First Safety Analyses for an EFIT Type Accelerator Driven Transmuter

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The EFIT development, the European Facility for Industrial Transmutation, aims at a generic conceptual design of a full Accelerator Driven Transmuter (ADT). Within EUROTRANS, the Domain 3 named 'AFTRA', is responsible to a deeper assessment of the behavior of dedicated fuels and to provide the fuel data base for the core design of the EFIT. To test and assess the behavior of the currently chosen CERCER (MgO) and CERMET (Mo) fuels under normal operation and transient conditions, the AFTRA Domain has performed some preliminary core design studies on an EFIT (hereafter called AFTRA-EFIT). Special attention has been devoted to the safety performance of these innovative fuels. In this paper, first safety analyses of 2-zone CERCER and CERMET fuelled AFTRA-EFIT cores are presented. The analyses are performed with the SIMMER-III code, which has been further developed to take into account the specifics of the ADT, as the external neutron source, the new fuels and the heavy metal coolant. Besides the steady state core layout calculations for the AFTRA-EFIT cores, transient calculations are performed for the unprotected loss of flow accident (ULOF) and the unprotected blockage accident (UBA). Based on the analyses, first conclusions on the transient behavior of a typical EFIT type ADT are drawn.

I. INTRODUCTION

Accelerator Driven Systems (ADS), which combine a sub-critical reactor with a high energy proton accelerator via a spallation target, are developed with the goal of efficient incineration/transmutation of Minor Actinides (MAs). So-called 'dedicated' fertile-free oxide fuels, in the form of CERCERs and CERMETs composites, were firstly investigated within the EC FUTURE 5th framework project.[1)] The recommendation of the FUTURE project,[2)] which was re-stated by AFTRA within IP EUROTRANS,[3,4)] was to select the composite CERMET fuel (Pu, Am, Cm)O_{2-x} –Mo (with the isotope ^{92}Mo comprising about 93% of the molybdenum) as the primary candidate for the EFIT design. This CERMET fuel fulfils adopted criteria for fabrication and reprocessing, and provides the best safety margins based on the analyses performed up to now. Disadvantages include the cost for enrichment of ^{92}Mo and a lower specific transmutation rate of minor actinides due to the higher neutron absorption cross-section of the matrix. The composite CERCER fuel (Pu, Am, Cm)O_{2-x} – MgO has therefore been recommended as a backup solution as it is thought to offer a higher consumption rate of minor actinides, and can be manufactured for a lower unit cost. Many other matrices have been investigated during the FUTURE and EUROTRANS-AFTRA studies but discarded because of fabrication, reprocessing, operational and safety reasons.

To test and assess the behavior of the chosen CERCER (MgO) and CERMET (Mo) fuels within FUTURE, an Accelerator Driven Transmuter (ADT) of the 800 MWth power class (ADT-800) has been developed. This ADT-800 core had relatively high fuel power densities, in the range of ~700 MW/m^3 and ~800 MW/m^3 for the CERCER and CERMET fuels respectively. In the IP EUROTRANS the EFIT power level has been chosen in the range of ~ 400MWth. Various design variants of EFIT cores have been developed within the AFTRA domain with the goal to investigate the behavior of the proposed fuels under various transient conditions. The final design of the EFIT including the whole reactor plant is within the responsibility of the DESIGN team (Domain 1) of EUROTRANS. Key core safety related issues were the influence of the power density and the achievement of a flat axial and radial power profile. Both the FUTURE ADT-800 analyses and other investigations[5,6,7)] revealed high coolant and clad temperatures for various transients in case of high power density cores. The concept of variable matrix volume fractions, used in the FUTURE ADT design to flatten the power profiles, has been proven reasonable for EFIT too. For first screening analyses, several design options have been investigated within AFTRA.[8,9] These include single zone cores with a high power density, low power density 2-zone cores, and high/low power density 3-zone cores. As mentioned before, these EFIT CERCER and CERMET fuelled cores are in the 400 MWth ADT class with fuel volumetric powers between 250 – 550 MW/m3.

For a safety classification AFTRA has provided fuel limits related to the different safety categories of the defense in depth concept. To test the safety classification, the fuels have been subjected to various transients under EFIT core conditions. A first set of failure limits for the T91 clad have also been provided by Domain 1.[10] Analyses within the FUTURE project already revealed the sensitivity of the accident scenarios depending on the clad failure behavior.[5,6] In Ref. 7, it is shown that clad failures could lead to the blow-down of fission gases and helium, triggering a core voiding process. With the high power conditions and the large positive void worth of the ADT-800 cores, pin failure propagation is achieved with the potential of a sharp power increase.

The performance of these fuels under transients which could lead to high temperature conditions is of interest. The investigation of design extension condition behavior and the identification of any cliff-edge effects [5] is complex and needs special efforts as fuel data are scarce in the high temperature domain. Therefore, transient analysis of the AFTRA cores have been started to better understand the phenomenology and accident scenarios. The SIMMER-III code [11,12] is used as a main tool for the safety analysis and it has been adapted for the conditions of innovative fuels in a heavy liquid metal cooling environment, including multi-phase flow conditions.

II. TEMPERATURE LIMITATIONS OF FUELS

The safety objectives common to all approaches for nuclear plants, including ADTs, are that all reasonably practicable measures are taken to prevent accidents in nuclear installations, and to mitigate their consequences. This is achieved through the application of the defense-in-depth concept. The demonstration of the adequacy of design with the safety objectives is structured along three kinds of basic conditions: The Design Basis Conditions (DBC – structured in 4 Categories), Design Extension Conditions (DEC - limiting events, complex sequences and severe accidents) and Residual Risk Situations.[13] For innovative reactors such as the ADT cliff-edge effects should be identified and excluded.[14]

The fuel limits under the various accident categories have been specified in Table 1 for fuels at the beginning of life (BOL).[15] Due to the existing uncertainties, fuel ‘melting’ should only be allowed in the DEC category. The safety relevant peak temperature limit is given by the temperature of the individual component which first achieves ‘melting’. The in-pile experiments planned within AFTRA, FUTURIX (Phenix)[16] , will provide information on the irradiation behavior of CERCER and CERMET fuels. Information on He release will be provided by the HELIOS [17] and BODEX [18] experiments. As this information will become available only towards the end of the AFTRA project, the current temperature limitations are recommended for EUROTRANS, while further updated temperature limits will have to be provided in the future. Besides the fuel limits, clad limits are of major concern. Clad creep induced fuel pin failures for T91 were given in Ref. 10 at expected EFIT plenum pressures in a short time range with around 1100 K.

The values given in Table 1 should be regarded as working hypothesis. To substantiate the limits, fuel performance and transient calculations have to be performed. The fuel performance codes could provide the fuel temperature, gas pressure, clad strain development dimensional changes and loadings on fuel and cladding, given the design and irradiation history. Power to melt, stored energy, gas pressures etc. must be evaluated providing also the initial conditions of the transient calculations. Safety analyses for the CERCER and the CERMET core show that especially for unprotected transients as the ULOF or UBA the clad limits are the dominating issue.

Table 1 Categorization of Fuel Limiting Temperatures (BOL fuel)

			MgO-CERCER	Mo-CERMET
"Melting" temperature		Matrix	2150 K*	2896 K
		Fuel	2450 K	2450 K
DBC	Category I	No melting/disintegration	1750 K	2300 K
	Category II	No melting/disintegration	1850 K	2350 K
	Category III	No melting/disintegration	1950 K	2400 K
	Category IV	No ‘melting’ for CERCER & CERMET fuels	1950 K	2400 K
DEC		Limited up to extended ‘melting’	2150 K	2450 K

* Matrix evaporation limit

III. AFTRA 2-ZONE DESIGN DATA AND STEADY STATE ANALYSIS

III.A. 2-ZONE Design Data

In the framework of EUROTRANS, the AFTRA Domain developed various proposals for EFIT single-zone, two-zone and three-zone cores. This work was in support of the EUROTRANS DESIGN group which is responsible for the development of the XT-ADS and EFIT overall designs. The design studies for AFTRA were mainly performed by Serco Assurance (UK) and SCK·CEN (Belgium) and KTH (Sweden). Important design parameters for optimization are a high transmutation efficiency, a low reactivity swing during burn-up, a low beam current requirement, a flat power distribution, low linear rating, keeping the necessary matrix/TRU ratio, respecting fuel and clad safety limits, a low core pressure drop, a limitation of the coolant flow velocity and small temperature differences across the subassembly rings. In addition, the void worth of the core should not become too large in comparison with the subcriticality level. The accelerator delivers a proton-beam energy of 600 MeV and a beam current up to 20 mA. According to the analysis on the single zone cores, which have been reported in Ref. 19, multiple zone cores are required for obtaining reasonable operational and safety parameters. Besides, an important limiting parameter for the fuel is the matrix volume fraction in the composite fuels, which should not fall below 50%. The minor actinide vector of the fuel is typical for MOX fuel reprocessed 30 years after irradiation. Neutronic calculations have been mainly performed with the ERANOS code system.[20)] with a confirmation calculation by SIMMER-III. In order to best flatten the flux and power profiles both a 'variable pin diameter technique' and a 'variable matrix technique' have been followed. Both techniques lead to an increase in the fuel (TRU) volume fraction in the radial direction so that the fluxes in the outer core zones are similar to the inner zones. Each technique has advantages and disadvantages (fabrication, cost, flux profiles etc.). Currently the 'variable matrix technique' is favored in AFTRA, because with the alternative method (increasing the pin size and reducing the coolant volume fraction) the maximum allowable linear rating is reached before achieving the optimal power profile.

Table 2 to 4 presents the fuel pin, fuel assembly and neutronics parameters of two-zone AFTRA low power density core designs while more detail design data of the core geometries are given in Ref. 21. The main safety parameters of the core, the void worth and the Doppler constants are shown in Table 4, as we can see that the Doppler effect is insignificant while the positive void worth values are higher than the subcriticality level of K-eff = 0.97 for both MgO-CERCER and Mo-CERMET cores. Fortunately, these values are still compatible with the safety indicator developed in Ref. 22, which relates the magnitude of the void worth to the subcriticality margin.

Table 2 Fuel Pin Parameters of the 2-Zone Core

Fuel Pin Dimensions	MgO-CERCER	Mo-CERMET
Pellet diameter (mm)	7.20	8.98
Pellet height (mm)	10.0	10.0
Radial Gap (micron)	160.0	160.0
Clad inner diameter (mm)	7.52	9.30
Clad thickness (mm)	0.600	0.600
Clad Outer diameter (mm)	8.72	10.50
Fuel column height (mm)	900	900
Gas plenum length (mm)	274 + 854	274 + 854
Caps (mm)	20 + 40	20 + 40
Fuel pin length (mm)	2100	2100

Table 3 Fuel Assembly Parameters of the 2-Zone Core

Fuel Assembly Dimensions (hexagonal)	MgO-CERCER	Mo-CERMET
Fuel pin pitch (mm)	13.63	13.48
P/D ratio	1.5634	1.2845
Number of fuel pins per assembly	168 (+ 1 central steel pin of 12 mm diameter)	168 (+ 1 central steel pin of 12 mm diameter)
Wrapper inner width (mm)	178.0	178.0
Wrapper wall thickness (mm)	4.0	4.0
Distance between neighbor assemblies (mm)	5.0	5.0
Assembly pitch (mm)	191.0	191.0
Fuel pin bundle length (mm)	2100.0	2100.0
Assembly total length (mm)	4080.0	4080.0
Target assemblies	19	19
Total fuel assemblies	252	180

Table 4 Neutronic Parameters of 2-Zone Core

Parameters	MgO-CERCER	Mo-CERMET
Nom. Thermal power (MW)	400	400
Matrix to TRU ratio	62.5/37.5, 50/50	70/30, 53/47
Pu to MA ratio	49.8/50.2	39/61
Core average linear rating (W/cm)	104	145
Peak power (pin) (W/cm)	161	210
Peak power (Pellet) (W/cm)	190	250
Radial form factor	1.55	1.45
Axial form factor	1.18	1.19
K-effective, Start of life	0.97	0.97
Void worth: Core (pcm)	8732	6161
Fuel Doppler coefficient (pcm/K)	2.3E-04	1.1E-04
Delayed neutron fraction	190	179
Prompt neutron lifetime (s)	5.74374E-07	3.19891E-07

III.B. Steady-State Analysis

For SIMMER-III simulations, the total fuel assemblies have been meshed into 7 fuel rings in the MgO-CERCER core and 6 fuel rings in the Mo-CERMET core in the radial direction of the cylindrical geometry.

The steady-state results of the thermal hydraulic performance (at BOL), in terms of coolant, clad and fuel temperatures, are given below in Figs. 1 and 2 for the core loaded with the MgO matrix CERCER and in Figs. 3 to 4 for the core loaded with the Mo matrix CERMET. Figs. 1 and 3 show the temperature distributions in the axial direction along the first fuel ring. Figs. 2 and 4 show the radial temperatures at the mid-plane of the active core. Because of the radial flatten of flux and power of the core, the second fuel ring shows a lower temperature than that of the third fuel ring in Fig. 2 and 4.

It can be seen that the current design can assure that the average coolant outlet temperature arrives at 753 K from its inlet value of 673 K while the fuel pin and clad temperatures for both the MgO and Mo matrix fuel satisfy the design limiting criteria for the AFTRA-EFIT core.[21,23)] Meanwhile, roughly comparing Fig. 1 and 3 or Fig. 2 and 4, we can see that the Mo-CERMET core has a lower fuel operating temperature than the MgO-CERCER core. Together with the higher temperature limitations of Mo-CERMET fuel shown in Table 1, it is clear that the Mo-CERMET has larger safety margin than MgO- CERCER

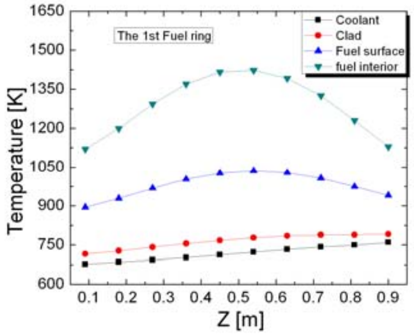

Fig. 1 Axial temperature distribution (CERCER)

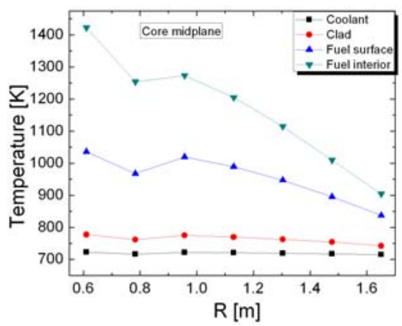

Fig. 2 Radial temperature distribution (CERCER)

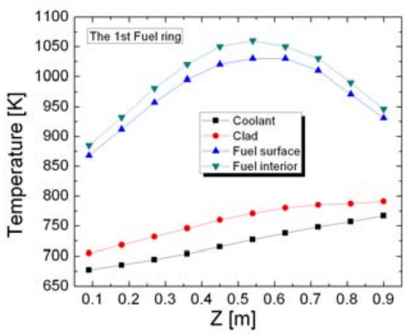

Fig. 3 Axial temperature distribution (CERMET)

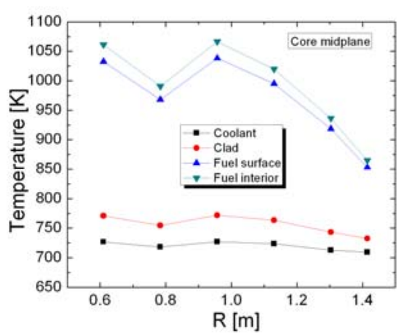

Fig. 4 Radial temperature distribution (CERMET)

fuel with the current core design. This is because of the high thermal conductivity of Mo matrix. Figs. 5 and 6

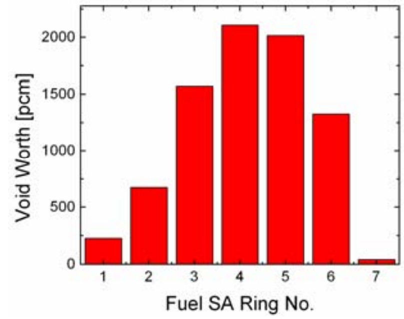

Fig. 5 Void worth per fuel ring (CERCER)

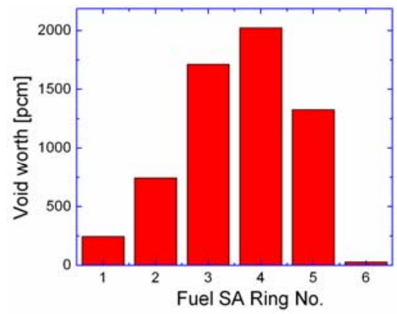

Fig. 6 Void worth per fuel ring (CERMET)

show the void worth of each fuel ring assuming that each of them are separately voided.

IV. TRANSIENT ANALYSIS

For assessing the safety behavior of the different core designs, two typical transients have been selected and analyzed with the SIMMER-III code. One is unprotected loss of flow (ULOF) and the other is unprotected blockage accident (UBA).

After pump coasting, an ULOF happens, the coolant flow mechanism transfers from forced convection to natural convection. A good core design should assure that the remained coolant nature convection can sufficiently remove the produced heat from the active core and, in turn, limit the temperatures under a certain level in order to help the core to survive from any serious damage and give enough time for the operating staff to response to this accident.

UBA is considered here because a blockage potential might exist due to the use of grid-spacers and the HLM technology with oxygen control proposed in current AFTRA domain DM3 and DESIGN domain DM1.

IV.A. ULOF

The ULOF, as a typical transient, is of interests because of the sensitivity of the clad and coolant temperatures. Clad failure could then trigger a global gas release from the plena. Massive voiding could then effectively drive a pin-failure-propagation.

Figs. 7 and 9 show the power and reactivity transients during an ULOF for MgO-CERCER and Mo-CERMET core, respectively. Figs. 8 and 10 show the temperature transients at the core location which has the highest coolant, clad, and fuel temperature, respectively. The coolant flow rates in the two kinds of cores are also shown in Figs. 8 and 10, respectively. These figures indicate that the failure limitations of the clad and fuel temperature are respected because of the remained high coolant flow rate due to the nature convection. Therefore, with the current design, the core can survive an ULOF. Again, the Mo-CERMET core show larger safety margin concerning the temperature limitations.

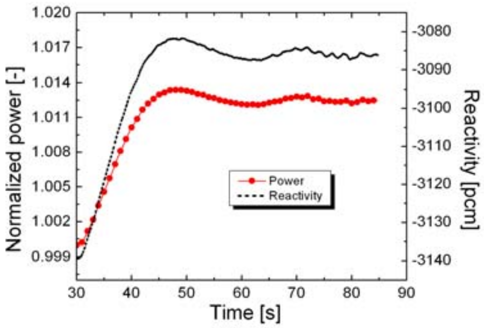

Fig. 7 Power and reactivity transients (CERCER)

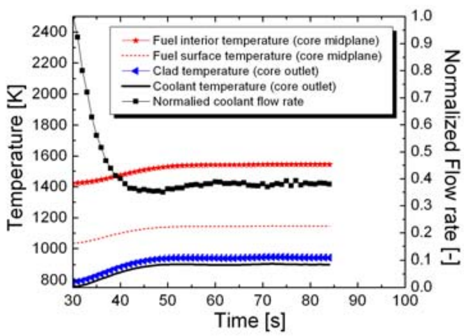

Fig. 8 Temperature and Pb flow rate transients (CERCER)

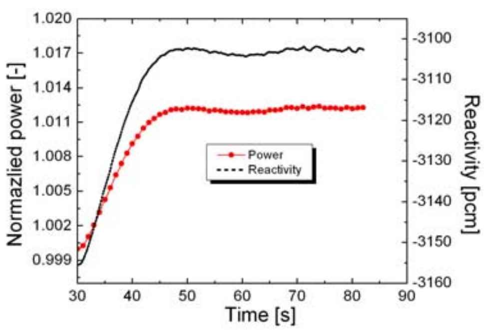

Fig. 9 Power and reactivity transients (CERMET)

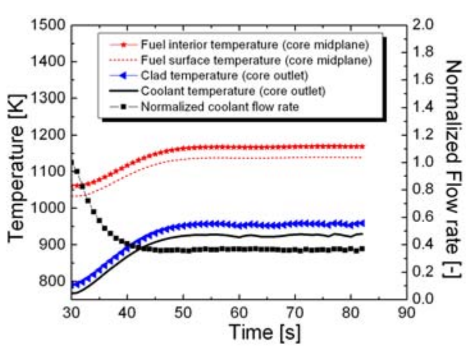

Fig. 10 Temperature and Pb flow rate transient (CERMET)

IV.B. UBA

For the blockage accidents, in case of pin failures, the release of helium, which may cause voiding and a reactivity increase and swing, could be a concern in an ADT, as no limiting Doppler effect is available during a transient. Analyses have however shown the mitigating potential of a fuel sweep-out effect.

In SIMMER-III simulations, the following assumptions are defined. The blockage location in both MgO-CERCER and Mo-CERMET cores are chosen at the core inlet of the first fuel ring and the coolant mass flow rate reduce to 6.5% in the blocked channel. The clad will first fail at 1120 K (see Ref. 10) which causes a gas blowout but the fuel is still covered by the clad and clad removal is assumed to occur at around 1700 K, the clad melting temperature. The fuel then is assumed to break up into fuel chunks with a particle diameter of 1 mm. Hexagonal wrapper (called Can-wall in SIMMER-III) temperatures are also in the range close to melting in the current simulation.

With the current assumptions, both cores show a similar behavior during UBA. Figs. 11 and 12 show the power, reactivity and temperature transients during an UBA in the MgO-CERCER core while Figs. 14 and 15 show that in the Mo-CERMET core. As shown in Fig. 12 and Fig. 15 the gas blow-down takes place when the clad temperature arrives at 1120 K which causes a positive void effect and, in turn, a power and reactivity increase. Fortunately, the positive void does not induce a very significant reactivity/power increase. And hereafter with the fuel pin failure, broken fuel particles can be swept out from the blocked fuel ring, as shown in Fig. 13, which

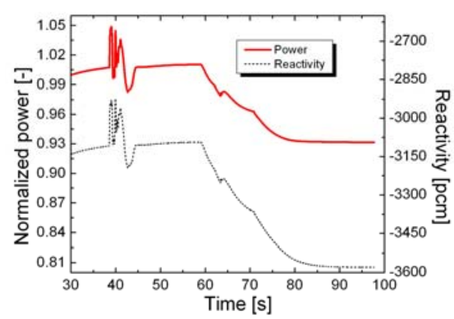

Fig. 11 Power and reactivity transients in an UBA (CERCER)

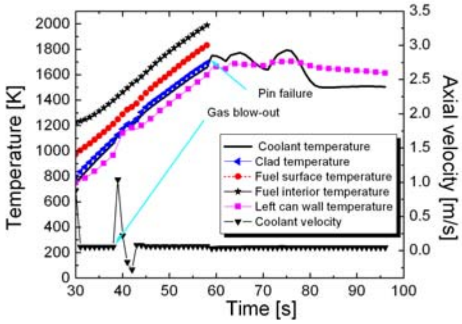

Fig. 12 Temperature development in an UBA (CERCER)

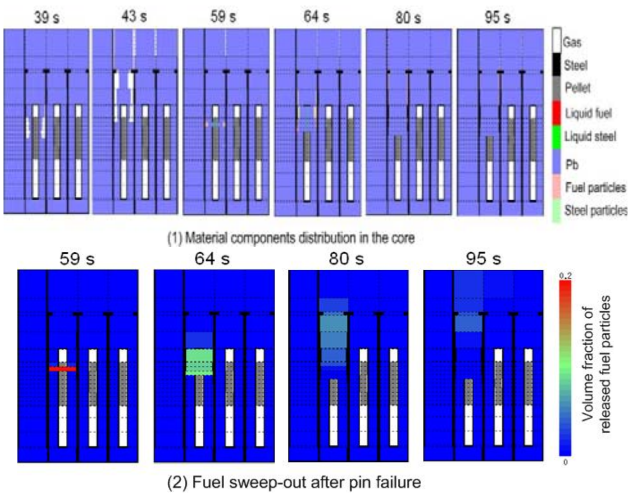

Fig. 13 Material distribution and released fuel particle distribution in the first three fuel rings (CERCER)

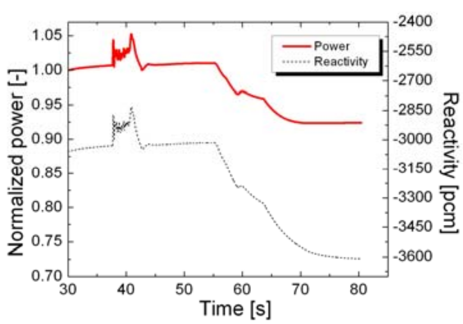

Fig. 14 Power and reactivity transients in an UBA (CERMET)

finally decrease the power and reactivity. The decrease of power is limited in a source driven system but helps to allow for a longer grace time to shut down the beam before a damage-propagation might commence.

The influence of the failure temperatures of the cladding (failure temperature for gas blow-down and temperature for release of fuel pellets or chunks from pellet stack), the behavior of the pellets and the influence of the upper pin and bundle structures have been analyzed and a good understanding of the possible phenomena and

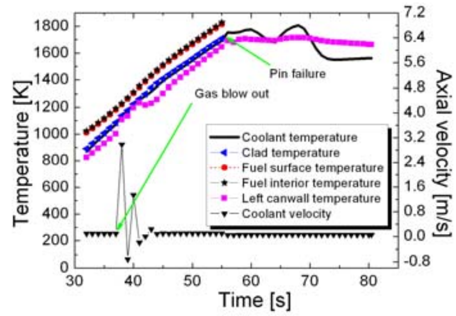

Fig. 15 Temperature development in an UBA (CERMET)

scenario routes has been obtained. The sensitive points could be identified and some important issues of the sensitivity analysis are presented in the next section.

V. SENSITIVITY ANALYSIS OF UBA

In the above section, for SIMMER-III simulations, gaps between each fuel assembly are considered together with the corresponding fuel ring. For a sensitive analysis, coolant flow in these gaps is simulated separately from the fuel rings. With the same assumptions, based on the Mo-CERMET core, UBA is analyzed again with the geometry having those separated gap flows. In Figs. 16 and 17, the one labeled with "R=0.5mm, Tclad-removal=1700K" is the corresponding transient results. We can see that in the simulations with separated gap channels, the pin failure happens several seconds later than in the simulation without the separated gap channels. This is because, with the separated gap channels, SIMMER-III can simulate the radial heat transfer better than simulations without the separated gap channels. The designed coolant mass flow rate in these gaps is very small so that the assumed SIMMER-III simulation geometry used in the above sections is adequate.

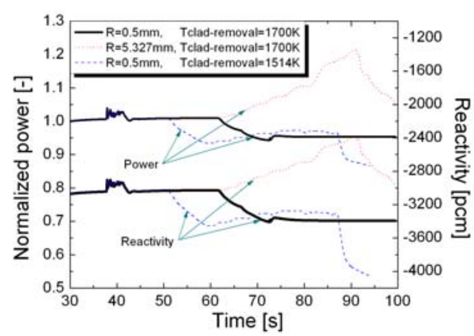

Fig. 16 Power and reactivity transients in different UBA cases (CERMET)

Further parametric analyses have been performed based on the SIMMER-III geometry with the gap channels. The new-born fuel particle size and the clad

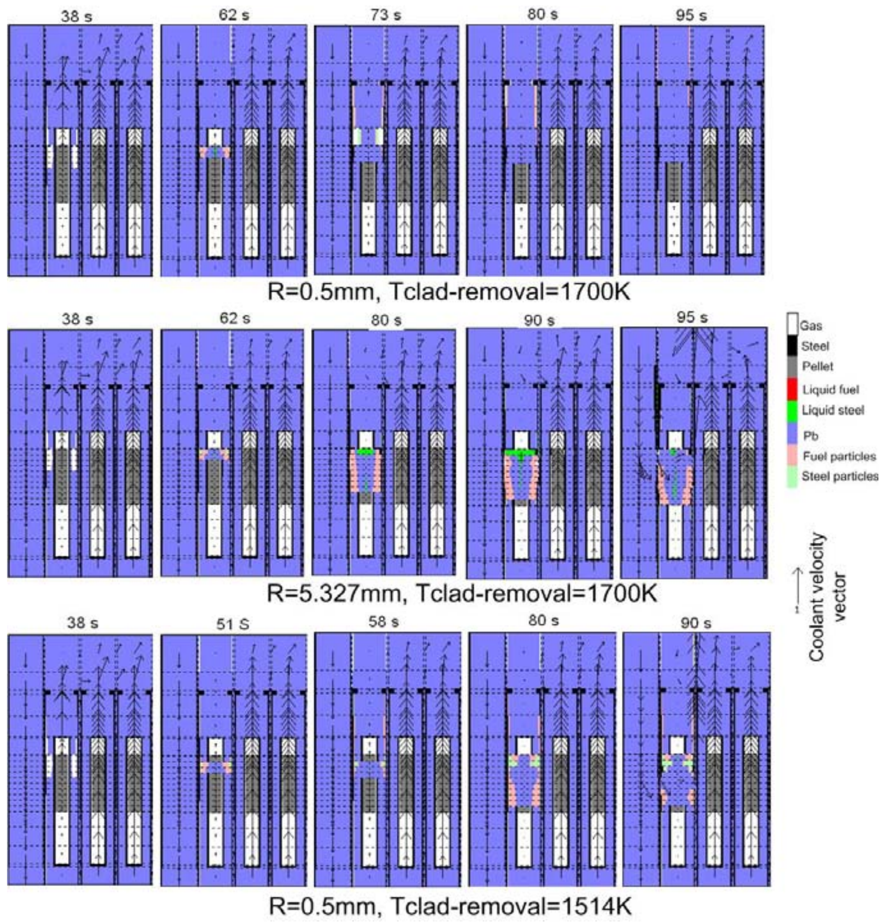

Fig. 17 Material distribution in the first three fuel rings in different UBA cases (CERMET)

removal temperature, by which the clad melted or broken into solid particles and thereafter the fuel pellet break into fuel particles, are chosen as the parameters to be analyzed, because so far the fuel/clad behavior at high temperature is experimentally unclear.

The new-born fuel particles are assumed having a very fine size of 0.5 mm radius as in the above sections as well as a size of 5.327 mm radius which volumetrically equals to a fuel pellet. The clad is assumed to be removed around its melting point or has no more strength to confine the pellet stack at a lower temperature as 1514 K. Figs. 16 and 17 show the comparisons of the transient results between cases with these different assumptions.

As we can see from the two figures that when the clad removal temperature is fixed, after the pin failure, the power and reactivity increases to around 20% higher than its operating value and then drops sharply. This is because after the pin failure, with much larger fuel particles volumetrically as fuel pellets, the fuel sweep-out from the blocked channel becomes more difficult as shown in Fig. 17. Finally, a failure-propagation is initiated, the wrapper of fuel assemblies melts so that the fuel escapes from the blocked channel to the target unit or its neighboring gap channel. If the fuel particle size is fixed while the pin fails at 1514 K, similar phenomena happen inside the blocked fuel ring because with lower failure limits, there are much more fuel particles born, which also causes the fuel sweep-out become difficult. Since the clad will lose its strength probably far before its melting point, the clad is more likely to remove at 1514 K with an equivalent radius up to 5.327 mm. It is clear that the new-born fuel particle size and the clad removal temperature have significant influence on the inherent fuel sweep-out mechanism. Therefore, the clad and fuel behavior at the high temperature range should be experimentally understood.

VI. CONCLUSIONS

A preliminary safety analysis for an AFTRA-EFIT type ADT with 2-zone MgO-CERCER and Mo92-CERMET cores has been performed. Both cores can survive a ULOF because of the remained high coolant flow rate. The Mo92-CERMET has a larger safety margin. For the UBA, with an assumption of small new-born fuel particles and high pin failure temperatures, a serious damage in the core and failure propagation has not been identified in both cores because of the inherent fuel sweep-out mechanism. However, this fuel sweep-out mechanism is subjected to the fuel particle size and also the clad removal temperature. Therefore, it is of necessity to experimentally understand the clad and fuel behavior at the high temperature range.

Since the fuel enrichment in the 2-zone designs slightly differs from that in the so-called "42-0" strategic design, [23] which is the preferred approach, 3-zone cores for both MgO-CERCER and Mo92-CERMET fuels which satisfies the "42-0" strategy will be designed by AFTRA, and in turn, the safety tests of the fuels based on the new designs will also be performed in the near future.

ACKNOWLEDGMENTS

The authors appreciate the efforts and support of all the scientists and institutions involved in IP EUROTRANS, as well as the financial support of the European Commission through the contract FI6W-CT-2004-516520.

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