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Inert matrix and thoria fuel irradiation at an international research reactor

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Abstract

A major issue in the public debate on nuclear power, is how to break down the large plutonium stockpiles. Different concepts have been developed during the last years to burn plutonium. Two such concepts are stabilised zirconia based inert matrix (IM) and thoria (T) fuels. By using of IM fuels a larger fraction of plutonium could potentially be consumed without breeding new plutonium in comparison with todays MOX fuels. The aim of the presented study is to measure the general thermal behaviour of IM, inert matrix doped with thoria (IMT) and thoria under irradiation conditions similar to those in current light water reactor (LWRs). Of particular interest are the fuel thermal conductivity (and its degradation with burnup), fission gas release (FGR), fuel densification and fuel swelling. The irradiation is performed under HBWR conditions and a target burnup of ~400–450 kW d cm^{-3}, which is equivalent to ~40–45 MW d kg^{-1} for the MOX fuel, is envisaged. Among other things considerably higher operating temperatures in the IM and IMT rods have been observed compared with those in the thoria fuel. The higher temperatures, which were caused by the lower thermal conductivity of IM, result in higher FGR of the IM and IMT fuel. This work gives the obtained results after 6 cycles (671 days) of irradiation.

1. Introduction

The present large stockpiles of reactor and weapon grade plutonium worldwide are of major concern from non-proliferation and economic point of view. To reduce these stockpiles several treatments are possible. The plutonium could be treated as waste and be put in a final disposal, but there are many problems with this open fuel cycle and the energy potential of the material, which is of economic interest is lost. Reprocessing the plutonium and closing the fuel cycle with the use of fast reactors would optimise the utilisation of nuclear fuel. This development is today delayed due to political reasons. However, today's recycling is focused on uranium plutonium oxide fuel, the so-called mixed oxide fuels (MOX). The MOX is already in commercial use as a fuel in today's LWRs and this is

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a reasonable possibility to use the energy source plutonium. Unfortunately the total amount of plutonium is not significantly reduced due to the breeding of plutonium in the uranium matrix present. In addition recycling of second or third generation plutonium as MOX in LWRs, seems to be economical unfavourable. To reduce the plutonium stockpile and also the amount of other transuranium elements (TRU) in the nuclear waste, concepts have been developed during the last years to transmute TRU using an uranium free inert matrix fuels (IMF) in a once-through-cycle. For today's LWRs calcium stabilised zirconia (CSZ) and thoria fuels have been identified to be suitable to burn weapon or civilian plutonium and to act also as possible carrier for the transmutation of other TRU [1]. By using of IMF a larger fraction of plutonium could potentially be consumed in comparison with MOX fuels without breeding new plutonium.

The aim of the present study is to measure the general thermal behaviour of CSZ IMF (IM), CSZ IMF containing thoria (IMT) and thoria (T) fuel under irradiation conditions similar to those in current LWR's. Of particular interest are the fuel thermal conductivity (and its degradation with burnup), fission gas release (FGR), fuel densification and fuel swelling.

The presented study is a joint experiment of ENEA and the OECD-Halden-reactor-project (HRP).

The irradiation is performed under Halden boiling water reactor (HBWR) conditions (i.e., ~34 bar D_2O at ~510 K) and has reached an average assembly burnup of ~283 kW d cm^{-3} until end of 2004, which is equivalent to ~28 MW d kg^{-1} for the UOX fuel with a target burnup of ~400–450 kW d cm^{-3}, which is equivalent to ~40 MW d kg^{-1} for the MOX fuel. This report summarises the results after 6 cycles of irradiation (until end of 2004).

2. Experimental setup

The irradiation experiment (IFA-652) contains one rig (Fig. 1) holding a cluster of six highly instrumented rods. Two rods of each fuel type (IM, IMT, T) all manufactured at IFE Kjeller [2,3], using standard methods by mixing and blending dry powder and sintering in dry hydrogen at 1975 K for 4 h. In all the three fuel variants the included fissile material is high enriched uranium (HEU), instead of plutonium. The reason for this choice is that the manufacturing of Pu containing fuels is more difficult and there were no facility available to do that for the time being. However, it is expected that the relative behaviour of the different kind of matrices is only slightly dependent on the adopted fissile material. The comparison between the three fuels can thus be transposed also to the case of plutonium bearing fuels.

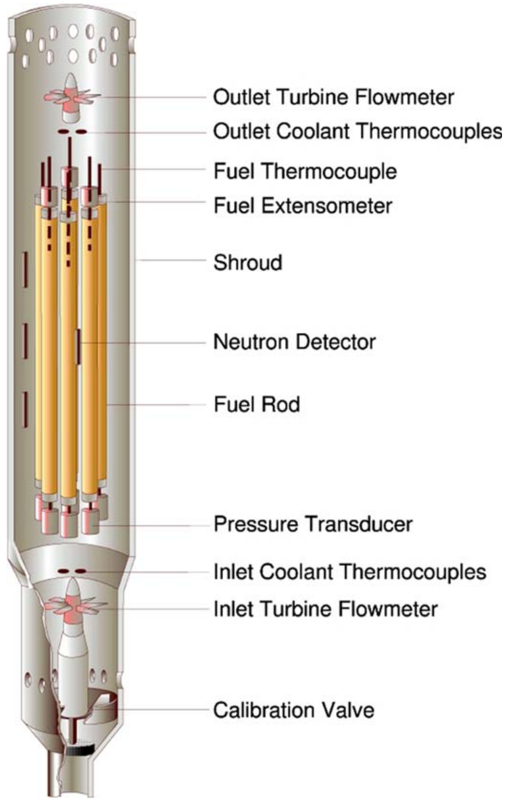

Fig. 1. Schematic view of IFA-652 rig.

All rods have thermocouple at the top end and pressure transducers at the bottom end. In addition, three rods, one of each type, are instrumented with stack elongation detectors at the top of the fuel stack.

In order to obtain an accurate record of the axial flux distribution, the rig is instrumented with three co-linear neutron detectors (NDs 1, 2 and 5) at three different elevations. The radial flux distribution is measured by three axisymmetric neutron detectors (NDs 2, 3 and 4), which are placed at the central elevation corresponding to the fuel stack midpoint. This is also the axial position of maximum flux in the HBWR.

A summary of all rod fabrication data is given in Table 1.

Table 1
Summary of rod fabrication data in IFA-652

Rod number	1	2	3	4	5	6
Fuel pellets						
Fuel type	IM	IM	IMT	T	T	IMT
Enrichment, %U fissle	19	19	16	11.7	11.7	16
Density, g/cm^3	5.64	5.64	7.00	8.18	8.18	7.00
Density, %TD	90	90	93	82	82	93
Outer diameter, mm	8.19					
Pellet length, mm	10 ± 1.5					
Dishing	Both ends					
Cladding						
Material	Zircaloy-4					
Outer diameter, mm	9.5					
Cladding thickness, mm	0.57					
Fuel rod						
Fill gas and pressure	Helium, 10 bar g					
Free volume, cc	9.3	8.4	8.1	12.8	12.2	8.7
Active fuel length, mm	499.7	499.7	499.6	499.9	499.8	499.2
Active fuel mass, kg	0.139	0.146	0.182	0.211	0.211	0.182
Instrumentation	TF, PF	TF, PF, EF	TF, PF	TF, PF, EF	TF, PF	TF, PF, EF

3. Irradiation history

The IFA-652 rig contained originally a cluster of 6 rods (~50 cm), two of each fuel type. Due to a delay in production of rod 3 the experiment was started with a dummy rod in this position. The rig is being irradiated under HBWR conditions. Irradiation of the first loading began at the end of June 2000 and the assembly average burnup at the end of October 2000 was ~52 kW d cm^{-3} (equivalent to ~5 MW d kg^{-1} for the MOX fuel). The dummy rod was exchanged with the origin IMT rod and the irradiation of the second loading from the mid of January 2001 the till mid the of May 2003 ends with a burnup of ~210 kW d cm^{-3}. Thoria rod number 4 was discharged and irradiation of the third loading began at the beginning of February 2004. The assembly average burnup at the mid of October 2004 was ~283 kW d cm^{-3}. The target burnup is ~400 kW d cm^{-3} (equivalent to ~40 MW d kg^{-1}), which should be achieved over a period of ~6 calendar years.

For the major part of the irradiation the rods have been operated in the range 25–30 kW m^{-1}. A pronounced temperature increase was registered for a given rating up to 50 kW d cm^{-3} for both T-rods, while fairly stable behaviour was observed in the IM- and IMT-rods during the same period. In common with IFA-651, this rig also experienced upratings in September 2001 and June 2002. Pressure jumps occurred for all rods, in particular during the second power ramp. The largest FGR were measured in the IM- and IMT-rods, where the partial poisoning of gap gas resulted in a slight shift in the temperature – power relationship. During March/April 2003, the rod instrumentation and visual inspection revealed that a leak had developed in rod 4 (thoria) and the rod was unloaded. Irradiation of the rig continued with the five remaining rods in the test matrix. The PIE of thoria rod 4 is still pending.

The instrumentation in the remaining five rods has been working well for the main part up to this point and the plan is to continue at about the same power as before interspersed with small power ramps to further explore fission gas retention (or FGR) for inert matrix fuels.

Powers upto 35 kW m^{-1} were achieved with temperatures of 1775–1875 K measured in IM and IMT rods and 1575–1675 K in the ThO_2 rods. Fig. 2 shows the irradiation history and the burnups of the rig IFA 652 during the first six irradiation cycles. The Assembly power is given in kW and the average linear heat rate in kW m^{-1}. The burnup is given in kW d cm^{-3} to have the possibility to compare IM with thoria fuel.

4. Results and discussion

The operating temperatures in the IM and IMT rods have been considerably higher than those in the thoria fuel due to the lower thermal conductivity of IM fuel. Fig. 3 shows the fuel temperature in °C

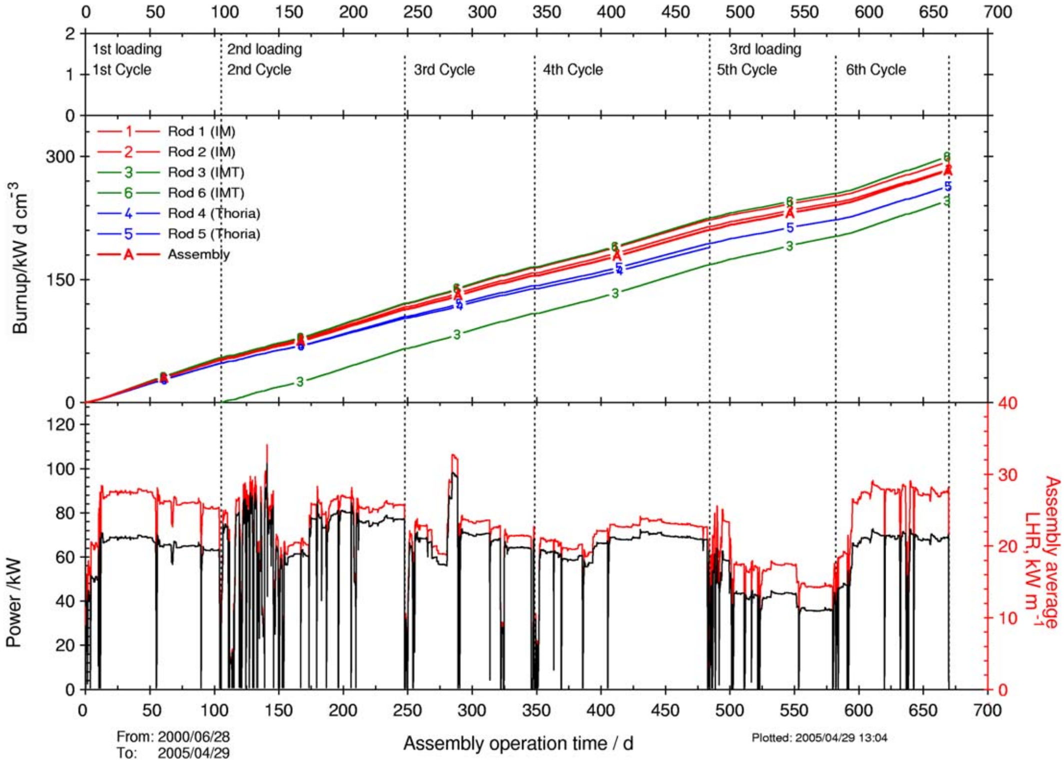

Fig. 2. Irradiation history of IFA-652.

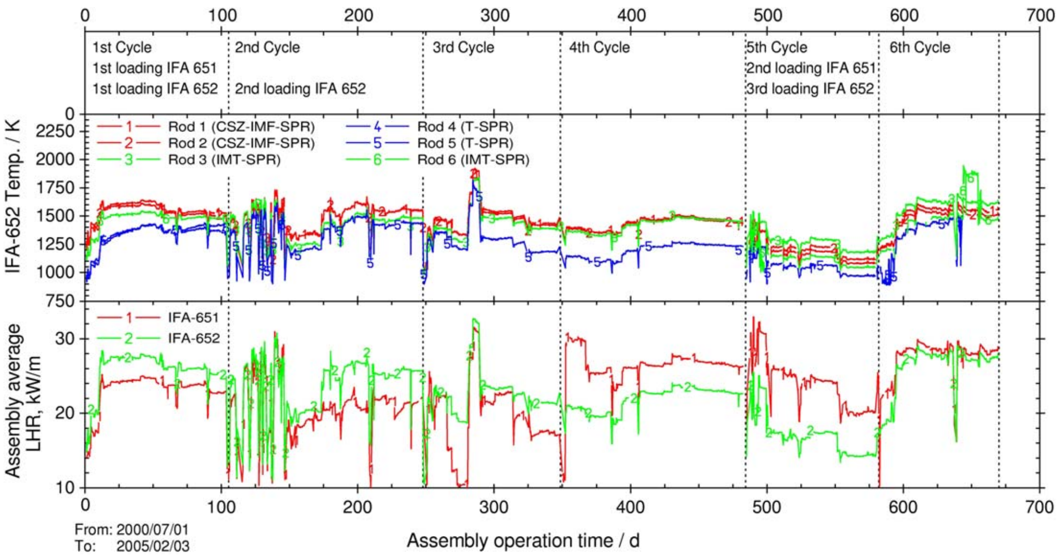

Fig. 3. Fuel temperature of IFA-652.

and the average linear heat rate in $kW\,m^{-1}$ as a function of the burnup in $kW\ d\ cm^{-3}$. The thoria content seems not to affect the thermal behaviour significantly. During operation the temperature signals of rod 1, 4 and 6 failed. Some values could be recovered and obvious incorrect values were not used in the figures.

For the IM a densification of some 2.0% was determined by rod inner pressure measurements while for the IMT roughly 1.3% was deduced. The

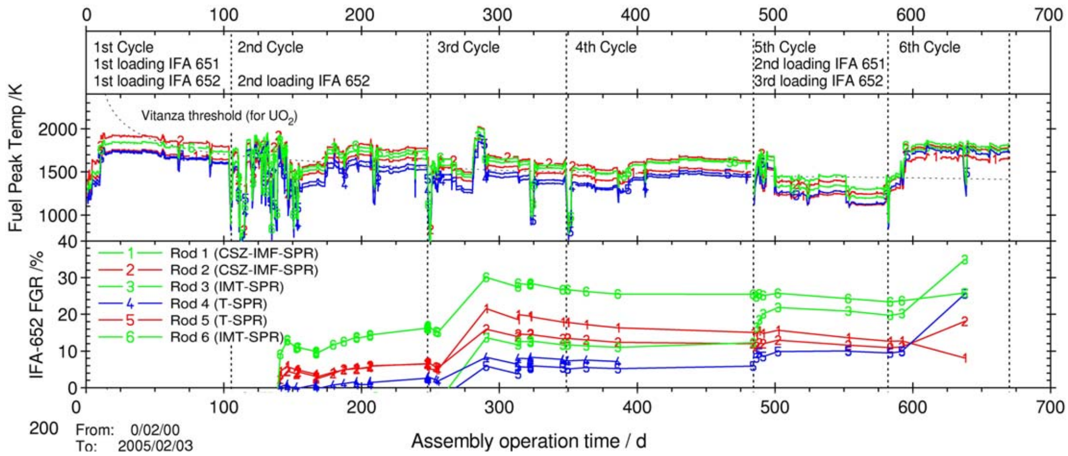

Fig. 4. Fuel peak temperature, normalised rod internal pressure and FGR against burnup of IFA-652.

maximal densification was reached after a burnup of some 60 kW d cm^{-3}. The comparison with the fuel elongation signal indicates that the densification is more distinct in the hot inner part, while the colder shoulders of the dished pellets determining the fuel stack elongation shows less densification.

As the operation temperatures the IM rods show higher fission gas release than the thoria rods. Fig. 4 shows the relative fission gas (FGR) release in % and the measured internal rod pressure in bar, compared to the peak fuel temperature in K as a function of operation time in days.

Till the end of the second cycle rod pressure measurements indicated no appreciable FGR in the thoria rods, but FGR in the range 4–15% for all IM rods. The second uprating to 30–32 kW m^{-1} in June 2002 produced FGR for the IM and the IMT in the range 13–30%, whereas the thoria rods showed releases of 5–8%.

The FGR after the sixth cycle (October 2004) has been estimated as 26% for the remaining thoria rod 5, IMT rod 3 gives the highest FGR of this rig with 36%. IM rod 2 shows a FGR of 18% whereas the pressure measurement of IM rod 1 and IMT rod 6 are unreliable during the last part of the sixth cycle.

All rods showed significant FGR upon crossing the UO_2 derived FGR threshold, also known as Halden threshold [4], indicating that it may be applicable to both thoria and significantly IM fuels. However, caution must be applied since the threshold was rapidly crossed in most instances rather than by a slow stepwise increase in the LHRs. It was also exceeded by a large amount in most cases and therefore it is difficult to exactly ascertain the position of the FGR thresholds for IM.

5. Conclusions

The irradiation experiment is ongoing and currently shows no major problems, except two thermocouples and two pressure transducer have started to show unreliable behaviour towards the later part of the irradiation till now. All rods showed good irradiation stability till today. All IM- and IMT-rods showed higher temperatures compared to the thoria rods, due to lower thermal conductivity. As expected the IM- and IMT-rods released fission gas earlier and in higher amounts than the thoria rods, due to the higher temperatures. From todays dataset, the well known UO_2 threshold for fission gas release might be also applicable to IM fuel, but the release processes for fission gas in IM rods are not clear today. The need of PIE of irradiated IMF material is evident.

The PIE of the discharged thoria rod number 4 is pending. Higher burnup will be accumulated in the future irradiation.

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