following factors: thermal conductivity, relocation, densification and swelling, and radial power distribution.

The thermal conductivity was obtained from the measured thermal diffusivity values and specific heat capacity. The relocation is determined from the IFA-597, which includes comparable MOX fuel. The nuclear physical calculation code HELIOS yields the radial power distribution in a MOX pellet, which is implemented into the COSMOS code. The densification is given as an input parameter which is determined from the rod internal pressure measurement. Temperature analysis is performed both for the partly hollow pellet (MOX-ATT-TF) and the entirely hollow pellet (MOX-ATT-ET).

The measured and calculated fuel temperature at the thermocouple are compared in Figure 9. It can be seen that the estimated fuel centreline temperature at the tip of the thermocouple shows very good agreement. The comparison of measured and calculated rod internal pressure is also in good agreement as shown in Figure 10. This indicates that the COSMOS code simulates well the thermal behaviour with the partly hollow pellet in which the thermocouple is inserted.

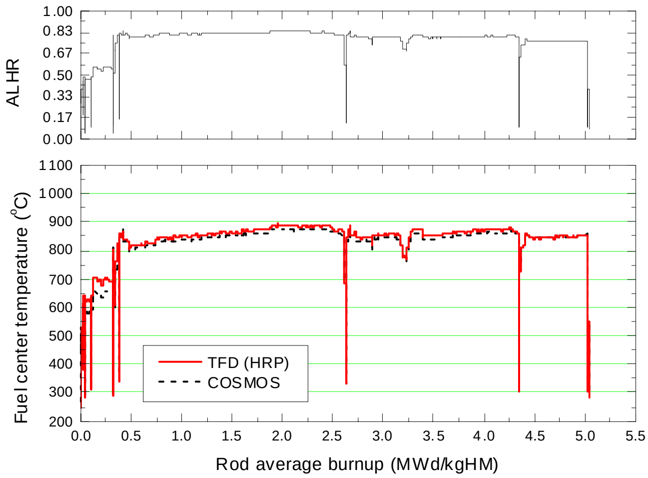

Figure 9. Comparison of COSMOS calculated centerline temperature with measured values for MOX-ATT-TF

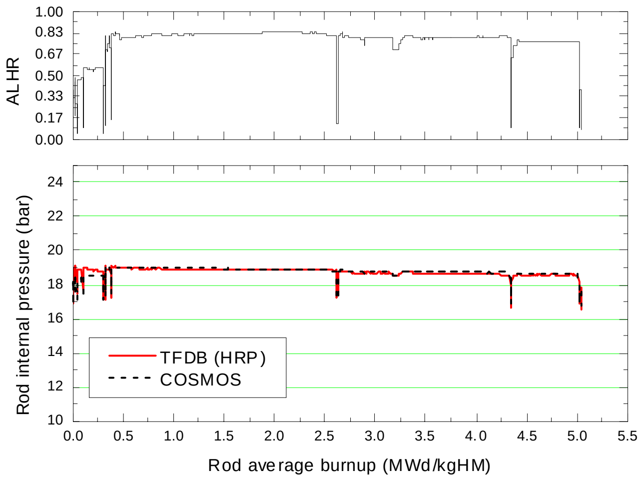

Figure 10. Comparison of COSMOS calculated RIP with measured values for MOX-ATT-TF

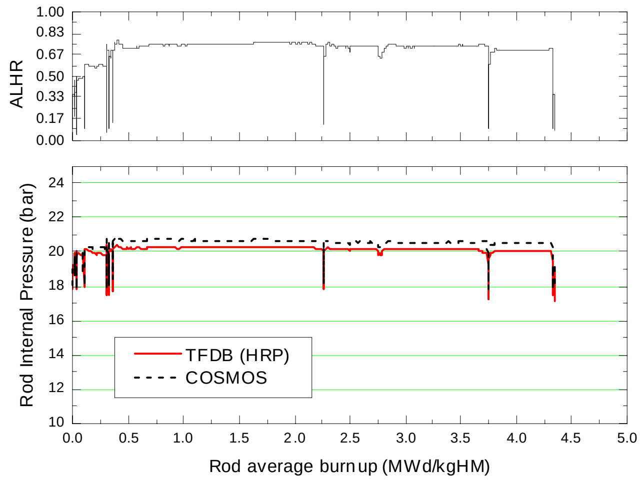

Figure 12. Comparison of COSMOS calculated RIP with measured values for MOX-ATT-ET

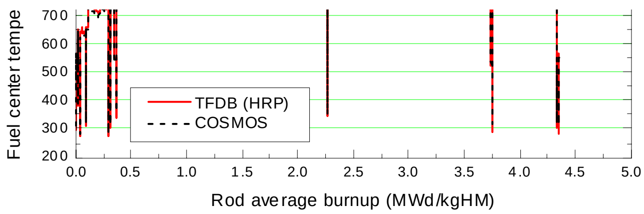

Figure 11. Comparison of COSMOS calculated centreline temperature with measured values for MOX-ATT-ET

On the other hand, the calculated centreline temperature in MOX-ATT-ET is slightly underpredicted as shown in Figure 11. This underprediction is thought to be affected by the densification inferred from measured pressure and initial free volume. Although the MOX-ATT-TF and the MOX-ATT-ET were fabricated by the same process, densification for the MOX-ATT-ET is lower than that in the MOX-ATT-TF. This difference in densification, which is given as input, could have influenced the thermal behaviour - the underprediction for the MOX-ATT-ET. Consequently, the predicted pressure is higher than the measured rod internal pressure as shown in Figure 12.

5. CONCLUSIONS

The first cycle irradiation of two MOX fuels have been performed in the Halden Boiling Water Reactor and the measured results were used for the verification of the COSMOS code. The main conclusions are summarized below:

(1) The MOX fuels fabricated by attrition milling have been successfully irradiated for one cycle.

(2) MOX-ATT fuels have demonstrated very comparable thermal behaviour with commercialised MOX fuel.

(3) The rod internal pressures were measured for all rods. The normalized values showed marked decreases with burnup consistent with fuel densification of ~ 1 to 2 vol% for the MOX fuel. There was no evidence of any fission gas release.

(4) The fuel stack elongation was measured for MOX-ATT-TF. The measured values at HSB indicated fuel densification of ~ 0.2 vol%. It is thought that the differences between the densifications deduced from the EF and PF measurements are due to the pellet geometry.

(5) The COMSOS fuel performance code shows the good agreement between measured and calculated fuel centerline temperature as well as the rod internal pressure.

Acknowledgements

The authors would like to express their appreciation to the Ministry of Science and Technology (MOST) of the Republic of Korea for its support of this work through the Mid- and Long-term Nuclear R&D Project.

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