DESIGN, SAFETY AND FUEL DEVELOPMENTS FOR THE EFIT ACCELERATOR DRIVEN SYSTEM WITH CERCER AND CERMET CORES

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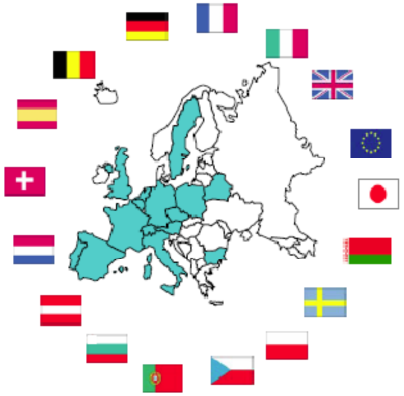
Content

I : Introduction

- EFIT, the European Facility for Industrial Transmutation developed within 6th FP EU EUROTRANS
- The Domain DM1 (DESIGN) responsible for overall design, integration and safety of EFIT
- The Domain DM3 (AFTRA) responsible for the fuel assessment and development
- AFTRA also involved in core design activities and safety studies for assessing individual fuels and provide recommendation on fuels

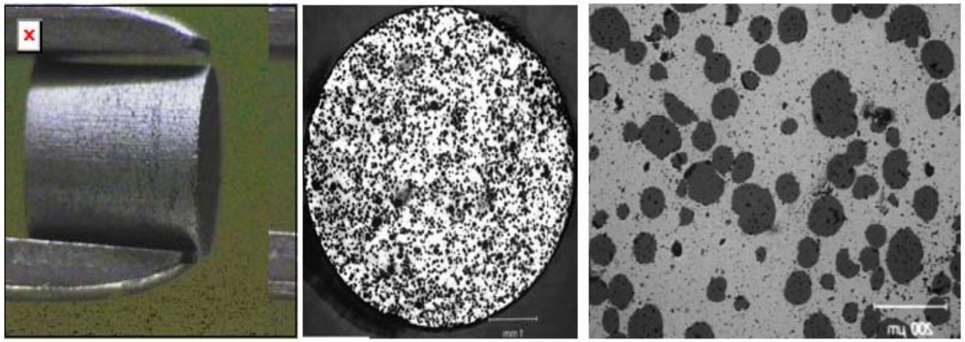


- Both CERCER and CERMET EFIT cores have been developed
- The CERCER core has been chosen as the reference core by DM1 and most extensive investigations on design and safety concentrate on this core
- The CERMET core has alternatively be developed by AFTRA

II : Fuels for Accelerator Driven Transmuters

Selection Criteria:

- Oxide fuels because of vast European experience
- Fabrication
- Feasibility: matrix volume fraction > 50%
- Clad and coolant compatibility
- Safety behavior
- Coolant void worth
- Reactivity loss
- Burnup
- Transmutation capability
- Reprocessing (aqueous)
- ………



Visual aspect and microstructure of a $Pu_{0.23}Am_{0.25}Zr_{0.52}O_2$ Mo 60 vol% pellet

- Solid Solution Fuel
  - $(Pu,Am,Cm,Zr)O_{2-x}$ or $(Pu,Am,Cm,Th)O_{2-x}$
- CERMET
  - $(Pu,Am,Cm)O_{2-x}$ + Mo, Mo^{92}, W, Cr or V
- CERCER
  - $(Pu,Am,Cm)O_{2-x}$ + MgO

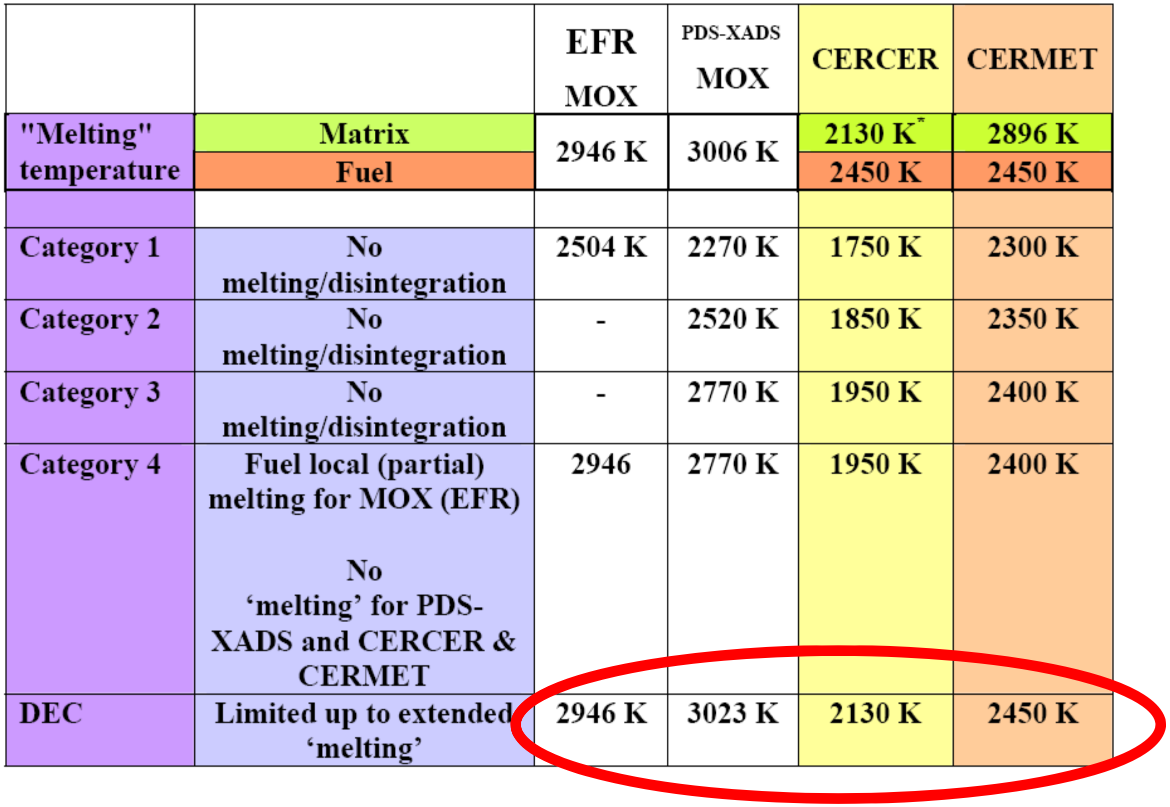
Final AFTRA Recommendation :

1) Mo-92 CERMET because of superior safety behaviour
2) Backup solution : MgO CERCER because of better neutronic performance

Safety Issues and Fuel Limiting Temperatures

Defence-in-Depth Categorization of Plant Conditions :

- Requirement of ‚no melting‘ up to DBC Category 4 (restrictive limit taken because of uncertainties)
- Main reason for AFTRA recommendation for CERMET motivated by safety concerns in the light of limited data and phenomenological uncertainties in high temperature region (‚melting‘ as composite disintegration, eutectic formation,…. at much lower temperatures than MOX)



		EFR MOX	PDS-XADS MOX	CERCER	CERMET
"Melting" temperature	Matrix	2946 K	3006 K	2130 K*	2896 K
	Fuel			2450 K	2450 K
Category 1	No melting/disintegration	2504 K	2270 K	1750 K	2300 K
Category 2	No melting/disintegration	-	2520 K	1850 K	2350 K
Category 3	No melting/disintegration	-	2770 K	1950 K	2400 K
Category 4	Fuel local (partial) melting for MOX (EFR) No ‘melting’ for PDS-XADS and CERCER & CERMET	2946	2770 K	1950 K	2400 K
DEC	Limited up to extended ‘melting’	2946 K	3023 K	2130 K	2450 K

- Matrix evaporation limit

Categorization of Fuel Limiting Temperatures (BOL Fuel)

Specific CERCER Related Problems

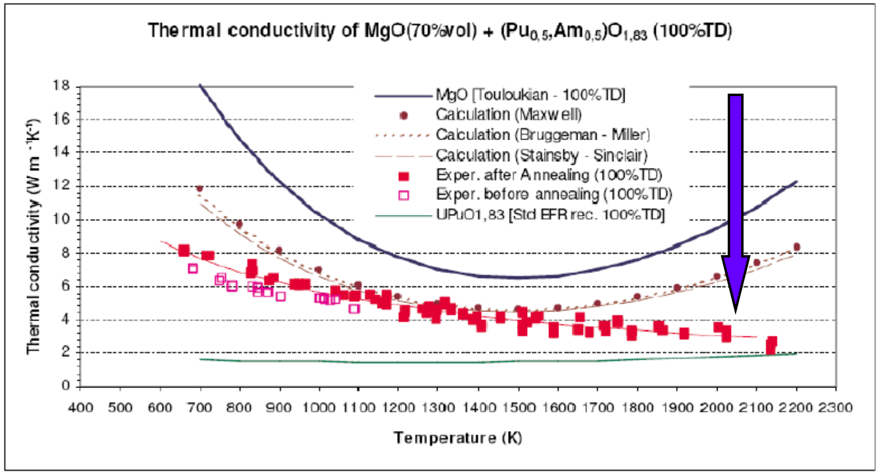
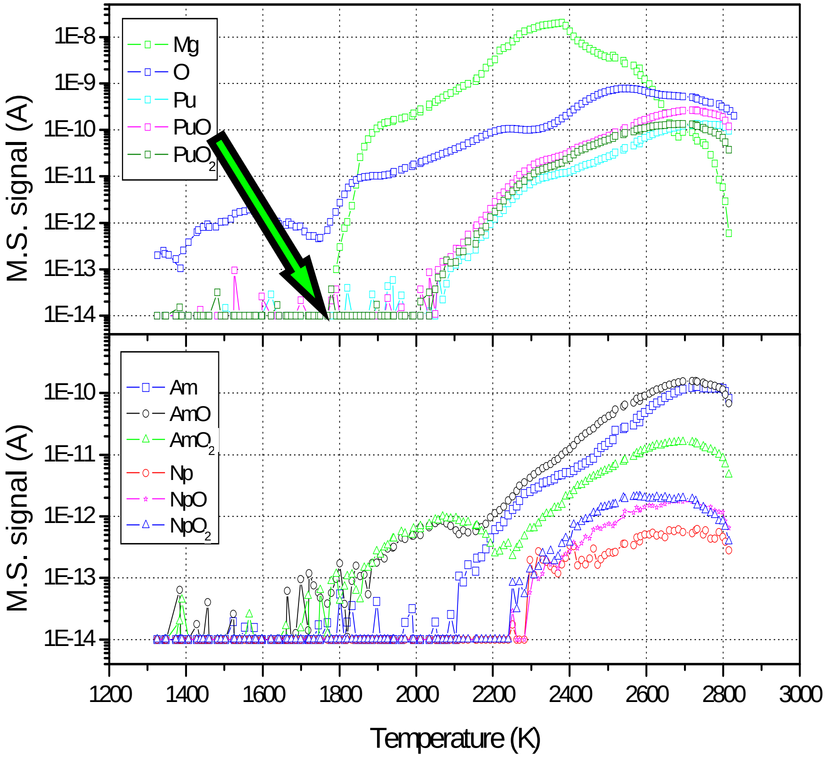


Fig. II.2 Temperature dependence of theoretical conductivity of fuel from batch n°1. Comparison with MgO and calculated values /1/



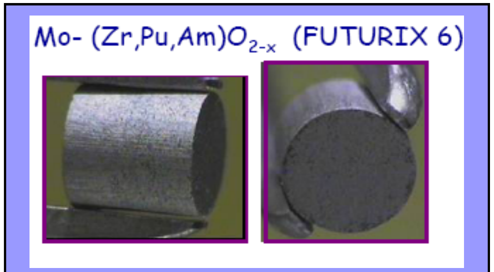
- MgO shows a significant decrease in the thermal conductivities at higher temperatures (1500 K) – CEA measurement
- Irradiation leads to further deterioration

- MgO shows tendency for disintegration at higher temperatures - Knudsen cell tests ITU
- Safety behavior under un-clad conditions not known
- Potential for fuel/matrix separation

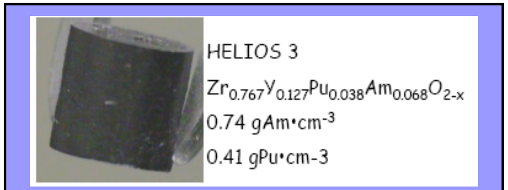
Fuel Irradiation Experiments in Phenix & HFR Reactors

EUROTRANS Experiments : FUTURIX-FTA , HELIOS and BODEX

- **Demonstration of the fabrication feasibility**
- **Determination of material properties**
- **FUTURIX- FTA : Irradiation behaviour in fast neutron environment for oxide, nitride, metallic fuels – for EUROTRANS only CERMET (Phenix)**
- **HELIOS : Helium release mechanisms & swelling in MA fuels (HFR)**
- **BODEX : Helium build-up and release mechanisms on inert matrices**
- **Problem : Results of experiments expected at end of EUROTRANS**



FUTURIX 6 CERMET Pellet

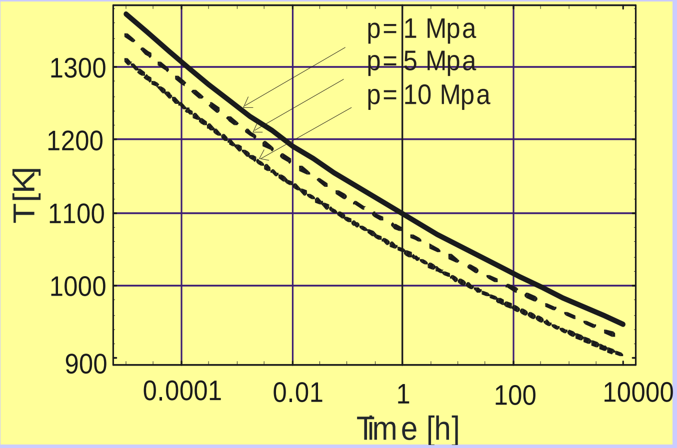


HELIOS 3 Pellet

BODEX Pellet

Further Safety Related Boundary Conditions given by Clad and Pb Coolant

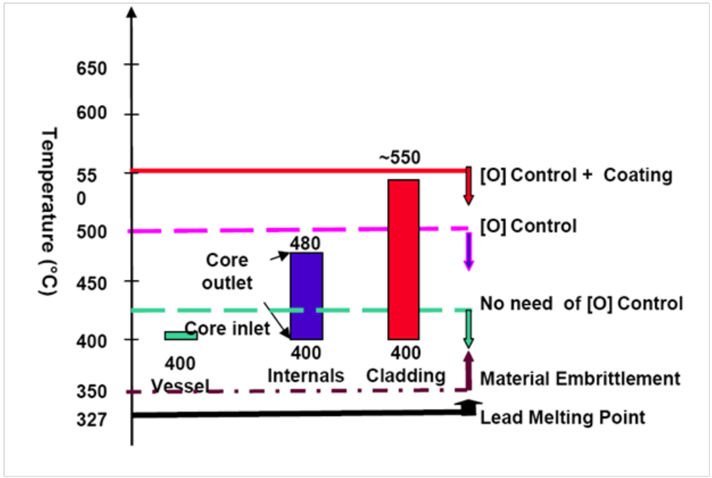
T91 Clad

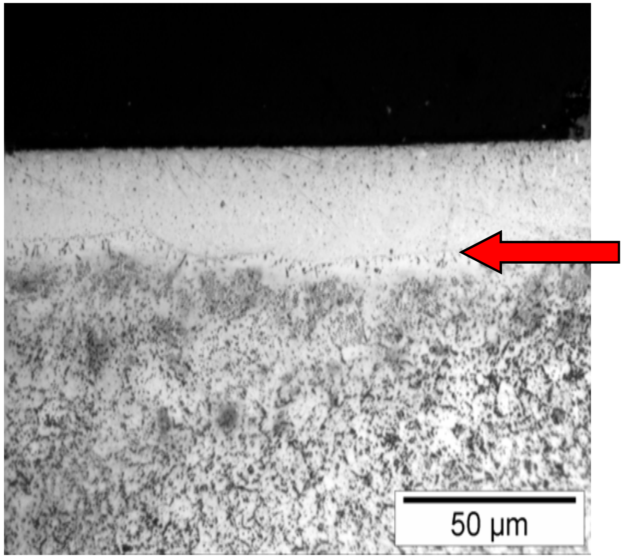


T91 cladding temperature versus time to failure by creep rupture

- **Derivation of failure data based on LMP**
- **Uncertainties in LMP for fast transients**
- **Uncertainties under HLM conditions and irradiation**
- **Other failure modes not investigated**

Lead Coolant

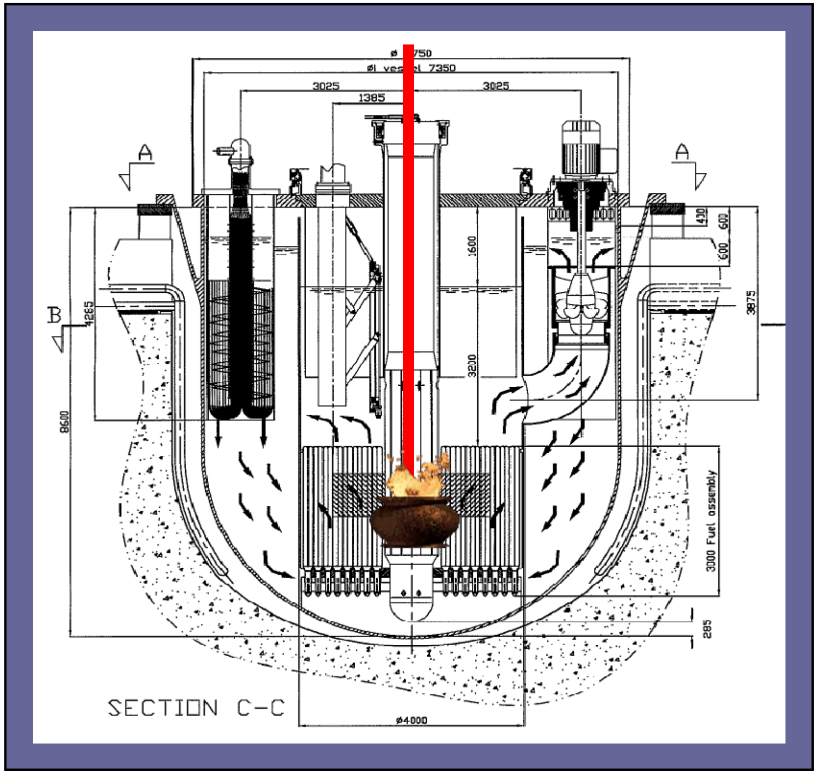


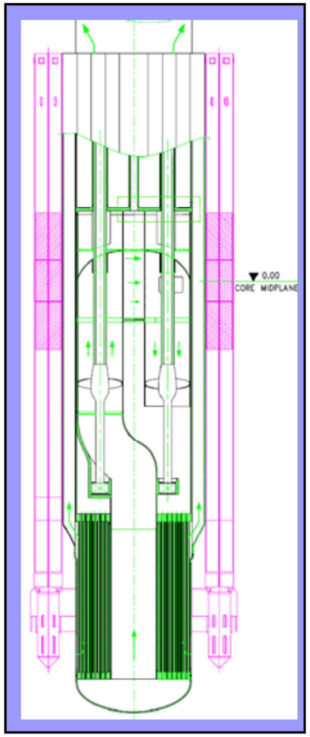


EFIT :

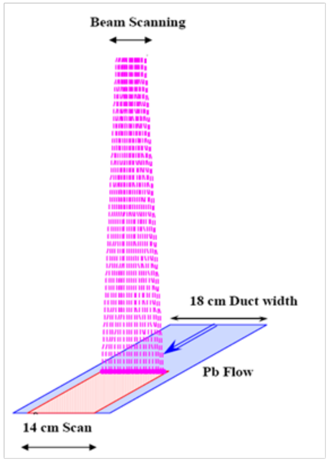
- **GESA treated clad without conductivity reducing oxide layers**
- **Use of optimized clad for EFIT design**

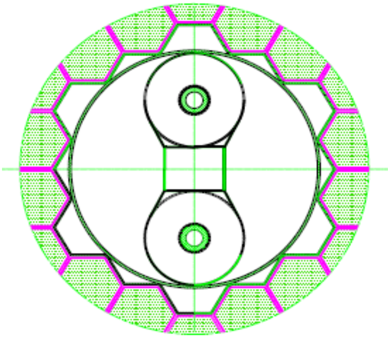
III : The EFIT (European Facility for Industrial Transmutation)





- Power = 400 MWth
- Beam : 800 MeV, 20 mA
- Keff = 0.97
- Pool type reactor with hot leg pump
- No intermediate loop
- Pb coolant
- T-in / T-out = 673/753 K
- Fuel : CERCER & CERMET
- Clad = T91





- Target Unit Type:
  - Windowless with Mechanical Pumps
  - Heat Sink below Free Level
- Proton Beam:
  - 800 MeV; 20 mA
  - Proton Travel Depth in Lead about 43 cm
- Deposited Power and Irradiation Damage:
  - 70% Proton Beam Power (11.2 MW)
  - Max dpa 100 to 130
- Max Coolant Velocity:
  - About 1 m/s (except around the pump) impeller)
- Low Pressure Losses
  - About 50÷60 kPa
- Temperature:
  - Primary Coolant Inlet 673 K
  - Max Average Target Coolant 793 K

The CERCER EFIT Transmutation Concept

The 42 : 0 Concept

Fission Rate ≅ 42 kg/TWth →

-42 kg (MA) / TWh

0 kg (Pu) / TWh

E = Pu /(MA + Pu)
MA: (Np, Am, Cm)

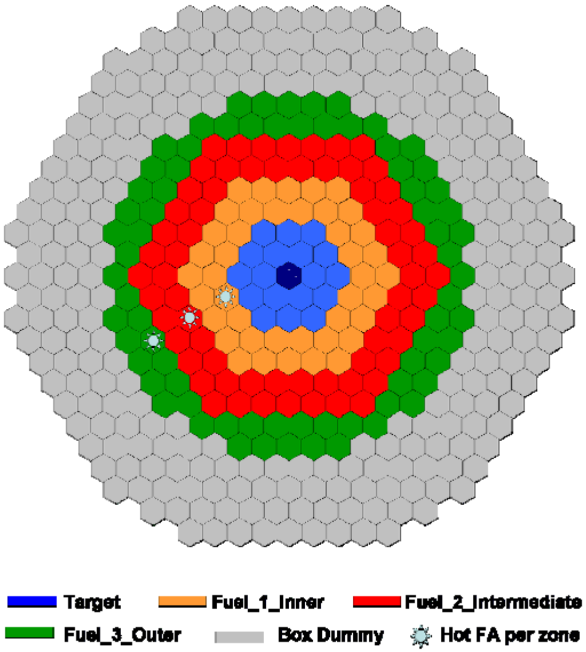
f (fuel E = 45,7%)

EFIT designed as a MA burner

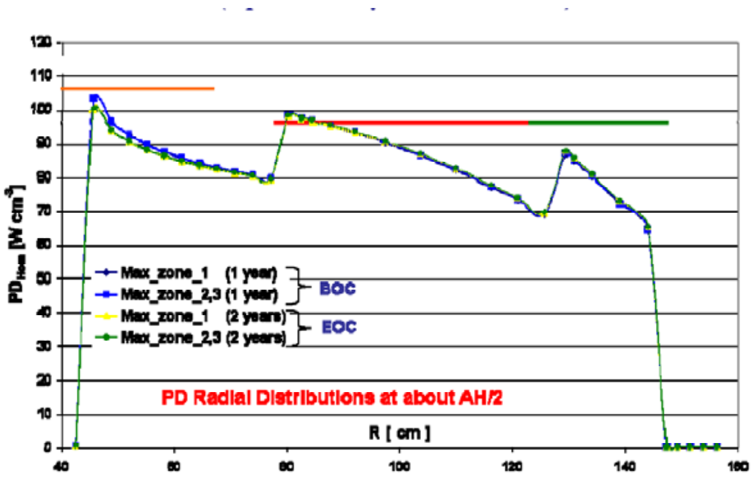
Boundary Conditions for CERCER Core :

- 3 core zones for power flattening
- Matrix ratio : 57 : 50 : 50 % / → Max lin. pow. ≅ 200 : 180 : 180 W/cm
- Max. fuel operating temperature 1650 K
- Max clad operating temperature 823 K
- Lead coolant (velocity ~ 1 m/s; T_{in} = 673 K; T_{out} = 753 K)
- Residence time 3 years → Pb corrosion could define limit → GESA treatment !!!
- Limited reactivity loss over 3 years (constant beam power requirement)

The CERCER EFIT Operational and Safety Data



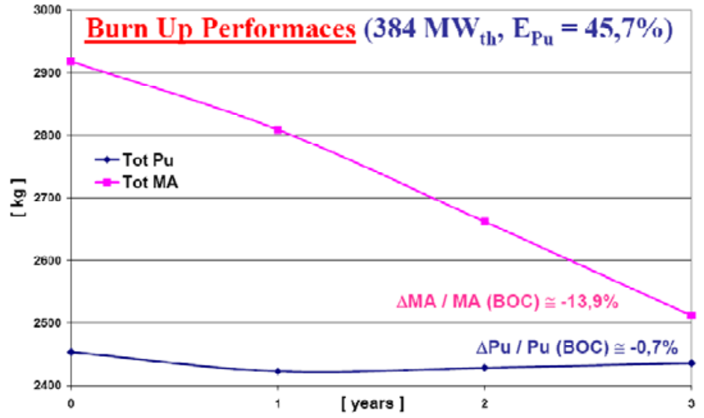
EFIT MgO CERCER Core



Power Profile

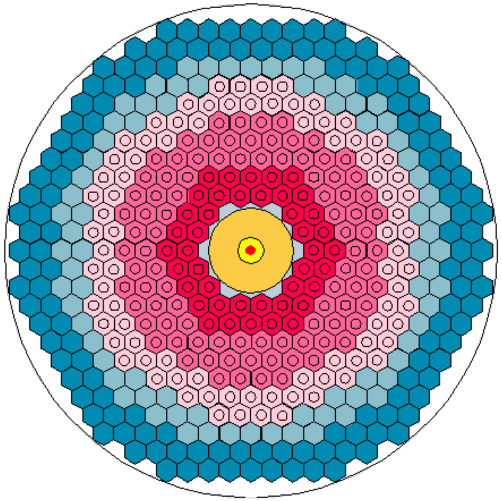
Subcriticality	Void Worth	Doppler constant	Beta-eff	Neutron generation time
3000 pcm	6600 pcm	23 pcm	150 pcm	$8.80 * 10^{-7}$

Safety Coefficients



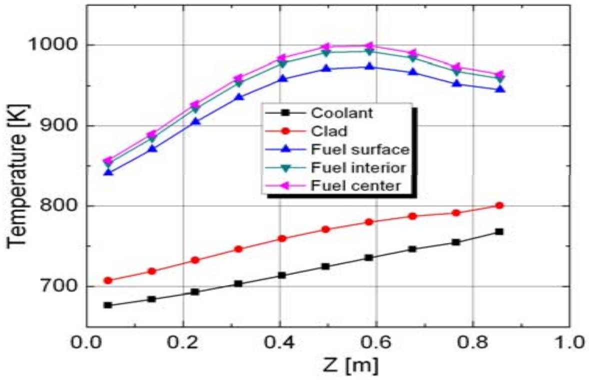
Transmutation Efficiency

The CERMET EFIT Transmutation Concept



EFIT Mo CERMET Core

Mo-92 Basis (Enrichment !)



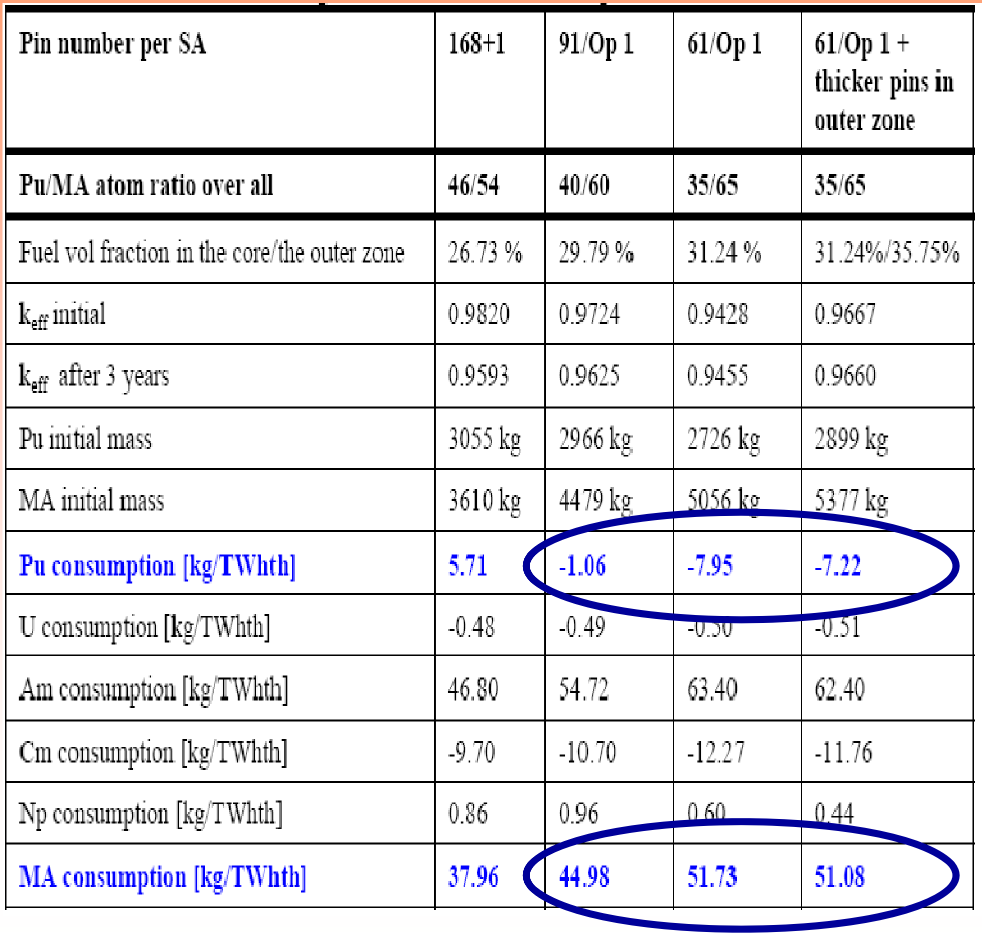
Axial fuel, clad and coolant temperatures in peak power subassembly

AFTRA Mo-92 CERMET Core :

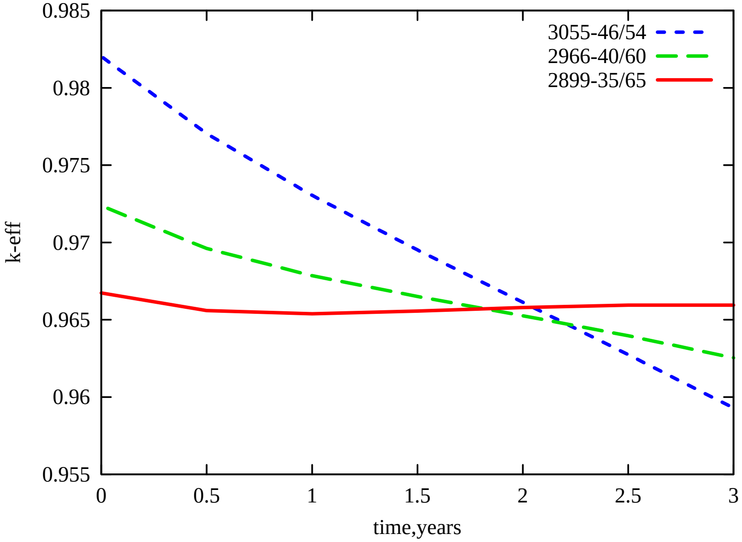
- CERMET core fits into overall design of EFIT given by ANSALDO & ENEA (CERCER EFIT)
- Due to less favourable neutronic characteristics of Mo-92 (higher n-absorption) Pu/MA ratio has to be increased if same design parameters (pin, fuel/matrix volume fractions, subcriticalty) are taken as in CERCER core
- High Pu/MA ratio leads to less MA incineration & stronger reactivity loss
- Solution to achieve low Pu/MA : increase of fuel volume ratio via thicker pins respecting thermal-hydraulic and clad conditions
- ‚Fat‘ pins no problem for CERMET because of high thermal conductivity – safety assured
- High MA incineration achieved but 42:0 strategy slightly violated
- Low reactivity swing over burn-up

The CERMET EFIT Operational and Safety Data

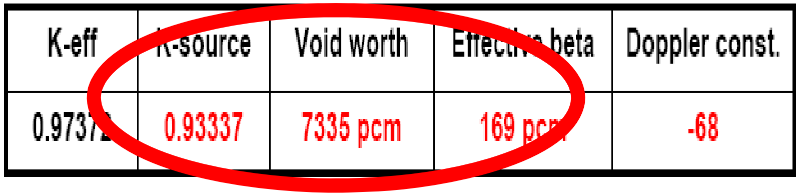
Burn-up calculation results for different Pu/MA ratios



Pin number per SA	168+1	91/Op 1	61/Op 1	61/Op 1 + thicker pins in outer zone
Pu/MA atom ratio over all	46/54	40/60	35/65	35/65
Fuel vol fraction in the core/the outer zone	26.73 %	29.79 %	31.24 %	31.24%/35.75%
k_{eff} initial	0.9820	0.9724	0.9428	0.9667
k_{eff} after 3 years	0.9593	0.9625	0.9455	0.9660
Pu initial mass	3055 kg	2966 kg	2726 kg	2899 kg
MA initial mass	3610 kg	4479 kg	5056 kg	5377 kg
Pu consumption [kg/TWhth]	5.71	-1.06	-7.95	-7.22
U consumption [kg/TWhth]	-0.48	-0.49	-0.50	-0.51
Am consumption [kg/TWhth]	46.80	54.72	63.40	62.40
Cm consumption [kg/TWhth]	-9.70	-10.70	-12.27	-11.76
Np consumption [kg/TWhth]	0.86	0.96	0.60	0.44
MA consumption [kg/TWhth]	37.96	44.98	51.73	51.08



Reactivity swing as function of (Pu/MA) ratio



K-eff	K-source	Void worth	Effective beta	Doppler const.
0.97372	0.93337	7335 pcm	169 pcm	-68

CERMET core safety parameters

Note : Void worth values given in tables serve as indicators (similar as in SFR safety)

IV : Safety Analyses for AFTRA CERMET EFIT

- Currently extensive and paramount safety analyses under way for CERCER EFIT
- For CERMET EFIT only limited analyses performed for most important transients to identify key safety issues of CERMET and identify differences to CERCER
- General impact of U-free fuels on global core dynamics and safety :
  - No prompt (negative) feedback effects (Doppler)
  - Strong delayed (positive) feedback effects by high reactivity worths (coolant void worths generally larger than subcriticality)
  - Deteriorated kinetics parameters

➔ Subcriticality could be eliminated (in contrast to Doppler)

➔ Subcriticality is essential and is 'the' stabilizing physical mechanism

Safety Concern :

- Under DEC safety conditions
- Elimination of significant part of subcriticality in case of core degradation

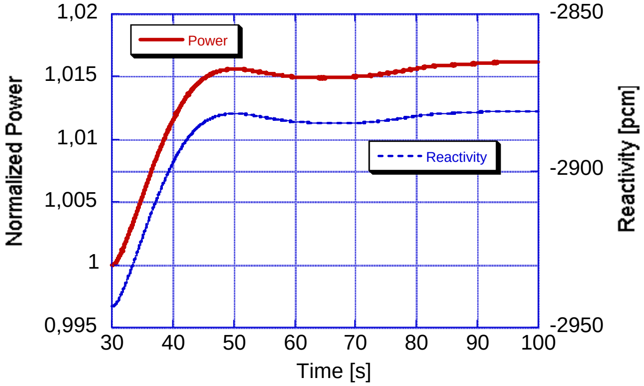
➔ Potential for power excursion

➔ Analyses indicate the potential for void consumption under severe conditions

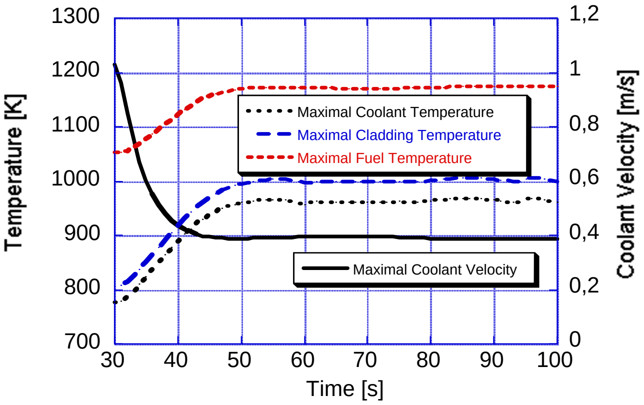
Examples of Safety Analyses : ULOF

Mo-92 CERMET 400 MWth EFIT low power density core

- 3–zone core with low power density of ~ 250 MW/m^3
- Natural convection flow ~ 40 %



- Slight power increase by 1.7 % due to the positive coolant feedback
- No pin failures
- Max. fuel temperatures far below the failure limits
- Max. clad temperatures (1000K) below failure limits (creep)



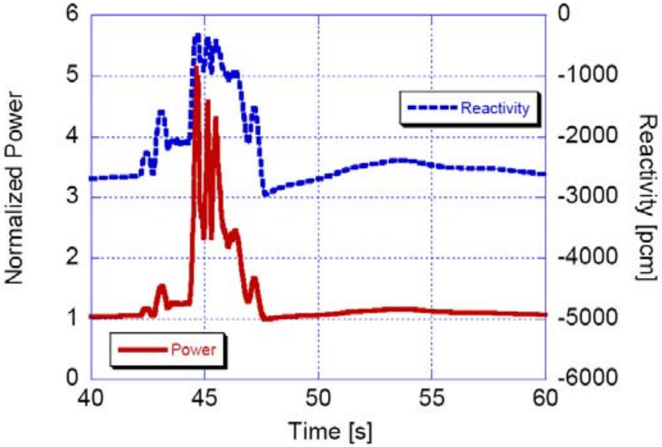
SIMMER-III Analyses of ULOF

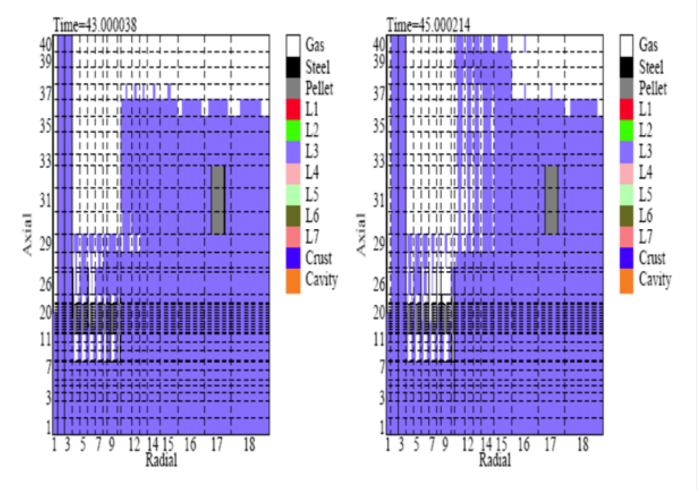
- Top : Power and reactivity trace
- Bottom : Fuel, clad, coolant temperatures

Examples of Safety Analyses : ULOF high power density core

Mo-92 CERMET 800 MWth EFIT high power density core

- 3–zone core with high power density of ~ 500 MW/m^3
- Power stretching to increase transmutation performance
- In-pin pressure = 30 bars
- Investigation of pin failure and failure propagation





- Pin failure & void propagation & power surge
- Max. clad temperatures (1250K) above failure limits (creep)
- Coherence of clad & coolant temperatures under ULOF conditions lead to propagation potential

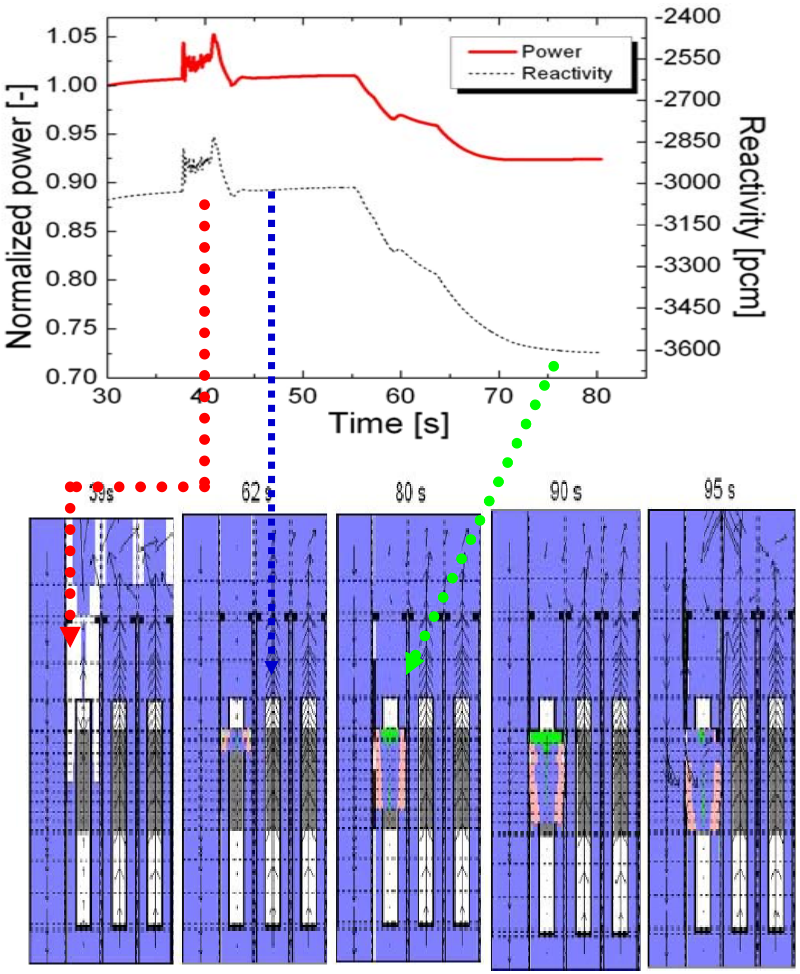
SIMMER-III Analyses of ULOF

- Top : Power and reactivity trace
- Bottom : Void distribution

Examples of Safety Analyses : UBA CERMET Core

Mo-92 CERMET EFIT 400 MWth low power density core

- The innermost SA-ring is blocked
- UBA outcome depends on many parameters :
  - Gas plenum pressure, clad failure temperature (gas release), clad loss of mechanical strength, clad melting, fuel pin break-up, pellet/particle behavior, upper structure behavior



- Gas blow-down causes short reactivity/power increase due the positive void feedback but rewetting prevents coherent failure propagation
- Reactivity/power decrease in this special case due to fuel sweep-out from the blocked core region
- Investigations show that realistically subassembly damage propagation to be expected until opening of larger fuel escape paths without power excursion
- Note : phenomenology independent of 2D or 3D simulation

SIMMER-III Analyses of UBA

- Top : Power and reactivity trace
- Bottom : Material distribution

V : Conclusions

- CERCER EFIT developed as reference design option
- CERMET EFIT offers alternative, especially because of safety performance
- Both CERCER and CERMET cores offer good transmutation performance
- Future work on cores with different transmutation strategies
- Further design optimization and assessment of power upgrading option

- For fuels, the irradiation results of FUTURIX, BODEX and HELIOS are urgently awaited
- Based on current analyses and knowledge, fuels generally do not pose limit on design and safety, but the T91 clad
- CERMET fuel has very large margins to failure
- Limited knowledge on fuel behavior under irradiation, transient and high temperature conditions; ‘microphysics’ of fuel must be understood and modeled in codes

Conclusions (cont.)

- For ADTs, high coolant reactivity feedback and lack of Doppler are features to consider in safety analyses
- Massive voiding only in case of extensive pin failures or introduction of steam/water after a SGTR accident with coolant-coolant interaction (CCI)
  - For current EFIT design SIMMER analyses do not show massive pin-to-pin failure propagation
  - For current design SIMMER analyses do not show introduction of steam into the core after a SGTR

- Needs for understanding fuel behavior under irradiation and impact on operational conditions, transients and accidents
- Needs for understanding 'pin failure' under various transient conditions
- T91 creep failure data (short time phenomena, high temperature) and other clad failure mechanisms to be investigated
- Needs for extensive transient tests of advanced fuels and clad
- Needs for code development