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VERIFICATION OF COSMOS CODE USING IN-PILE DATA OF RE-INSTRUMENTED MOX FUELS

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ABSTRACT

Two MIMAS MOX fuel rods base-irradiated in a commercial PWR have been re-instrumented and irradiated at a test reactor. The fabrication data for two MOX rods are characterized together with base irradiation information. Both rods were re-instrumented to be fitted with thermocouple to measure centerline temperature of fuel. One rod was equipped with a pressure transducer for rod internal pressure, whereas the other with a cladding elongation detector. The post irradiation examinations for various items were performed to determine fuel and cladding in-pile behavior after base irradiation. By using well characterized fabrication and re-instrumentation data and power history, the fuel performance code, COSMOS, is verified with measured in-pile and PIE information. The COSMOS code shows good agreement for the cladding oxidation and creep, and fission gas release when compared with PIE data after base irradiation. Based on the re-instrumentation information and power history measured in-pile, the COSMOS predicts re-instrumented in-pile thermal behaviour during the power up-ramp and steady operation with acceptable accuracy. The rod internal pressure is also well simulated by COSMOS code. Therefore, with all the other verification by COSMOS code up to now, it can be concluded that the COMSOS fuel performance code is applicable for the design and license for MOX fuel rods up to high burnup.

1. INTRODUCTION

At present, large stockpiles of plutonium have been accumulating worldwide, which 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 method and the energy potential of the plutonium is lost. Alternatively, the plutonium can be burned as fuel in commercial nuclear reactors with energy production. The latter option can be achieved by incorporating the plutonium into MOX (Mixed OXide) fuel or IMF (Inert Matrix Fuel).

To utilize MOX fuels in commercial reactors, there are many researches showing comparable properties of MOX to UO_2 fuel. One of the important differences is the slightly lower thermal conductivity of MOX fuel compared with that of UO_2 fuel, which leads to different central fuel temperatures and consequently results in different fission gas release for the same power. Therefore, it is prerequisite to predict a more accurate temperature in MOX fuel, which is determined from MOX thermal conductivity.

The fuel performance code, COSMOS [1], developed by KAERI has been verified with many international database (in particular, FIGARO and HRP's TFDB for MOX fuels).

In the present study, the COSMOS code is verified with a recently available database for re-instrumented MOX in-pile experiments. In addition, it is intended to check a developed thermal conductivity model for MOX fuel considering its microstructural characteristics.

Two MOX fuel rods base irradiated in a commercial PWR were re-instrumented and loaded in a test reactor with post irradiation examinations before re-instrumented irradiation. The primary aim of the in-pile experiment of MOX is the thermal behaviour of MOX fuel concerning thermal conductivity and its degradation with burnup.

The present paper briefly describes the base irradiation and re-instrumented experiment together with PIE results. And then the comparison by COSMOS with measured results is detailed to verify the COSMOS code to predict the in-pile behaviour of MOX.

2. BASE IRRADIATION AND RE-IRRADIATION

2.1 Fuel Rod Fabrication

The general fabrication data for the MOX rod segments are summarized below [3].

The MOX pellets were manufactured by BN by the MIMAS (Micronized Mater Blend) process. The fissile contents of two MOX rods are 4.304 wt % and 3.389 wt %, respectively. The re-sintering test shows good stability of pellets, with a thermal densification of less than 1 %. The Pu agglomerate size ranges from 15.6 to 17.9 μm. The grain size of the UO_2 matrix is ~8.0 μm, which does not change appreciably along the pellet radius. The O/M ratio was measured and yielded near stoichiometry (2.0).

The geometrical characteristics of fuel rods are very similar to those using a typical commercial PWR. The pellets are the dished and chamfered at both ends. All fuel gaps were filled with 26 bar helium at room temperature. The cladding is Zircaloy-4 stress relieved (SR) tube which was produced by Zircotube. The tubes were finally annealed at 460 °C for 3 to 6 hrs. The nominal values for inner and outer diameter are 8.36 mm and 9.50 mm, respectively. The cladding has a standard Sn content, which ranges from 1.39 % to 1.50 %.

2.2 Base Irradiation Information

Two fuel rods were located in the same fuel assembly of a commercial PWR. The assembly was irradiated for 4 cycles with its positions in the core moved during these cycles.

The irradiation data of power history for the rods are presently available. The average linear heating rate during four cycles ranged from 190 to 200 W/cm for the rods. The distributions for axial power history with time and burnup are also available for 57 axial nodes for the whole fuel stack length. Node number 1 corresponds to the bottom of the fuel rod.

2.3 Re-instrumented irradiation

After base irradiation in a commercial PWR, two MOX rods were selected for re-fabrication and instrumentation. The two fuel rod segments were loaded into the representative PWR condition (155 bar and 300 ~ 320 ^oC for coolant conditions). Moreover, in order to provide a fast neutron flux representative of commercial PWRs, the rods were surrounded by several booster rods. Three vanadium neutron detectors are placed in order to monitor the flux distribution around the fuel segments.

The two fuel segments were fitted with centreline thermocouples. One rod was equipped with a bellows-type pressure transducer and the other with a clad extensometer. Re-instrumented fuel rods have been irradiated for two years over 50 MWd/kgMOX.

2.4. PIE after Irradiation

Non-destructive examinations were performed on the fuel stack length at the end of base irradiation. The examinations include the eddy current oxide thickness measurement, profilometry, gamma scanning and rod puncture measurements.

The rod puncturing was performed to evaluate the fission gas release after base irradiation. The results indicated a fission gas release less than 5%.

Metallography for one rod was performed to confirm the oxidation measurement from eddy current method. The observed outer oxide thickness show good agreement with the value estimated from eddy current method at the same position.

In addition, fuel density was measured at two positions of fuel. The density measured indicates volume increase of ~3 %.

3. 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 difference in microstructure arising from the addition of Pu, 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 heterogeneous microstructure of MOX fuel depending on the manufacturing method, and 4) high burnup phenomena of fuel such as rim formation and thermal conductivity degradation.

Considering above features of MOX fuel and high burnup characteristics, a computer code COSMOS [1] has been developed for the analysis of both MOX and UO_2 fuel during steady-state and transient operating conditions. The followings are main characteristics of the COSMOS:

- A mechanistic thermal conductivity model has been developed by using the concept of a two-phase thermal conductivity model [2], 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 microstructure of MOX fuel, uses the concept of an equivalent spherical cell composed of an equivalent spherical particle and the surrounding UO_2 matrix [4]. The difference in fission densities in the two regions is one of dominant factors that would cause different gas release behavior in MOX and UO_2 fuel. Furthermore, a mechanistic fission gas release model [5] was developed

with emphasis on the effect of external restraint on gas bubbles behavior 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 the radial distribution of Xe gas across fuel pellet under various operating conditions.

- Based on the measured rim characteristics of high burnup UO_2 fuel, the pressure of rim pores and additional pellet swelling due to rim formation have been modelled as a function of temperature, pellet average burnup and pore radius [6]. 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 [7].
- Cladding oxidation [8] and creep modelling [9] are improved to take into account the void effect combined with water chemistry and heat treatment for cladding fabrication in high burnup fuels. They are verified by many international database such as EPRI-PFCC, FIGARO, and NFIR.
- 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 a database obtained from international projects such as HALDEN and RISO, many of which were collected from re-fabricated fuel segments. In particular, the COSMOS code has been improved to simulate the hole for a thermocouple to estimate the fuel centreline temperature of MOX fuel rods equipped with a thermocouple.

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

4. INPUT PREPARATION OF COSMOS

The two rods irradiated for 4 cycles at a PWR were selected for re-irradiation. Accurate analysis for base irradiation is required to estimate the fuel in-pile behaviour during re-instrumented experiment. Furthermore, the PIE results performed after base irradiation enable to verify COSMOS for oxidation and creep of cladding and fission gas release for high burnup MOX rods.

4.1 Input Preparation for Base Irradiation

The data for base irradiation were obtained by including the power history, axial power and burnup distribution. The power history designated for 57 axial nodes is directly used without compressing multiple axial nodes. The linear heating rate ranges from 130 to 250 W/cm.

The rods were irradiated in typical PWR conditions:

- Coolant type : H_2O
- Coolant inlet temperature and pressure: 286℃ / 155 bar

The heat transfer coefficient of 3.1×10^4 W/m^2-℃ is obtained by using mass flow rate and related hydraulic parameters.

The general fabrication data for the selected fuel segments are obtained from [10]. The microstructure considering MOX heterogeneity is summarized in Table 4-1. The following assumptions are used to determine fissile Pu contents in Pu agglomerate and matrix of MOX fuel.

- The MOX type is MIMAS-AUC
- The theoretical density of MOX is 11 g/cc.

The unknown parameters are assumed that the properties of fuels base irradiated are the same as those of the general MIMAS fuel as listed in Table 4-2 [11].

Table 4-1 Input for microstructure of MOX fuel.

		Rod 1	Rod 2
Initial grain diameter in matrix	μm	8.0	7.0
Initial grain diameter in PuO_2 spot	μm	8.0	7.0
Pu agglomerate average diameter	μm	15.6	16.7
Pellet avg. Pu-fissile content	%	4.30	3.39
Avg. Pu-fissile content of Pu agglomerate	%	10.60	8.38
Pu-fissile content in matrix	%	2.23	1.75

Table 4-2 Area fraction of the phases and distribution of the input Plutonium in MOX fuel.

Fuel type	MIMAS-AUC	MIMAS-ADU	SBR
Area fraction of phase			
Matrix (%)	75.4	46.7	98-99
Pu-rich spot (%)	24.6	11.1	1-2
Coating around UO_2 particles (%)	-	42.2	-
Distribution of input plutonium			
Matrix (%)	39	15	96
Pu-rich spot (%)	61	39	4
Coating around UO_2 particles (%)	-	46	-

The porosity in plutonium agglomerate would be higher than that of the as-fabricated matrix, in particular, with irradiation. However, the relevant information is not available at the present so the matrix porosity is assumed to follow the as-fabricated porosity.

The fuel behaviour for densification and swelling is adopted from the relevant in-pile data from other MOX experiments:

- Maximum volume reduction: 1.0 vol % and
- Matrix swelling rate : 0.8 vol% / (10MWd/kgHM)

4.2 Input Preparation for Re-Irradiation

The input to simulate the performance of re-instrumented MOX fuel is carefully prepared using the power history with axial distribution and in-pile data measured by thermocouple and pressure transducer. However, the axial power distribution is not directly applicable in COSMOS so that the given power history is managed in the way described below.

The power history and irradiation data measured from the on-line instruments have been registered every 15 minutes. This irradiation data are huge for COSMOS calculation so all in-pile measured data are extracted to represent the original power history shape together with temperature and rod internal pressure. In particular, the power of the rods has been measured at four different axial elevation of bottom, medium, top and thermocouple tip. The fuel rod is divided into 12 segments with the same length in which the linear heating rates are given by following interpolation equations.

$$q_j^{/} = \frac{(13-2\cdot j)\cdot q_B^{/} + (2\cdot j-1)\cdot q_m^{/}}{12} \quad \text{for} \quad 1 \le j \le 6$$

$$q_j^{/} = \frac{(25-2\cdot j)\cdot q_M^{/} + (2\cdot j-13)\cdot q_T^{/}}{12} \quad \text{for} \quad 7 \le j \le 11$$

$$q_j^{/} = \frac{q_{TF}^{/} + q_T^{/}}{2} \quad \text{for the top axial node (12) instrumented with a thermocouple}$$

The number of nodes, 12, is decided to provide that the temperature at the 12th node calculated by COSMOS code can be directed compared with measured values from thermocouple. Actually, the real thermocouple length is slightly different from the length of the 12^{th} node. This difference can be negligible due to the axial power distribution is quite flat during steady irradiation.

The operating condition in a test reactor is simulated to PWR condition:

- Coolant type: H_2O
- Average coolant temperature / pressure: 310℃ / 155 bar

The heat transfer coefficient of 3.0×10^4 W/m^2-℃ is obtained by using mass flow rate and related hydraulic parameters.

The as-fabricated microstructure information is applied during re-instrumented irradiation. The geometrical and nuclear characteristics are given using the COSMOS calculation from base irradiation. The recommend value of 0.8 vol % / (10 MWd/kgHM) is adopted for the matrix swelling rate.

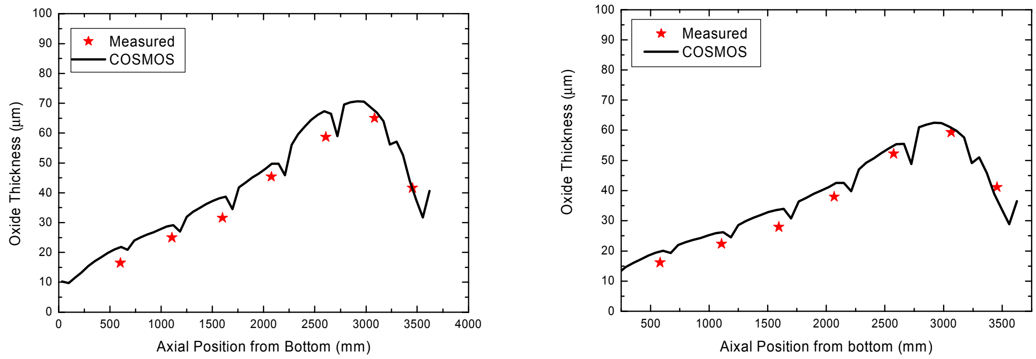
5. VERIFICATION OF COSMOS

The COSMOS code is verified by PIE results after base irradiation of two MOX fuels and their re-instrumented in-pile behaviour by on-line monitoring system.

5.1 Verification Using Base Irradiation Information

5.1.1 Oxidation and creep analysis of cladding

The cladding oxide and diameter of two rods selected for re-instrumentation have been measured after base irradiation in PWR. The measured oxide and diameter are compared with the prediction by COSMOS code which has already been implemented with rigorously verified corrosion [8] and creep model [9]. **Fig. 5-1** shows the oxide thickness and diameter measured after base irradiation, together with the predicted values by COSMOS. Measured oxide thickness profile is obtained from averaging along the four angular orientations. Only peak oxide thickness on each span is displayed in **Fig. 5-1**. The peak oxide thicknesses are approximately 60 to 70 μm at the sixth span. All rods show a significantly reduced oxidation between the spacer grids. For the analysis of corrosion, the Sn factor is set to unity since the cladding includes standard Sn contents ranging from 1.39% to 1.50%. The annealing condition is assumed to be the same as standard Zircaloy-4 manufacturing process since cladding manufacturing conditions are not relevant at the moment. Comparison between measured and calculated oxide thickness along the axis qualifies the corrosion model in COSMOS code up to the high burnup of MOX fuels.



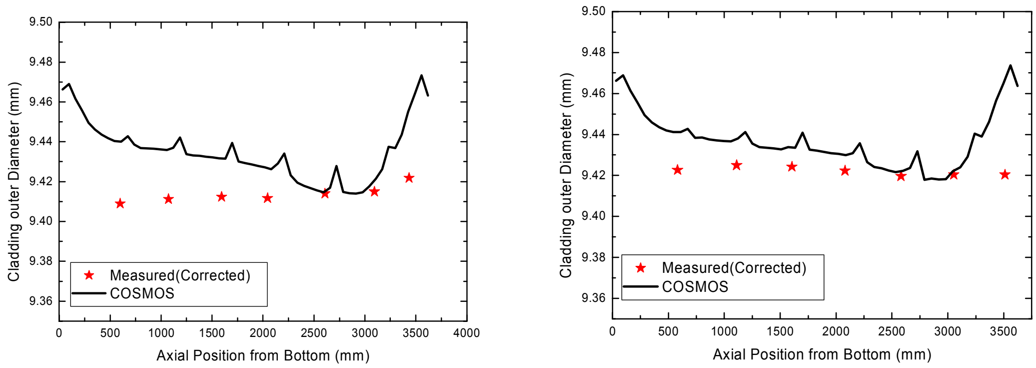
(a) (b)

Fig. 5-1 Comparison of measured and calculated oxide thickness of (a) Rod 1 (b) Rod 2 cladding after base irradiation in PWR.

On the other hand, **Fig. 5-2** displays the corrected outer diameter profile together with the diameter calculated by COSMOS considering creep-down. It is worth noting that the measured diameters are corrected by

$$OD_{corr} = OD_{meas} - 0.72 \cdot \delta$$

where δ is measured oxide thickness. It can be observed that the measured outer diameter of cladding for both rods shows quite uniform along axis even though the axial power is lower in the bottom and top than in the central region. It is unclear why the creep-down does not depend on the axial power distribution at the moment. However, COSMOS creep model is well predicting in the highest creep-down region of rods, whereas the calculation shows a lower creep-down in the bottom and top than measurement.



(a) (b)

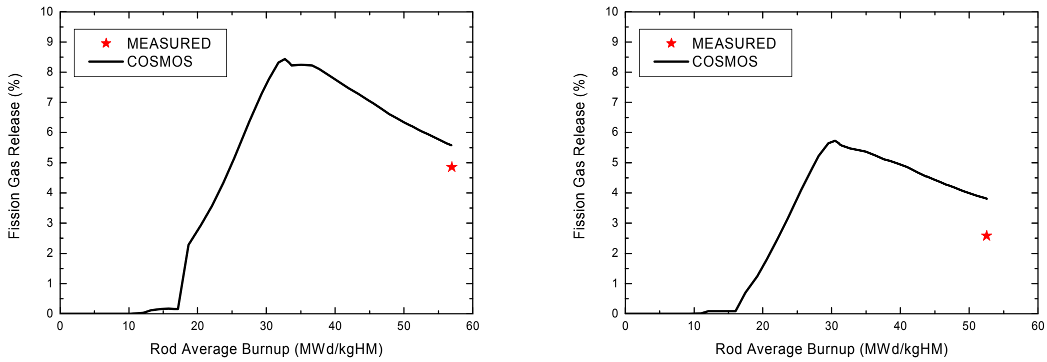
Fig. 5-2 Comparison of measured and calculated diameter of (a) Rod 1 (b) Rod 2 cladding after base irradiation in PWR.

5.1.2 Analysis of fission gas release

The fission gas release during base irradiation is estimated by the COMSOS code which has shown sufficiently good agreement with many other MOX in-pile test results. **Fig. 5-3** shows the puncturing results and the predicted evolution of fission gas release. The gas puncturing indicates less than 5% fission gas release at the end of base irradiation. There was a lower fission gas release in Rod 2 than in Rod 1, and could result from the lower irradiation power in Rod 2. The input parameters used for analysis are

- NM_{dif} : diffusion correlation = Turnbull (Harwell) model [12]
- NM_{sat} : saturation level correlation = modified White & Tacker model [13]
- NM_{ext} : external force $P_{ext} = P_{gas} + P_{cont}$
- NM_{cr} : consideration of microcracking at transient and
- NM_{res} : consideration of resolution back into grain.

As illustrated in **Fig. 5-3**, the calculated fission gas release shows slightly conservative result, which indicates little deviation less than 1% from measurement. The comparison shows the qualification of adopted input data and the incorporated fission gas release model in COSMOS.



(a) (b)

Fig. 5-3 Comparison of measured and calculated fission gas release of (a) Rod 1 and (b) Rod 2 after base irradiation in PWR.

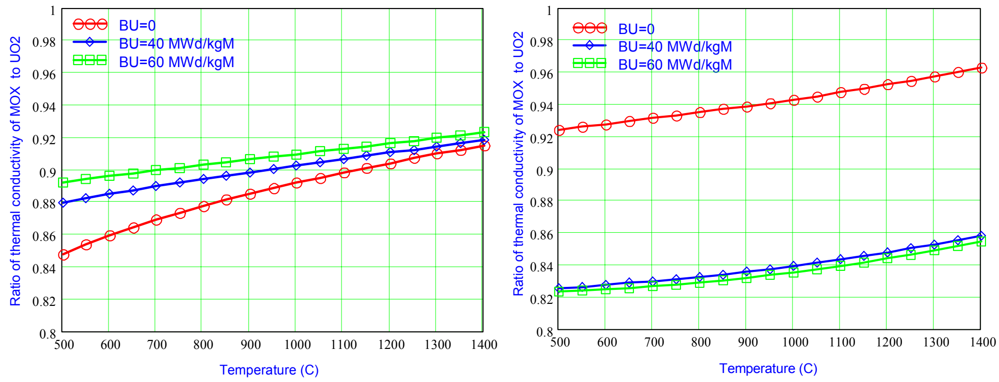
5.2 Verification Using Re-instrumented Irradiation Results

The in-pile testing results of two re-instrumented MOX fuel rods were used for COSMOS code verification.

5.2.1 Thermal analysis

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

Firstly, the thermal conductivity model is adopted by a recently developed model by KAERI [1]. The short description is as follows. It has been reported that the thermal conductivity of LWR MOX fuel ranges from 80 to 100 % of UO_2 fuel. The MOX fuel for LWR is fabricated either by direct mechanical blending of UO_2 and PuO_2 or by two stage mixing. Hence Pu-rich particles, whose Pu concentrations are higher than pellet average one and whose size distribution depends on a specific fabrication method, are inevitably dispersed in MOX pellet. A mechanistic thermal conductivity model for MOX fuel by considering this inhomogeneous microstructure is developed. **Fig. 5-4** illustrates the ratio of MOX to UO_2 thermal conductivity for the plutonium contents of ~7% which is the typical contents in the LWR MOX fuel. The thermal conductivity in MOX fuels is estimated assuming the same degree of burnup degradation effect in UO_2 fuel.



(a) (b)

Fig. 5-4. Ratio of MOX to UO_2 thermal conductivity for (a) homogeneous and (b) inhomogeneous MOX as a function of temperature.

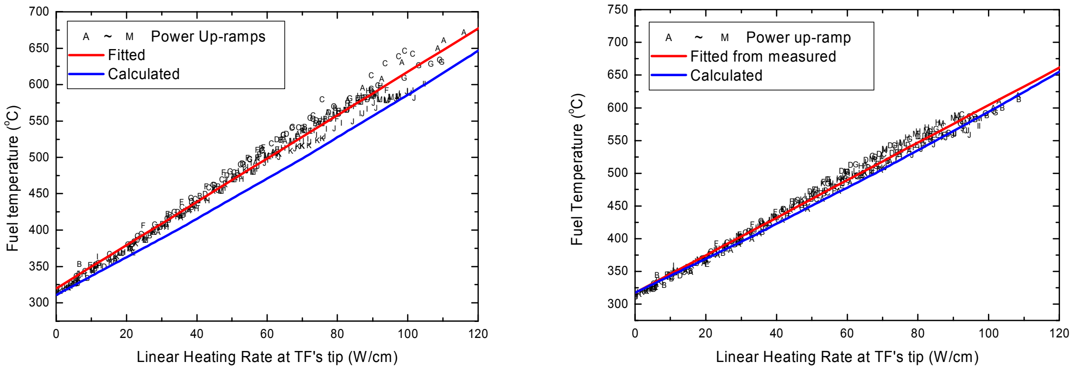
For both homogeneous and inhomogeneous MOX fuel, the difference between MOX and UO_2 thermal conductivity decreases with temperature because the electronic conduction becomes dominant at high temperatures.

It should be noticed that the burnup effect on the thermal conductivity seems more significant in inhomogeneous MOX than in UO_2 fuel. This is caused by assuming that the burnup is 3 times as high in the Pu-rich agglomerates as in the matrix. If the burnup in the agglomerate is lower, the burnup effect in an inhomogeneous MOX would be reduced.

Secondly, the relocation is determined from the other experiment which includes comparable MOX fuel. The densification is neglected due to high burnup of two rods. At last, the nuclear physical calculation code HELIOS yields the radial power distribution in MOX pellet, which is implemented into COSMOS code.

Thermal analysis is performed for the two rods which are equipped with the thermocouple in the center hole and except for the hole the other part was solid. The temperature was restricted to avoid the fission gas release.

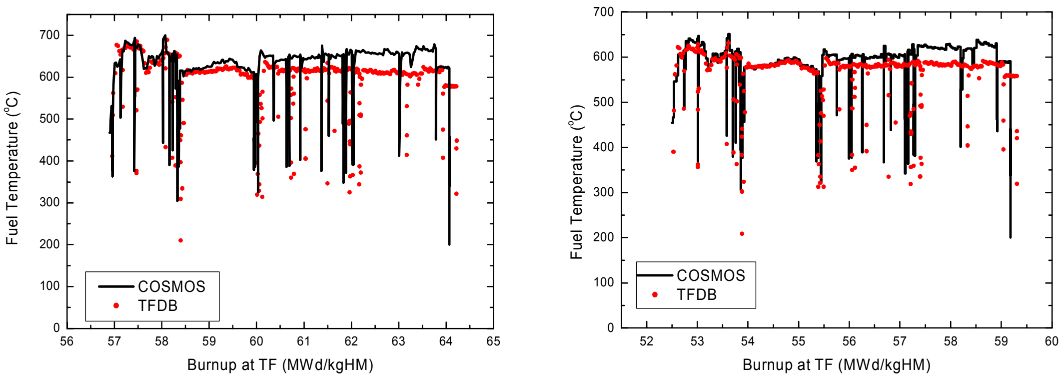
In order to check whether the input and modelling parameters including thermal conductivity model are appropriate, the calculated fuel temperature at the thermocouple are compared with the measured fuel temperature increase during power up-ramp at the beginning of irradiation (**Fig. 5-5**). It can be seen that the estimated fuel centreline temperature at the tip of thermocouple shows a good agreement. The temperature for Rod 1 shows slight under-prediction whereas that of Rod 2 is consistent with the measured centerline temperature. This agreement results from the appropriate initial gap width as well as the other reasonable assumption for re-fabricated fuel rods.



(a) (b)

Fig. 5-5 Power up-ramp data with fitted curve of (a) Rod 1 and (b) Rod 2 in re-instrumented irradiation.

The irradiation effect on fuel geometry (swelling) and the burnup degradation effect on thermal conductivity can be confirmed by analogy between the calculated with measured temperature with historical irradiation. **Fig. 5-6** shows the fuel temperature measured by thermocouple along with calculated values with COSMOS code. For both rods, the beginning-of-irradiation is satisfactorily simulated by COSMOS code. However, the slight over-prediction can be seen with irradiation. This discrepancy can be caused by the smaller fuel swelling behaviour in COSMOS than real fuel geometrical volume change and/or the excessive burnup degradation effect on thermal conductivity. The first possibility of different swelling behaviour during re-instrumented irradiation could lead to under-prediction of rod internal pressure. However, the comparison between measured and calculated rod pressure (**Fig. 5-7**) indicates the opposite of what is expected. While thermal conductivity of MOX fuel is undoubtedly affected by additional burnup degradation, it is likely that its degree is less than expected in the inhomogeneous MOX fuel since the homogeneity of Pu agglomerate is substantially improved and thereby reducing the burnup degradation. Therefore, it is needed to take into account the improved homogeneity in the developed thermal conductivity model for MOX fuels.



(a) (b)

Fig. 5-6 Comparison of measured and calculated temperature of (a) Rod 1 and (b) Rod 2 at the TF's tip position during re-instrumented irradiation.

It is noteworthy that the COSMOS code predicts the experiment with acceptable accuracy for re-instrumentation of test fuel. In addition, this indicates that COSMOS code sufficiently simulates the thermal behaviour with partly hollow pellet in which thermocouple is inserted.

5.2.2 Analysis for rod internal pressure

The rod internal pressure in Rod 2 has been measured by the pressure transducer located in the bottom of the rod during irradiation. The rod internal pressure is influenced by the fuel geometrical deformation (relocation, densification and swelling) and fission gas release. The contribution from fission gas release to rod free volume is negligible since the fuel temperature is lower than threshold for fission gas release. The HRP (Halden Research Program) has suggested the following empirical threshold relationship with burnup:

$$T_f = \frac{9800}{\ln(200 \cdot BU)}$$

where the burnup is in MWd/kgOX. If the fuel burnup is assumed by ~50MWd/kgHM (≈44MWd/kgMox) and the MOX fuel has the same behaviour of fission gas release as UO_2, the temperature of 1,080 °C is needed for fission gas release. The fission gas release can therefore be neglected. Due to negligible fission gas release and high burnup fuel (no densification), the measured pressure just reflects the fuel geometrical change by fuel swelling. **Fig. 5-7** shows the comparison between measured and calculated rod internal pressure. In general, however, it can be seen that the COSMOS code well predicts the measured rod internal pressure for the re-instrumented fuel.

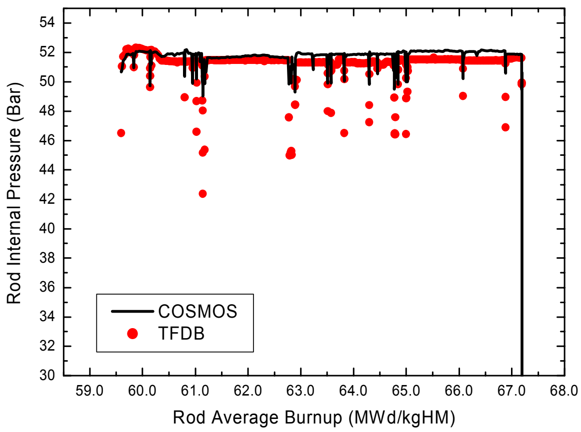


Fig. 5-7 Comparison of measured and predicted rod internal pressure of Rod 2 during re-instrumented irradiation.

6. CONCLUSIONS

Two MIMAS MOX fuel rods which were base-irradiated in a commercial PWR and re-instrumented and then irradiated at a test reactor are used to verify COSMOS code. Both rods were fitted with a thermocouple to measure centerline temperature of fuel. One rod was equipped with pressure transducer for rod internal pressure whereas the other with cladding elongation detector.

With the rigorously characterized fabrication data and base irradiation information, the post irradiation examinations results of cladding oxide and creep after base irradiation are compared with values calculated by COSMOS. The comparison shows the qualification of implemented corrosion and creep model into COSMOS code. In addition, the COSMOS code shows a good agreement for fission gas release when compared with gas puncturing data after base irradiation.

By using well characterized re-instrumentation data and power history, the calculation results by COSMOS code is compared with measured in-pile to verify the code's applicability for re-instrumented irradiation. Based on the re-instrumented in-pile data with power history measured by on-line system, the COSMOS code predicts accurate re-instrumented in-pile thermal behaviour during power up-ramp and steady operation. The rod internal pressure is also well simulated by COSMOS code.

Therefore, with all the other verification of COSMOS code up to now, it can be concluded that the COMSOS fuel performance code is applicable for the design and license for MOX fuel rods up to high burnup.

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