Report on Intermediate Results of the IAEA CRP on 'Studies of Advanced Reactor Technology Options for Effective Incineration of Radioactive Waste'

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FRAMEWORK

Technical Working Group on Fast Reactors

TWG-FR is a working tool:

1. **To promote exchange of information on national and multi-national fast reactor and hybrid systems (e.g. ADS) programs**
2. **To coordinate activities with other agency projects as well as with other international organizations (EU and NEA)**
3. **To stimulate and facilitate collaborative research and development in CRPs**

CRP : 'Studies of Advanced Reactor Technology Options for Effective Incineration of Radioactive Waste'

Sixteen institutions from twelve member states and one international organization participate in this CRP

SCOPE & OBJECTIVES of CRP (1)

SCOPE

- Collaborative R&D in the area of P&T with focus on reactor technology aspects
- R&D contributing towards the proof of practicality for long-lived waste transmutation
- Comparative assessment of transient behavior of various transmutation systems

OBJECTIVES

- Assess behavior of different transmutation systems under various transient conditions and deepen the understanding of the dynamics of transmutation systems
- Validate available methodologies (data and codes)
- Specify the validity range of existing methodologies
- Formulate requirements for theoretical developments
- Conclude on the potential need of transient experiments and make appropriate proposals for experimental programs

DETAILED WORK SCOPE OF CRP

- **Key issue : When dealing with transmutation systems with a high MA load one is faced with deteriorated safety coefficients (e.g. 'no' Doppler, small beta-eff, large void worth, ….)**

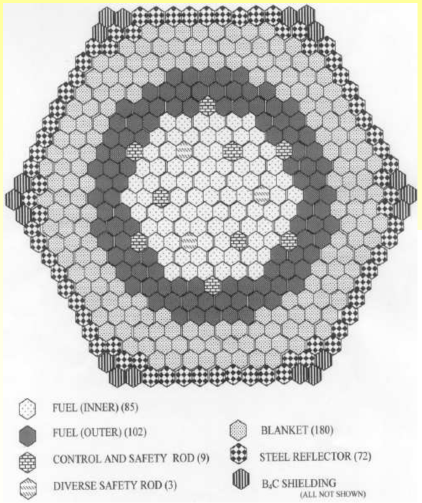
- **Benchmarking of transient/accident simulation codes focusing on the phenomena and effects relevant to various critical and sub-critical transmutation systems.**
- **Main thrust on long time-scale effects of transients initiated by strong perturbations of the core and/or the neutron source**
- **Step 1 : The safety and dynamic coefficients (prompt feedback effects like the Doppler effect, thermal fuel expansion, the delayed feedback from clad, coolant and kinetics parameters) are determined.**
- **Step 2 : Transient analyses are performed which reflect the generic behavior of the reactor types**
- **Issues as the transmutation potential, burn-up behavior and decay heat of MA bearing fuels are investigated.**

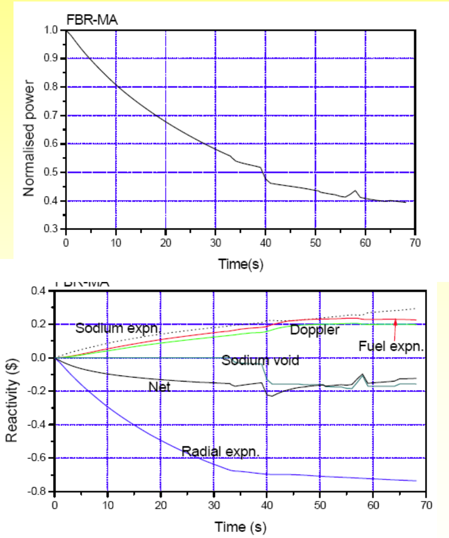
TRANSMUTATION SYSTEMS ANALYZED

- DOMAIN I : Critical transmuters with fertile fuel
- DOMAIN II : Critical transmuters with fertile-free fuel
- DOMAIN III : Hybrid systems (ADS) with fertile fuel
- DOMAIN IV : Hybrid systems (ADS) with fertile-free fuel
- DOMAIN V : Molten salt reactor systems with fertile fuel
- DOMAIN VI : Molten salt reactor systems with fertile-free fuel
- DOMAIN VII : Gas cooled reactor systems (ADS)
- DOMAIN VIII : Hybrid fusion/fission systems

Domain I: Critical Transmuters with Fertile Fuel (1)

The first concept, a benchmark model proposed by **IGCAR & BARC**, is a modification of the PFBR (500 MWe) sodium cooled fast reactor.



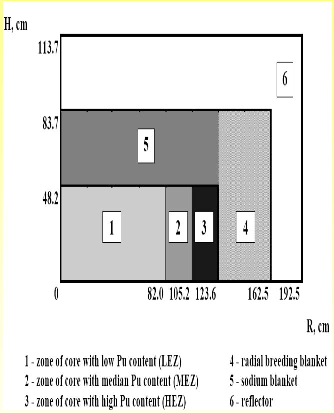


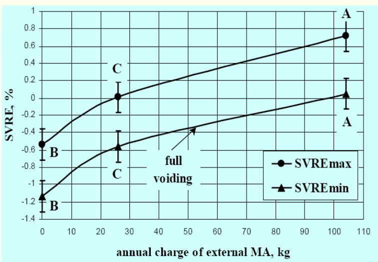
Results of ULOF simulation

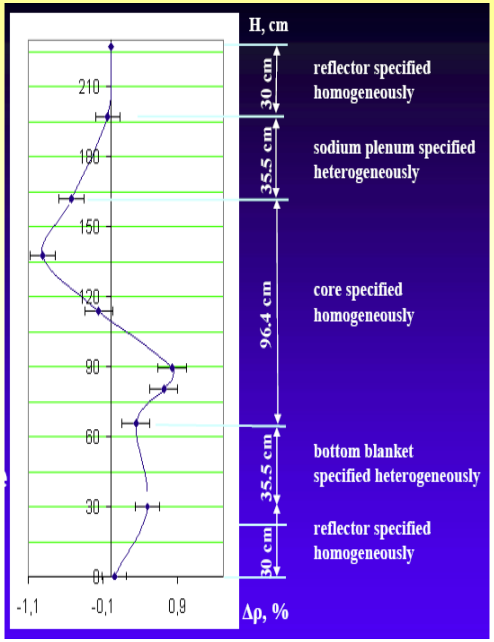
- **Fuel contains 5 % of MAs (from PHWR). The axial blanket is UO_2, the radial blanket is made of ThO_2 .**
- **A 10 % reduction in the long-lived MAs is attained during an EC, however accompanied by a substantial production of U233.**
- **The static neutronic analyses with ALCIALMI, NEWPERT codes, investigated the influence of nuclear data bases : ENDF/B-VI, JENDL-3.3 and JEFF-3.0 (CV2M, XSET98). The spread max/min k-eff ~ 200 pcm, overall material worth was in the range of +/- 10%, while the fuel Doppler values could be off by a factor of 3.**
- **The sodium void worth (+ ax. blankets) = 1323 pcm, β eff = 343 pcm.**
- **Transient analyses with PREDIS : ULOF and UTOP. Calculations show that the limited amount of MAs in the core does not compromise the safety of the reactor. The thermal expansion of the grid plate plays a dominant role and leads to the power reduction shown .**

Domain I: Critical Transmuters with Fertile Fuel (2)

The second concept, a benchmark model proposed by **IPPE**, is based on the BN-800 sodium cooled fast reactor and fuelled with Pu-Th-fuel containing MAs of VVER origin.



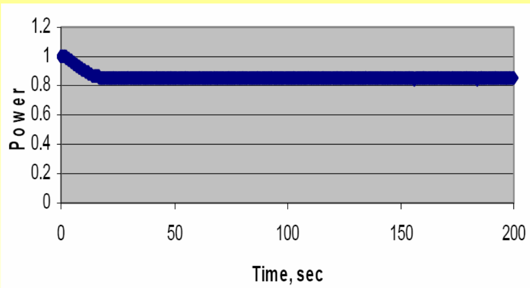




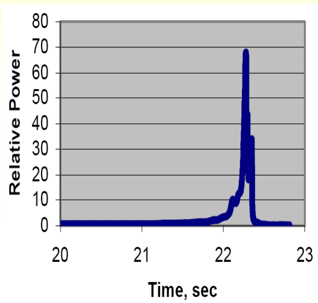
- **BN-800 type reactor (2100 MWth)**
- **Fuel made of (Pu-Th)O_2 containing MAs of VVER origin. The MAs produced during the burnup are recycled, hence added to those of VVER origin. The self-production of MAs is reduced and the bred U233 could be used to start a thorium cycle.**
- **Upper axial blanket replaced by sodium plenum; radial ThO_2 blankets**
- **Initial Pu loading that k-eff (EOEC) -> k-eff of (Pu-U)O_2 core, Pu238 < 5 %, rad. power f < 1.2, SVR < 0**
- **Static neutronic calculations show that a negative sodium void reactivity effect (SVRE) can be achieved in this BN-800 type reactor with PuO_2-ThO_2 in case an upper sodium plenum is provided. Beta-eff reduced by 30%, Doppler by 40% rel. to BN-800.**
- **For a negative SVRE no more than 26 kg of external VVER MAs per year should be added. In case of allowing a moderate positive void worth of 0.7 %dk/k the MA mass could increase to 104 kg/year. In this case 7 VVER-1000 reactors could be supported.**

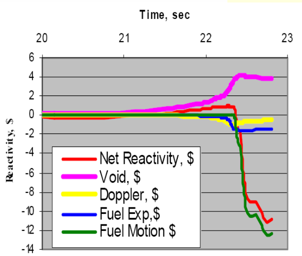
Domain II : Critical Transmuter with Fertile-Free Fuel

JRC has performed a comparative core performance analysis on the transmutation potential and on the transient safety behavior of an SFR and LFR waste burner.



LFR under ULOF conditions



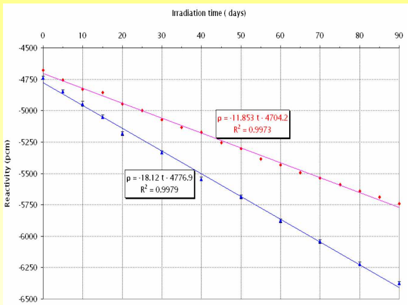


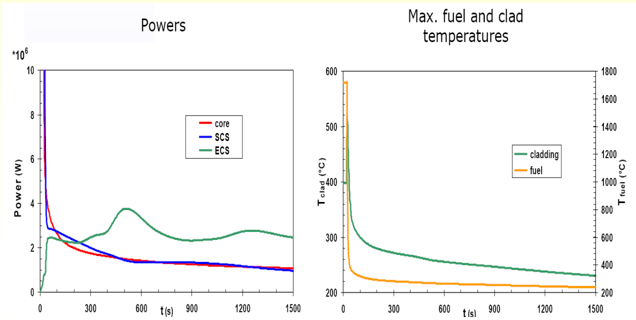
SFR under ULOF conditions

- **Two 600 MW$_e$ reactors, a lead and a sodium cooled are compared regarding safety coefficients, waste-burning capabilities and reactivity swings.**
- **Options : U-free CERMET fuel: ^{92}Mo matrix (and Th232 matrix).**
- **The LFR core is larger than the SFR due to the larger pitch-to-diameter ratio.**
- **Introduction of pins with BeO or CaH moderator in both cores provide a negative Doppler.**
- **Unprotected Loss-of-Flow (ULOF) and Loss-of-Heat Sink (ULOHS) have been simulated. The LFR overcomes the ULOF due to its superior natural circulation, the SFR gets into sodium boiling.**
- **In ULOHS the grace time of the LFR is considerably larger.**
- **The LFR burner annual transmutation rate ~ 300 kg of plutonium & MAs. The SFR annual burner rate ~ 263 kg.**

Domain III: Hybrid systems (ADS) with Fertile Fuel

The MYRRHA ADS design has been taken as the fertile hybrid benchmark case **(SCK•CEN, NRG, JRC).** The sub-critical core configuration consists of a two-enrichment MOX fuel core with and without transmutation fuel.



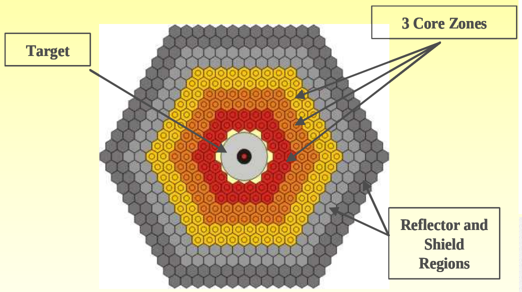


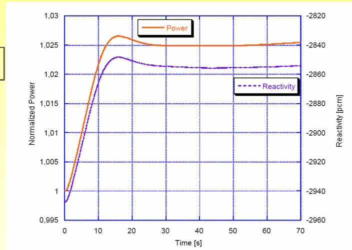
PLOF simulation with RELAP

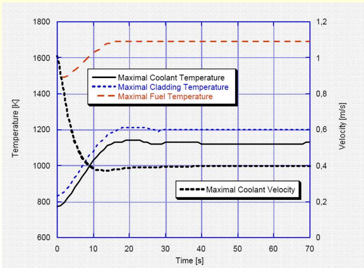
- **The Pb/Bi cooled MYRRHA sub-critical reactor with a thermal power of 50 MW. 1st core with 45 fuel assemblies containing 30 wt% Pu MOX fuel. 2nd core with 24 U-free MA and 48 MOX (72 assemblies). The U-free pins contain a MgO matrix.**
- **Neutronic analyses with MCNPX.2.5.0 code based on the JEFF3.1 & LA150 data files. The ALEPH code (MCNPX coupled ORIGEN2.2) used for burn-up calculations.**
- **Doppler and neutron generation time less than in a SFR. The core void worth is negative.**
- **Transient studies with RELAP and SITHER codes were used. Protected and unprotected transients analyzed.**
- **MYRRHA core survives most of the protected accidents without melting. Only the blockage accident leads to limited damage. For the unprotected accidents, clad temperatures are reaching 1300 K and failure will occur for the ULOF and the ULOHS. In case of a beam cut-off the transients could be coped with.**

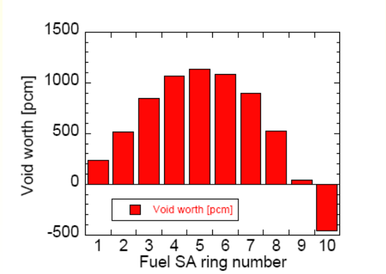
Domain IV: Hybrid systems (ADS) with Fertile-Free Fuel

FZK and **Kyushu University** contributed two benchmark cases. Two fertile-free ADS systems with 580 MWth power with three core zones have been developed and investigated. The fuels are based on a ZrO_2 and MgO inert matrix







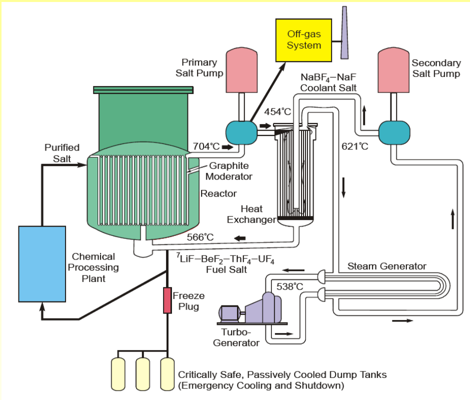


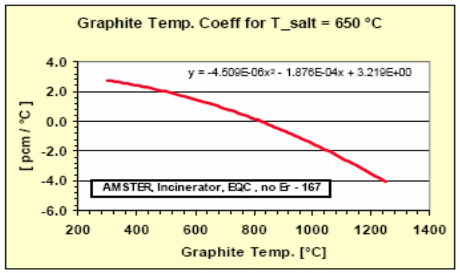
ULOF simulation with SIMMER-III

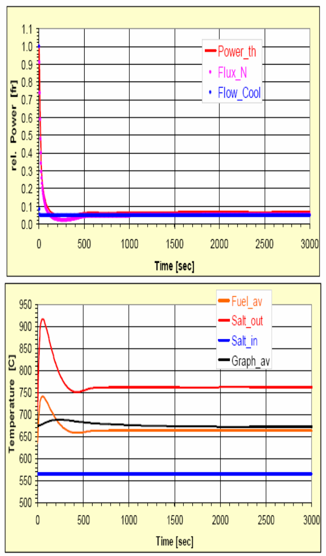
- **The fuels of the cores coming from a MOX LWR, contain 40 % Pu, 50 % Am and 10% Cm. Matrix fractions are 50 % and higher (3 core zones)**
- **Static/transient calculations by SIMMER-III. SIMMER–III benchmarked against MCNP, ERANOS, DANTSYS.**
- **SIMMER uses library based on FZK data. Benchmarking against JEF2.2, JEFF3.0, JENDL3.3 and ENDF/B-IV.8. Data processing with C4P code.**
- **Strong sensitivity of k-eff on libraries. LBE, nuclear data and also MgO a reason for deviations. Insensitivity in methods (MC versus deterministic).**
- **Large void worths for MgO and ZrO_2 cores : from 6500 pcm (FZK-11 group, JEF2.2-30groups) to 8300 pcm / 7700 pcm (JEFF3.0, JENDL3.3, both 30 groups).**
- **Transient analyses for UTOC, ULOF, UTOP, UB.**
- **Safety problems of the MgO matrix above 2100K . The results show that this temperature level is not reached in case of a ULOF, UTOC and UTOP.**

Domain V : Molten Salt Reactor Systems with Fertile Fuel

FZK, NRI, Polit. Turino specified a benchmark based on the Li/Be/Th-F AMSTER incinerator design of EdF. NRI gave a description of the front-end and back-end technology.





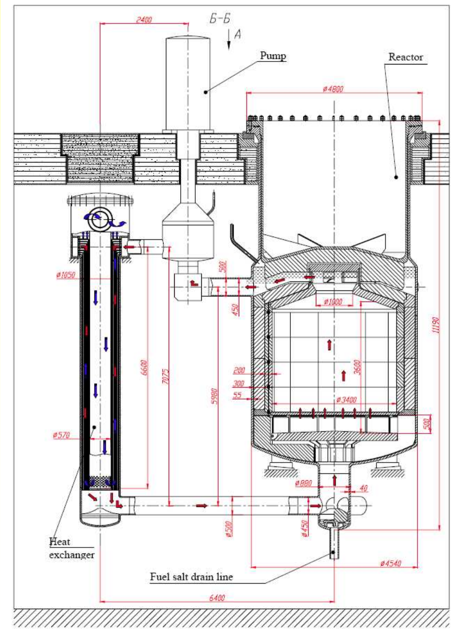


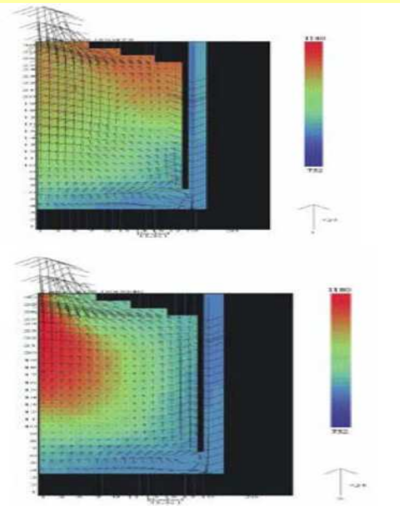
ULOF simulation with SimADS

- **AMSTER with Li/Be/Th-F salts based on MSBR design of ORNL. For the benchmark experimental results from former Oak-Ridge MSRE tests were taken.**
- **Safety coefficients by APOLLO2 & WIMS8.**
- **Data basis : JEF2.2 (CEA93), WIMS'97 (JEF2.0), C4P**
- **Code systems : SimADS, SIMMER-III, DYNAMOSS in pump startup and pump coast down tests.**
- **Because of the special dynamics of MSR, pump coast-down leads to an increase in reactivity in the reactor. Beta-loss ~ 25 %**
- **Various transients have been analyzed as ULOF, ULOHS and UTOP. A special transient is the unprotected overcooling of the primary fuel because of secondary side malfunctioning.**
- **Important finding was that ER-167 has to be added to the graphite to obtain a negative graphite reactivity coefficient to stabilize the reactor. At T> 1070 K no Er-167 needed. Generally, the large thermal inertia of the systems damps its dynamics and allows significant grace times for reaction.**

Domain VI : Molten Salt Reactor Systems with Fertile-Free Fuel

The benchmark is based on the Na/Li/Be-F MOSART concept **(RRC-KI, various institutions).** The RRC-KI group has produced the reactor core design data, neutronics and thermalhydraulics analyses. The MSR front-end process is described.



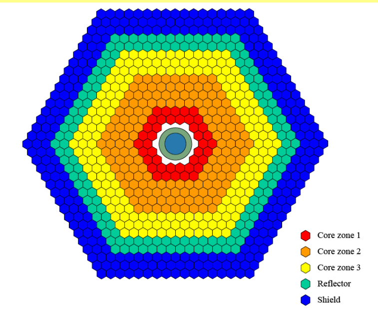


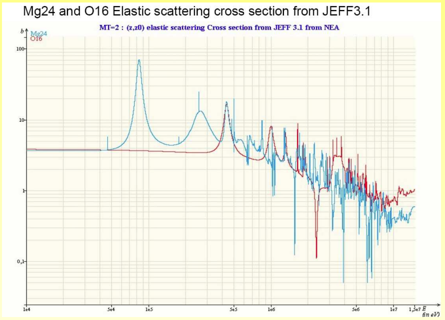
ULOF simulation with SIMMER-III

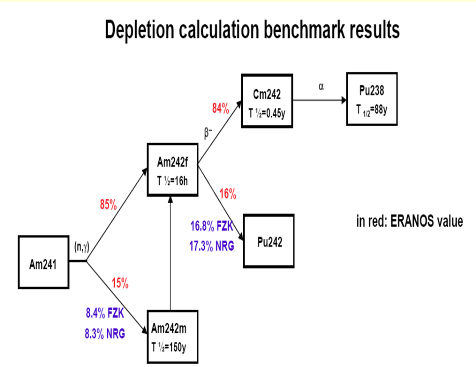
- **MOSART is used as TRU burner system (2400MWth) with fast neutron spectrum.. Graphite only as external reflector.**
- **Fuel salt is a 58NaF-15LiF-27BeF$_2$ (mole%) mixture with 752 K melting temperature with 1.05 mole% of (TRUF$_3$ +LnF$_3$). At 873K solubility of (TRUF$_3$ +LnF$_3$) = 2 mole%. Operating T ~ 1023 K. Primary circuit material is Hastelloy NM**
- **Static neutronics: DANTSYS, SIMMER-III, XSDRNPM, and MCNP, MCNPX, MCU. Good agreement found between codes.**
- **Nuclear data libraries (ENDF/B-VI, JEF 2.2, JEFF 3.0, JEFF 3.1, JENDL 3.3). As no 'fertiles' in the salt, reduced impact of data libraries on k-eff. Deviations caused by Cm, Be9, F19.**
- **Delayed precursors studied with SIMMER-III and DYNAMOSS. Space dependency of precursors leads to reduction of beta-eff. Beta-loss ~ 45 %**
- **Negative temperature coefficients (stability)**
- **Transients : UTOP, ULOF, ULOHS and UOC. Good safety performance. UTOP critical.**

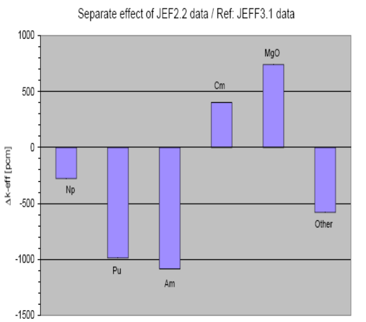
Domain VII : Gas Cooled Reactor System (ADS)

CEA, NRG, SCK.CEN, FZK proposed a benchmark based on a 400 MWth gas-cooled, inert (MgO) matrix fertile-free ADS.





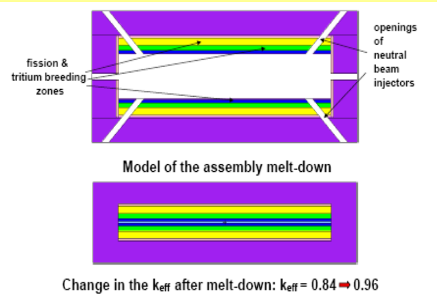


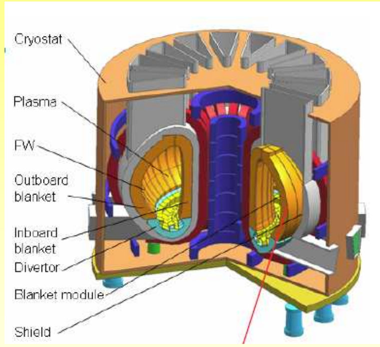


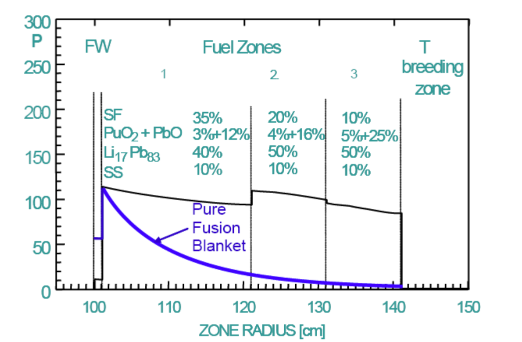
- **Helium cooled ADS with dedicated MA fuels based on a 400 MW_{th} gas-cooled, inert (MgO) matrix fertile-free fuel with Pu/(Pu+MA)=36%. Matrix/fuel ratio ~ 0.4**
- **Helium pressure is 60 bar, the pressure drop 0.5 bars, Average /peak vol. power is 44 W/cm^3 and 94 W/cm^3 .**
- **Several combinations of Monte-Carlo and deterministic codes ERANOS2.0,TRIPOLI4, MCNP4C, OCTOPUS (MCNP4C3+FISPACT), MCNPX.2.5, DANTSYS, C4P with (JEF2.2, JEFF3.1, JENDL3.3, ENDF/B-VI).**
- **Large impact of Am, Mg data & group structure**
- **First a large discrepancy observed for initial reactivity (ERANOS results). The recommendation for ERANOS is now to treat both Mg and O and Minor Actinides at the fine group level (1968 gr.) and with JEFF3.1 when large content of MgO and Minor Actinides.**
- **End of cycle reactivities are particularly sensitive to the branching ratios used in the TRU chains and to the fission product treatment. Necessity to improve the ERANOS results.**
- **Transient analyses still to be performed**

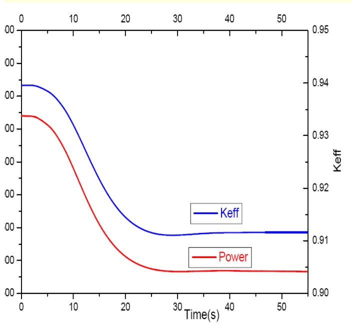
Domain VIII : Hybrid Fusion/Fission Systems

The Academy of M&M Cracow proposed a Tandem Mirror System. Another benchmark was proposed by **ASIPP** and is based on a tokamak fusion/fission hybrid concept called FDS-I.









- **Advantage of system lies in subcriticality, prospect of a radical reduction of necessary plasma energy gain, reduced load of the first wall with 14 MeV neutrons and homogeneous heating distribution.**
- **AMMC proposed 500 MWth TM with a k-eff of 0.84, Plasma Q ~ 0.6. TRU incineration = 420 kg/TWyr**
- **The FDS-I with 150 MWth with sub-critical blanket cooled by helium and lithium-lead eutectic. Particulate fuel in LiPb coolant.**
- **Neutron static calculation benchmarking with MCNPX, VisualBUS containing both S_N and Monte Carlo codes. The main data library was HENDL.**
- **TM collapse scenario : criticality is not reached.**
- **FDS-I : UPOP, UTOP, ULOF, LOHS, ULOC and collapse transients.**
- **FDS-I : ULOF : natural convection prevents the fuel particle melting and also melting of structures for 30 seconds. Negative density feedback due to fuel form. In collapse scenario subcriticality kept up to a collapse of three blanket modules .**

STATUS OF CURRENT RESULTS OF THE CRP (1)

- When dealing with transmutation systems with a high MA load one is faced with deteriorated safety coefficients (special measures to cope with !)
- For steady state analyses the neutronic tools in each domain are advanced enough to provide good agreement. This holds for the applied mechanistic S_N and Monte Carlo codes.
- Larger spreading of results is generally caused by the different nuclear data libraries used. These deviations may not only be caused by the minor actinide data but also by data and treatment of other constituents as e.g. matrix material in inert fuels, coolants, salts and fission products.
- For all domains transient calculations have been or will be performed. Important in this respect are deterministic neutronic methods based on few-group approximation (up to 30 - 50 gr.).
- Very different code systems were employed from point-kinetics to space-time kinetics, and also different levels in the sophistication of the thermal-hydraulic modelling.

STATUS OF CURRENT RESULTS OF THE CRP (2)

- **The benchmarking has nearly exclusively been performed in the range of transients and accidents without core disruption (1 exception).**
- **Within the current CRP also a comparison of the system dynamics is intended. For the fertile fuel systems, as expected, the prompt Doppler effect plays an important stabilizing role for curbing power excursions. For the non-fertile fuel systems similar balancing effects are provided e.g. by the thermal expansion feedbacks or the subcriticality of the system.**
- **Systems show very different time-scale characteristics**

- **Key safety issues and intrinsic dynamic features of the different systems will be identified and described.**
- **The comparison has to be balanced in the sense that a large knowledge base exists e.g. for the critical fast reactors whereas less is known e.g. on fusion-fission hybrid systems. Nevertheless characteristic transients, phenomena and time scales can already be identified.**

FINAL INTENDED OUTCOME OF THE CRP

General outcome of the CRP

- **Advancement of the proof of practicality for long-lived waste transmutation**
- **Fostering international team-building and laying the ground for further international collaborative R&D**

Specific outcomes of the CRP

- **Improve understanding of the participants' methodology to study the transient behavior of transmutation systems**
- **Advance the validation status of this methodology**
- **Critical assessment of tools and data**
- **Theoretical and experimental needs**
- **Further benchmarking**
- **Assessment of general behavior of systems studied (critical/subcritical, solid fuel/molten salt, liquid metals/gas)**