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Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions

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Spallation Data and Applications

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Relevance of High-Energy Data for IAEA's Activities in the Area of Accelerator Driven Systems

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Content

- Summary of IAEA's ADS Activities
- Preliminary Results
  - CRP on *Studies of Advanced Reactor Technology Options for Effective Incineration of Radioactive Waste*
  - CRP on *Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems*

IAEA ADS Activities

- ❑ Framework given by the Technical Working Group on Fast Reactors (TWG-FR)
- ❑ TWG-FR working tool to
  - ➢ Promote exchange of information on national and multi-national fast reactor and hybrid systems programs (e.g. ADS)
  - ➢ Stimulate and facilitate collaborative research and development (CRPs)
  - ➢ Coordinate activities with other Agency projects (e.g. in Safety, Physics, Nuclear Data), and international organizations (EC, ISTC, and NEA)

IAEA ADS Activities, cont'd

- **Education and Training**
  - **Provide educational and research opportunities for young nuclear professionals**
  - **Implemented in collaboration with ICTP**
  - **Most recent activity: *School on Physics, Technology and Applications of Accelerator Driven Systems (19 – 30 November 2007)***

IAEA ADS Activities, cont'd

- **Most recent activity: *School on Physics, Technology & Applications of ADS (19 – 30 Nov. 2007)*, attended by 29 students from 19 IAEA Member States**
  - ✓ ADS Physics
  - ✓ ADS Dynamics
  - ✓ Monte Carlo Methods
  - ✓ Engineering Design of the MYRRHA Proof-of-Principle ADS Facility
  - ✓ Thermal Hydraulics of Heavy Liquid Metal Target for ADS
  - ✓ Nuclear Reactions and Related Data Libraries at High Energies
  - ✓ Nuclear Reactions and Related Data Libraries at Low Energies
  - ✓ Science, Technology and Design of Accelerators for ADS
  - ✓ Spallation Target Design
  - ✓ Partitioning
  - ✓ Advanced Fuels for P&T
  - ✓ Impact of P&T on the Final Repository

IAEA ADS Activities, cont'd

- **Information Exchange**
  - ***Theoretical and Experimental Studies of Heavy Liquid Metal (HLM) Thermal Hydraulics* (IAEA-TECDOC-1520)**
  - **Updating the *Status Report on ADS Research and Technology Development***
  - **ADS Research and Development Database http://www-adsdb.iaea.org/index.cfm**

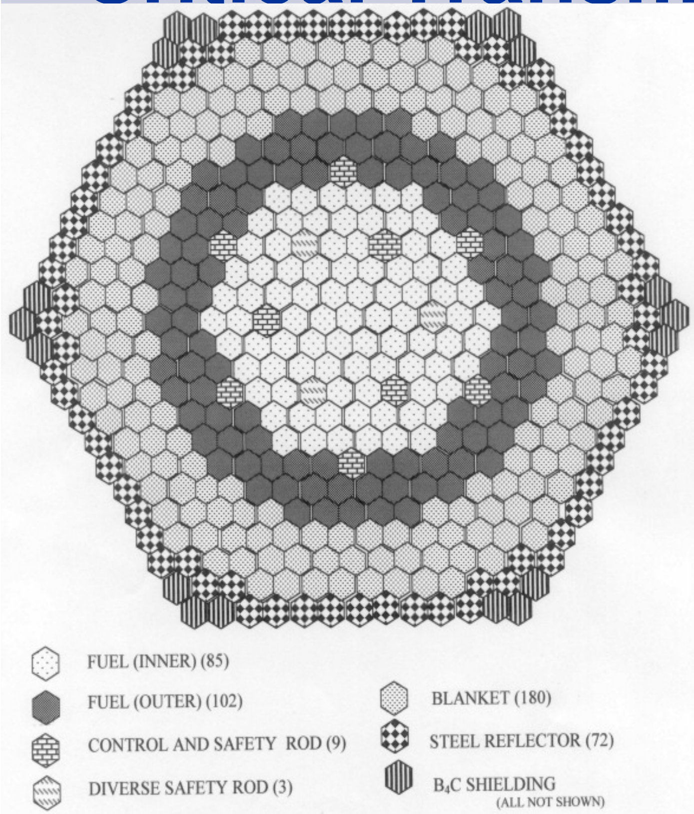
IAEA ADS Activities, cont'd

- **Coordinated Research Projects (CRPs)**
  - ***Studies of Advanced Reactor Technology Options for Effective Incineration of Radioactive Waste***
  - ***Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems***

Studies of Advanced Reactor Technology Options for Effective Incineration of Radioactive Waste

- CRP participants from 20 institutions in 15 IAEA Member States and one international organization
- CRP's objective: codes and data validation (kinetics and transient calculations for transmutation systems)
- Benchmark analyses
  - Transients in the ms to >1s time range
  - Thermal to fusion neutron energy spectra burner reactors and transmuters, sodium/heavy liquid metal/gas cooled, fertile and fertile-free, solid/molten fuels
- CRP participants
  - Calculated the safety coefficients (kinetics parameters, and prompt feedback effects e.g. Doppler, thermal fuel expansion as well as delayed ones from clad, coolant and other core constituents)
  - Performed transient analyses

Critical Transmuters, Solid Fertile Fuel



PFBR

Na cooled

UO_2 / ThO_2 ax. / rad. Blk.

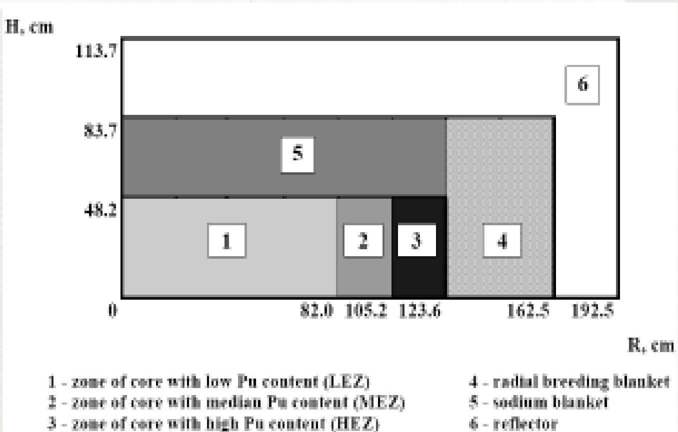
α_{Pu} 19.5 / 27.1 wt%

5% MA from Indian PHWRs

Max bu 100 GWd/t

BR 1.13

$\Delta\rho$ 1981 pcm per cycle



BN-800

Na cooled

$(Pu\text{-}Th)O_2$ fuel

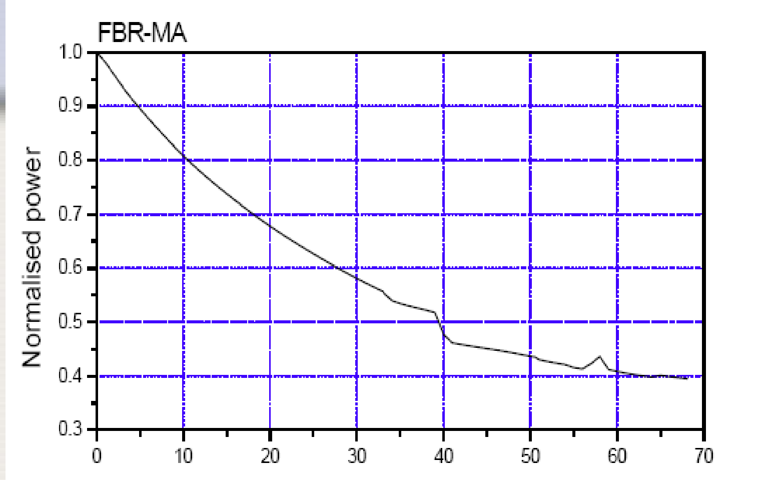
Var. MAs amounts from VVERs

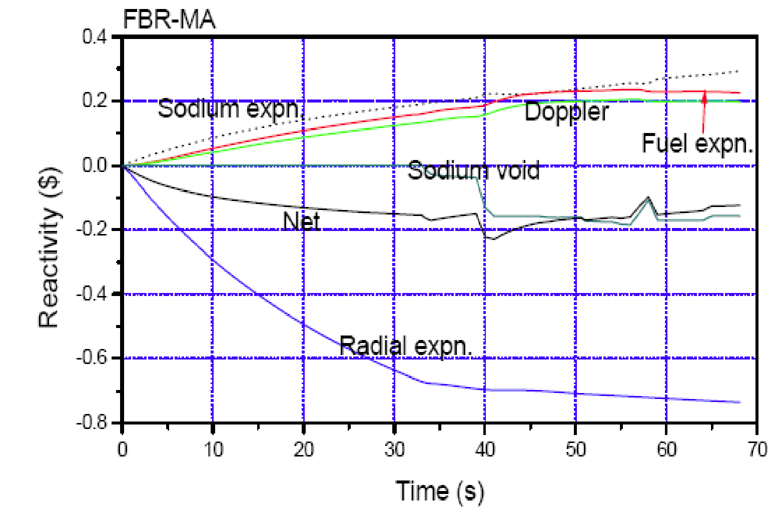
Na / ThO_2 upper ax. / rad. Blk.

Critical Transmuters, Solid Fertile Fuel

PFBR

- ~10% MAs red. per equ. cycle
- β_{eff} 343 pcm
- $\Delta\rho$ Na void 1323 pcm
- Total Doppler –430 pcm
- Data uncertainties: 200 pcm on k_{eff}; $\pm$ 10% on $\Delta\rho_{mat}$; up to factor of 3.5 on fuel Doppler
- ULOF (8 s Na flow halving time) and UTOP(4 pcm/s) ⇨addition of 5% MAs does not compromise reactor safety
- Dominant effect in ULOF is grid plate thermal expansion ⇨ rapid power reduction



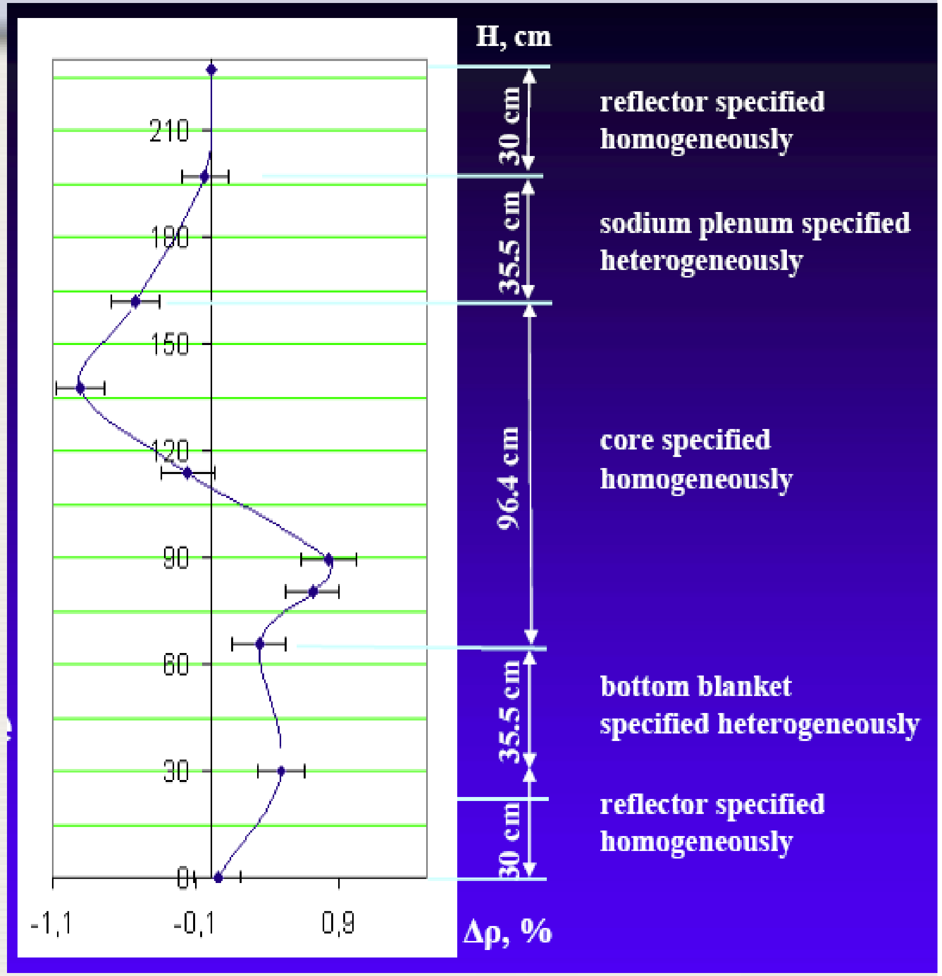


ULOF, Power and Reactivity Evolution

Critical Transmuters, Solid Fertile Fuel

BN-800

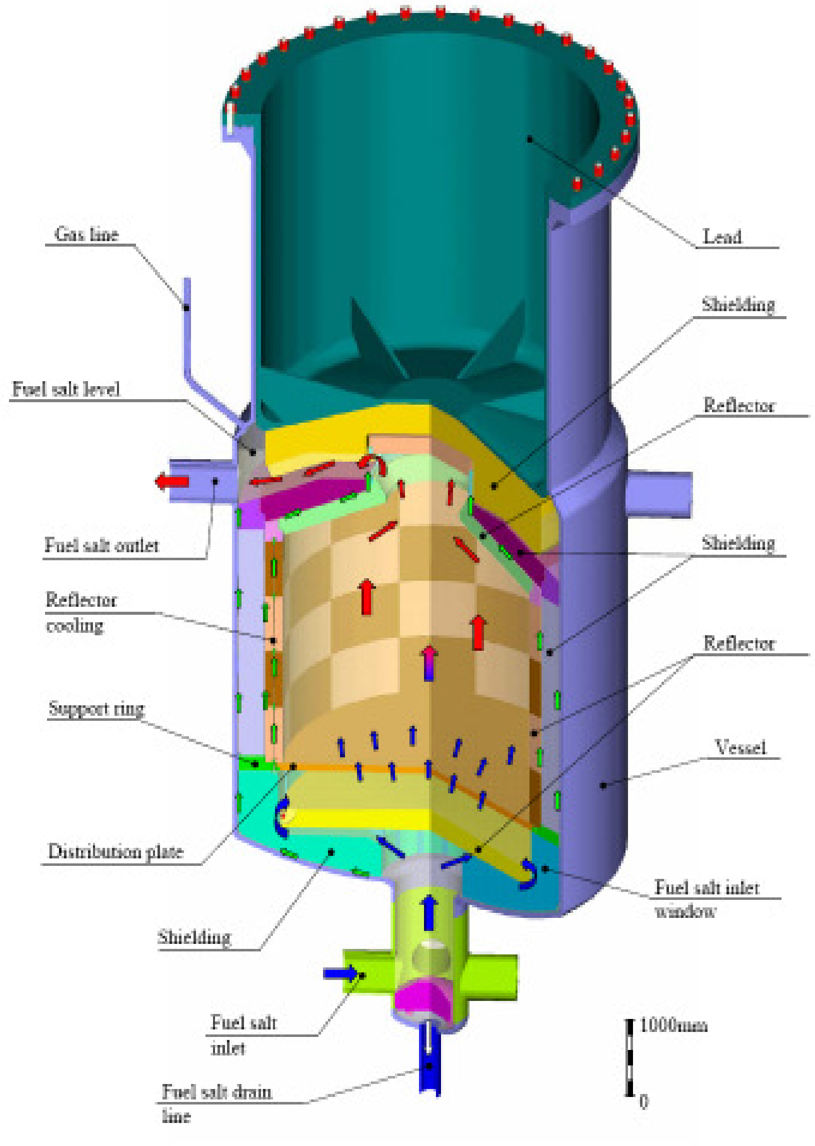
- Three fuel management variants
  - Recycle own MAs, no add. VVER MAs
    - ✓ Recycles only own MAs (~158 kg/yr)
    - ✓ Negative Max. Δρ Na void
  - Recycle own MAs and add. 52 kg VVER MAs at refuelling
    - ✓ 104 kg VVER MAs recycled per year ⇨ yearly production of 7 VVERs
    - ✓ Δρ Na void: Max. ⇨700 pcm; Total ⇨almost zero
    - ✓ Importance of Na upper plenum
  - Recycle own MAs and add. 13 kg VVER MAs at refuelling
    - ✓ 26 kg VVER MAs recycled per year ⇨ yearly production of 2 VVERs
    - ✓ Δρ Na void: Max. ⇨almost zero; Total ⇨ negative



Axial Dependency of Δρ Na Void

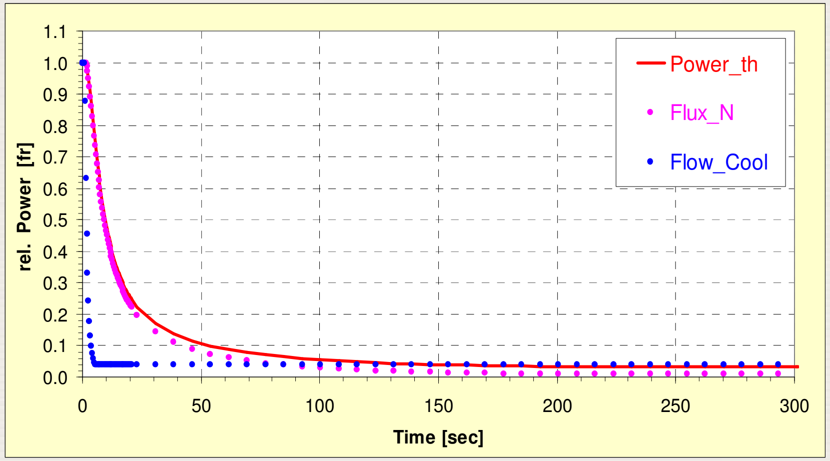
Critical Transmuters, Liquid Fertile-Free Fuel

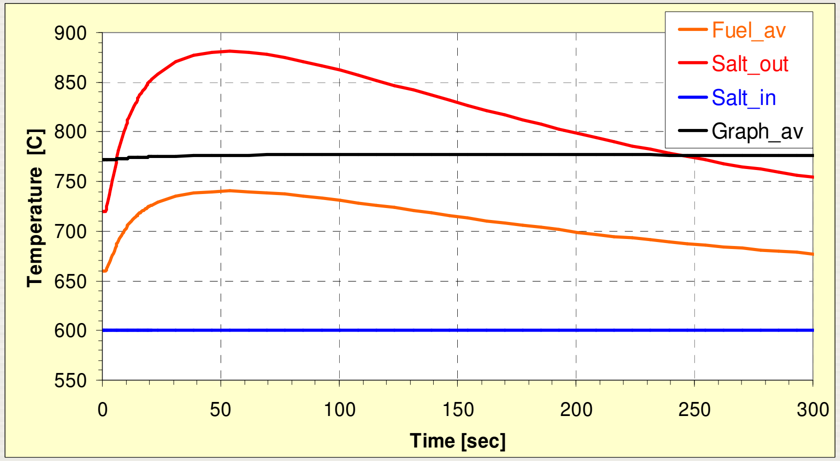
- 2400 MWth MOlten Salt Advanced Reactor Transmuter Benchmark (MOSART, 58NaF-27BeF2-15LiF mol%)
- Actinide composition ⇨ spent PWR UOX fuel (4.9% ^{235}U, 60 GWd/t, 1 yr cooling)
- Static neutronics ⇨ multi-group deterministic codes (DANTSYS18, SIMMER12, XSDRNPM19) and Monte-Carlo (MCNP20, MCNPX21, MCU22)
- Various nucl. data libraries (ENDF/B-VI, JEF 2.2, JEFF 3.0, JEFF 3.1, JENDL 3.3)
- Deterministic and Monte Carlo results are in excellent agreement
- Data uncertainties
  - 2500 pcm on k_{eff} (Cm, ^{9}Be ^{19}F)
  - satisfactory agreement on major kinetics parameters
  - good agreement on $\Delta\rho_{mat}$ and Doppler
- Effect of the movement of the delayed neutron precursors (SIMMER23 and the DYNAMOSS24) ⇨ β_{eff} reduction by 40 to 50% as compared to stationary fuel



Critical Transmuters, Liquid Fertile-Free Fuel

- UTOP, ULOF, and ULOHS
- ULOF ⇨ positive reactivity insertion in reactors with circulating fuel (83 pcm in this example)
- Due to the strong negative temperature effects, the transient leads to a power reduction

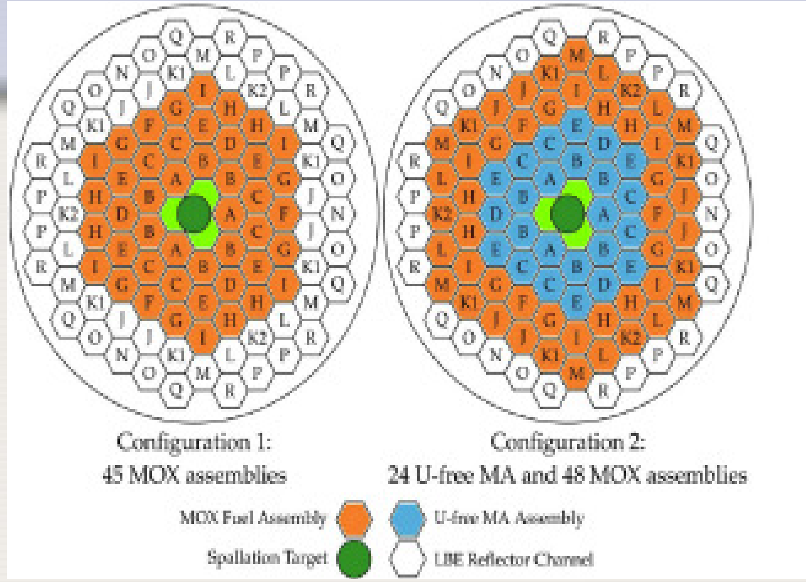




ADS With Fertile Fuel

MYRRHA: Pb-Bi, 50 MWth ADS

- ❑Reference configuration: 45 MOX (30 wt% Pu) fuel assemblies
- ❑Burner configuration: 48 MOX plus 24 uranium-free assemblies containing MAs embedded in an MgO matrix



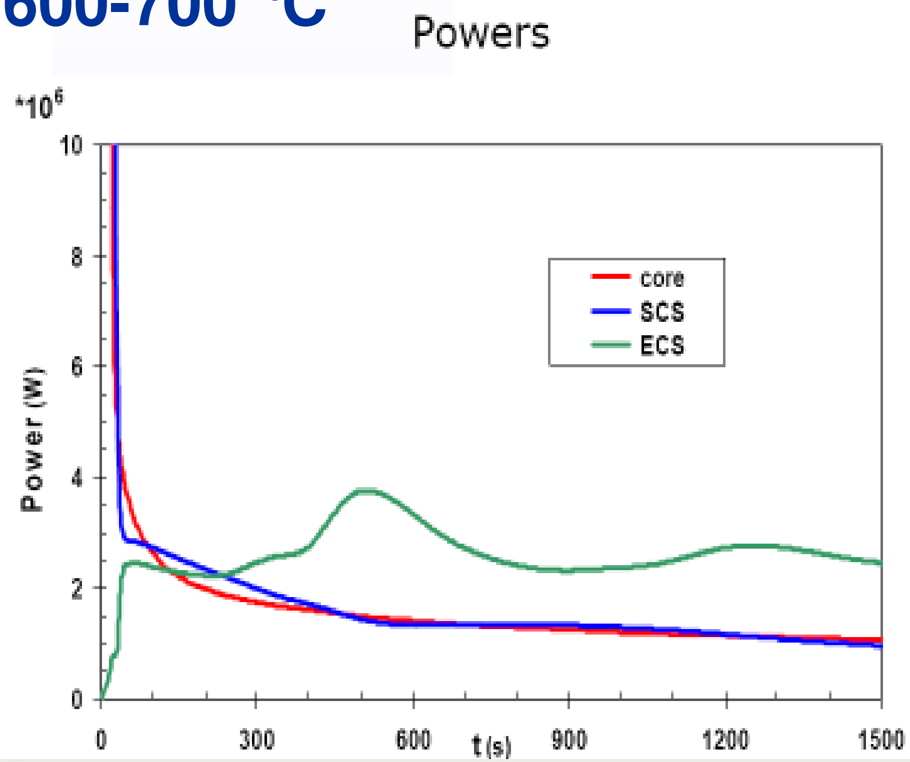
- ❑ Static neutronic calculations: MCNPX.2.5.0, JEFF3.1 file21
- ❑ Burnup calculations: ALEPH (MCNPX with ORIGEN2.2)
- ❑ Compared with Na fast reactor: $K_{Doppler}$ slightly lower; β_{eff} same order of magnitude; neutron generation time an order of magnitude larger
- ❑ Burner core: reduced $\Delta\rho_{bu}$; core $\Delta\rho_{void}$ negative

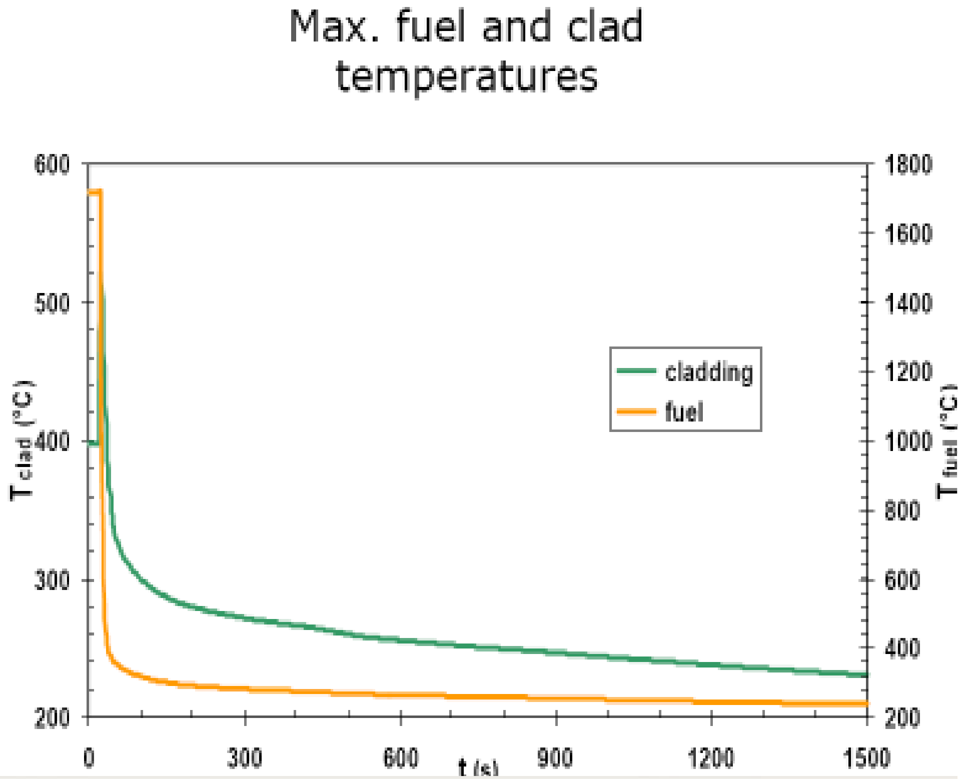
ADS With Fertile Fuel (MYRRHA)

- Transients analyzed
  - LOF: loss of forced circulation in primary cooling system
  - LOH: loss of secondary cooling system
  - Concomitant LOF and LOH
  - TOP: reactivity jump at hot full power (2000 and 2500 pcm in the unprotected and protected case, respectively)
  - Overcooling: secondary cooling system inlet temperature drops instantaneously to 40℃
  - Assembly Blockage: up to 30% and 50% reduction of the flow area in the hottest assembly in the unprotected and protected case, respectively
  - Unprotected Beam Overpower transient: beam power jump corresponding to a neutron source increase by up to 175% at hot full power
- Transient codes: RELAP28 and SITHER29

ADS With Fertile Fuel

MYRRHA reference and burner cores cope with most protected transients, e.g. LOF transient in the reference core ⇨ no melting, max. fuel / clad temp. < safety limits 2500 °C / 600-700 °C

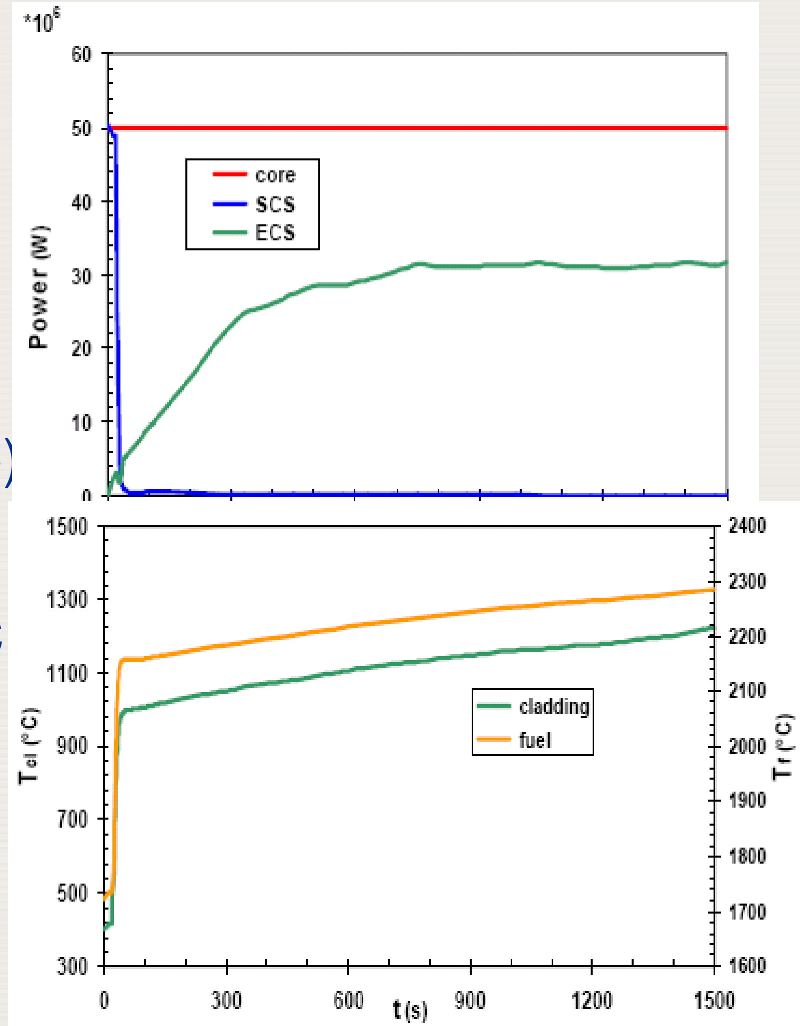




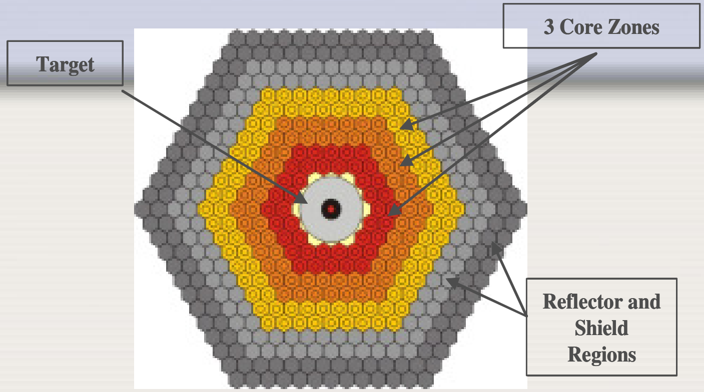
Exception: Assembly Blockage transient ⇨ limited damage for assembly flow area reduction factors larger than 30%

ADS With Fertile Fuel

- MYRRHA burner core ⇨ significant safety improvements for all unprotected transients compared to reference
- MYRRHA reference core ⇨ major problems with max. clad temp.
  - Total ULOF ⇨ pin failure (max. clad temp. ~1000 ℃, 7s grace time to 700℃)
  - ULOH ⇨ 600s grace time to 700℃
  - Concomitant ULOF and ULOH ⇨ clad temp. > 1200℃, 7s grace time to 700℃
  - Unprotected Overcooling transient ⇨ 14 min grace time to freezing (124 ℃)
  - Unprotected Beam Overpower transient ⇨ benign for beam power jumps at hot full power corresponding to a neutron source increase < 160%



ADS With Fertile-Free Fuel



Fertile-free ADS three-zone cores

- 580 MWth
- MOX of LWR origin (40% Pu, 50% Am and 10% Cm)
- Maximum fuel/matrix fraction 50%
- Two CERCER fuels (ZrO_2 and MgO matrices)
- CERMET fuel (^{92}Mo matrix)

Neutronics calculations

- SIMMER-III12, 35, MCNP20, ERANOS36 and DANTSYS18
- XS libraries: JEF2.2, JEFF3.0, JENDL3.3, ENDF/B-IV.8

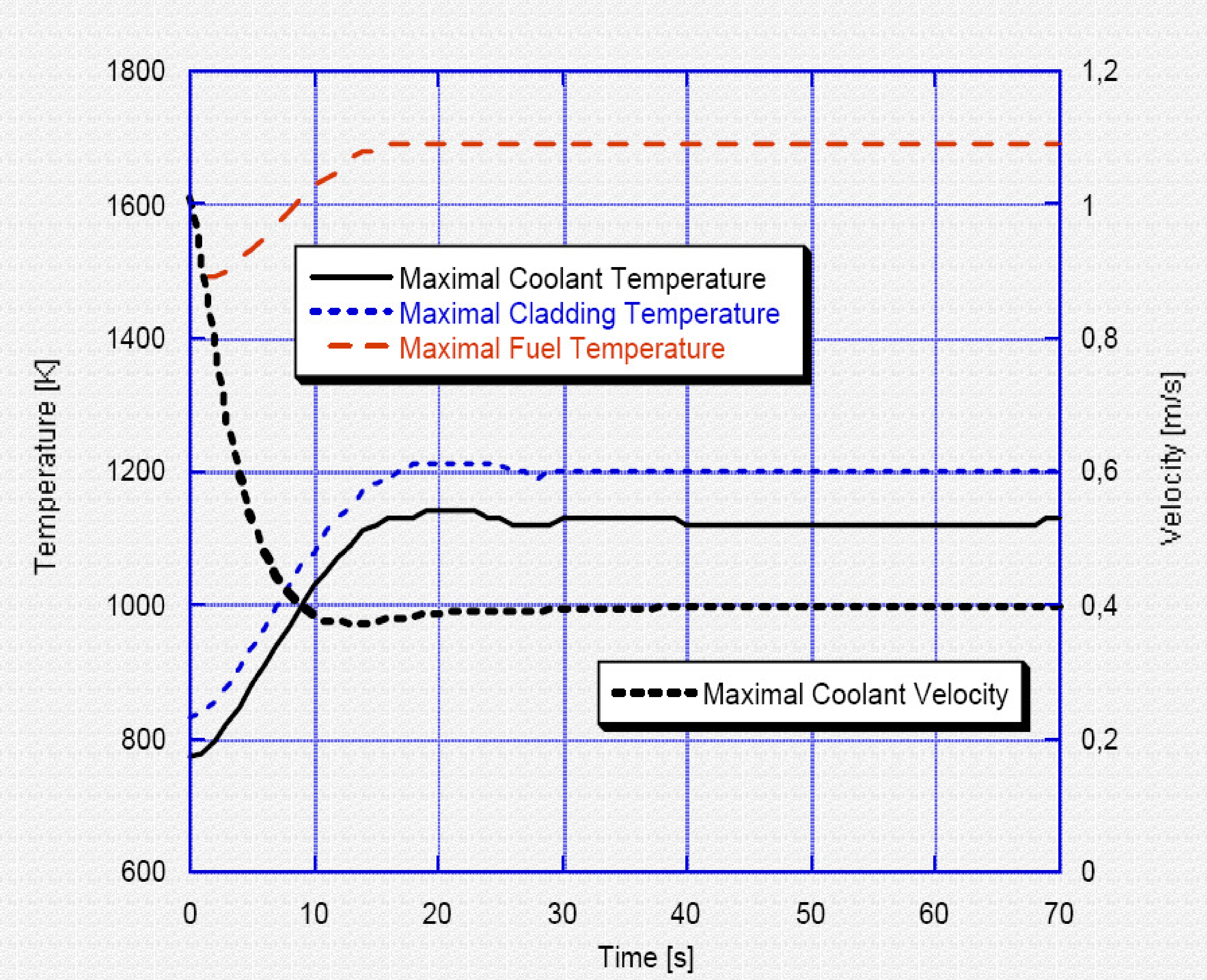
Conclusions

- Agreement satisfactory, e.g. CERCER Δρ Na core void 6500 / 7700 / 8300 pcm (JEF2.2 / JENDL3.3 / JEFF3.0)
- Major source of discrepancies ⇨ Pb and Bi nucl. data
- MgO matrix fuels ⇨ better transmutation characteristics
- ^{92}Mo CERMET ⇨ best transient behavior

ADS With Fertile-Free Fuel

Transients: ULOF, UTOP, unprotected Beam Overpower (150% and 200% proton beam overpower at hot full power), unprotected Assembly Blockage

CERCER (MgO) ULOF ⇨ max. fuel temp. < 1800 K (below 2100 K limit ⇨ possibility of MgO matrix disintegration)



ADS With Fertile-Free Fuel

- **Helium cooled ADS**
  - 400 MWth ADS
  - CERCER fuel (Pu enrichment 36.4wt%)
  - MgO matrix
  - fuel/matrix ratio of approximately 34%
- **Neutronics Calculations**
  - Codes: Monte-Carlo (TRIPOLI4 (Ref. 38), MCNP4C39, OCTOPUS (MCNP4C3+FISPACT)40, MCNPX.2.5.0, and deterministic (ERANOS2.0 (Ref. 36), DANTSYS18 + C4P37)
  - JEF2.2, JEFF3.1, JENDL3.3, ENDF/B-VI nuclear data libraries

ADS With Fertile-Free Fuel

- **Conclusions**
  - Initially, large discrepancies (ERANOS2.0) in sub-criticality level ⇨ overlapping effect of Mg and O_2 resonances ⇨ fine-group treatment required ⇨ ERANOS2.0 analyses of cores with large MgO and MAs content must use JEFF3.1 and fine-group treatment for Mg, O_2 and all MAs ⇨ BOL sub-criticality results converged to k_{eff}=0.98
  - $\Delta\rho_{bu}$ ⇨ large discrepancy between ERANOS2.0, JEFF3.1 (1965 pcm) and other results (2737-2847 pcm) ⇨ different ^{242m}Am branching ratio in ERANOS2.0
  - Total (U and Pu) transmutation rates ⇨ satisfactory agreement (-41 to -43 kg/TWh thermal)
  - Agreement for safety relevant static parameters: generally satisfactory
    - ✓ β_{eff}: 173-179 pcm, except for MCNP JEF2.2 (144 pcm)
    - ✓ $\Delta\rho$ depressurization (60 to 1 bar): 239-289 pcm
    - ✓ $\Delta\rho_{Doppler}$ large spread: 40 to 94 pcm (T_{fuel} 993→180°C)

Conclusions

- Steady state neutronics analyses
  - Both deterministic S_N and Monte Carlo codes are advanced enough to provide good agreement for all the considered systems
  - Larger uncertainties are generally caused by the different nuclear data libraries used; deviations may not only be caused by the minor actinides data, but also by fission products data and data of matrix materials in inert fuels

Conclusions, cont'd

- **Transient analyses**
  - Code systems of different level of sophistication (methodological, i.e. from point-kinetics to space-time kinetics, and thermal-hydraulic modelling) needed to cover all the time-scales of the different systems and all the transients: very detailed codes have difficulties in their running times, e.g. for long-lasting LOHS transients; less sophisticated codes neglect important phenomena ⇨ intermediate class of codes is needed
  - With one exception, the CRP benchmarking activities covered only transients and accidents without core disruption. Complexity and effort would greatly increase, should such severe transients be allowed for all the investigated transmutation systems. Such a task might be considered for a future CRP

Conclusions, cont'd

- Comparative assessment of the dynamic behaviour of the various transmutation systems
  - Importance of the prompt Doppler feedback effects in systems fuelled with fertile fuel in curbing power excursions
  - For the fertile-free systems similar mitigating effect provided either by the thermal expansion feedbacks or the sub-criticality of the system

Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems

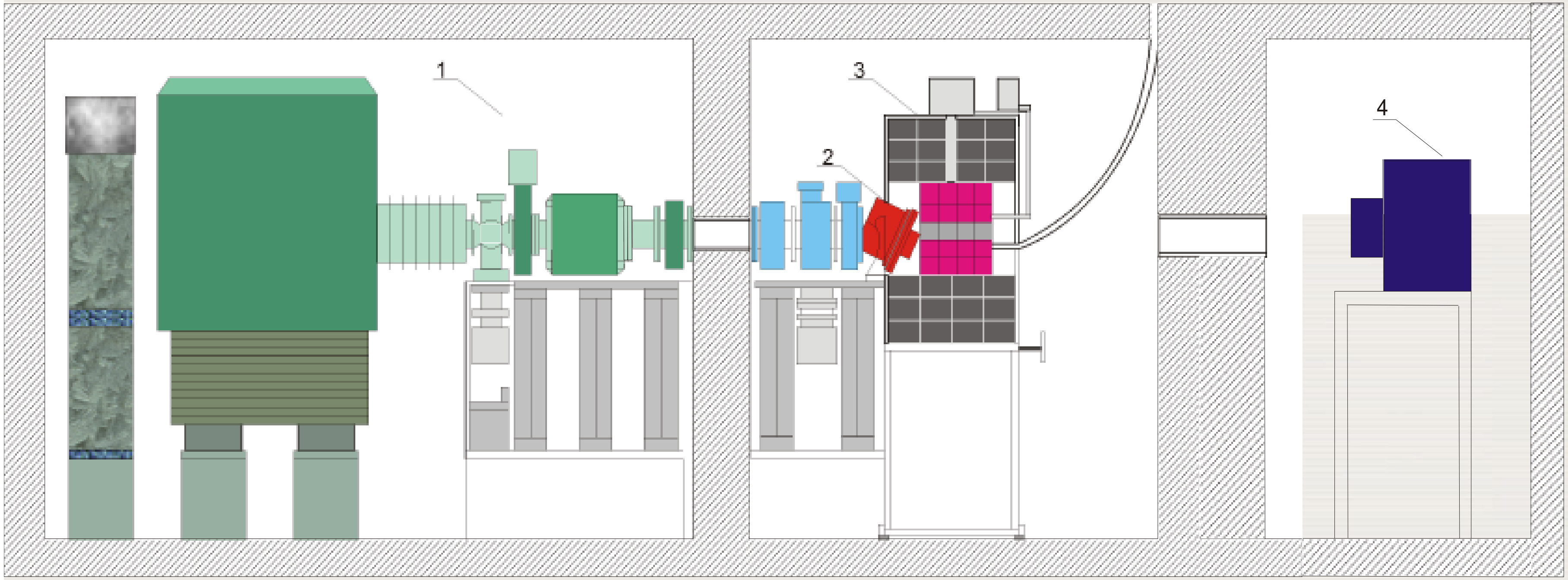
- **Objectives of the CRP**
  - Improve understanding of the coupling of an external neutron source with a sub-critical core
  - Validation of integrated calculation schemes ➔ experimental benchmarks
- **Participation: 27 institutions in 18 IAEA Member States**

YALINA-Booster

YALINA-Booster Facility (JIPNR, Minsk, Belarus)

(1) d-accelerator; (2) neutron source: Ti-d (or Ti-t) target

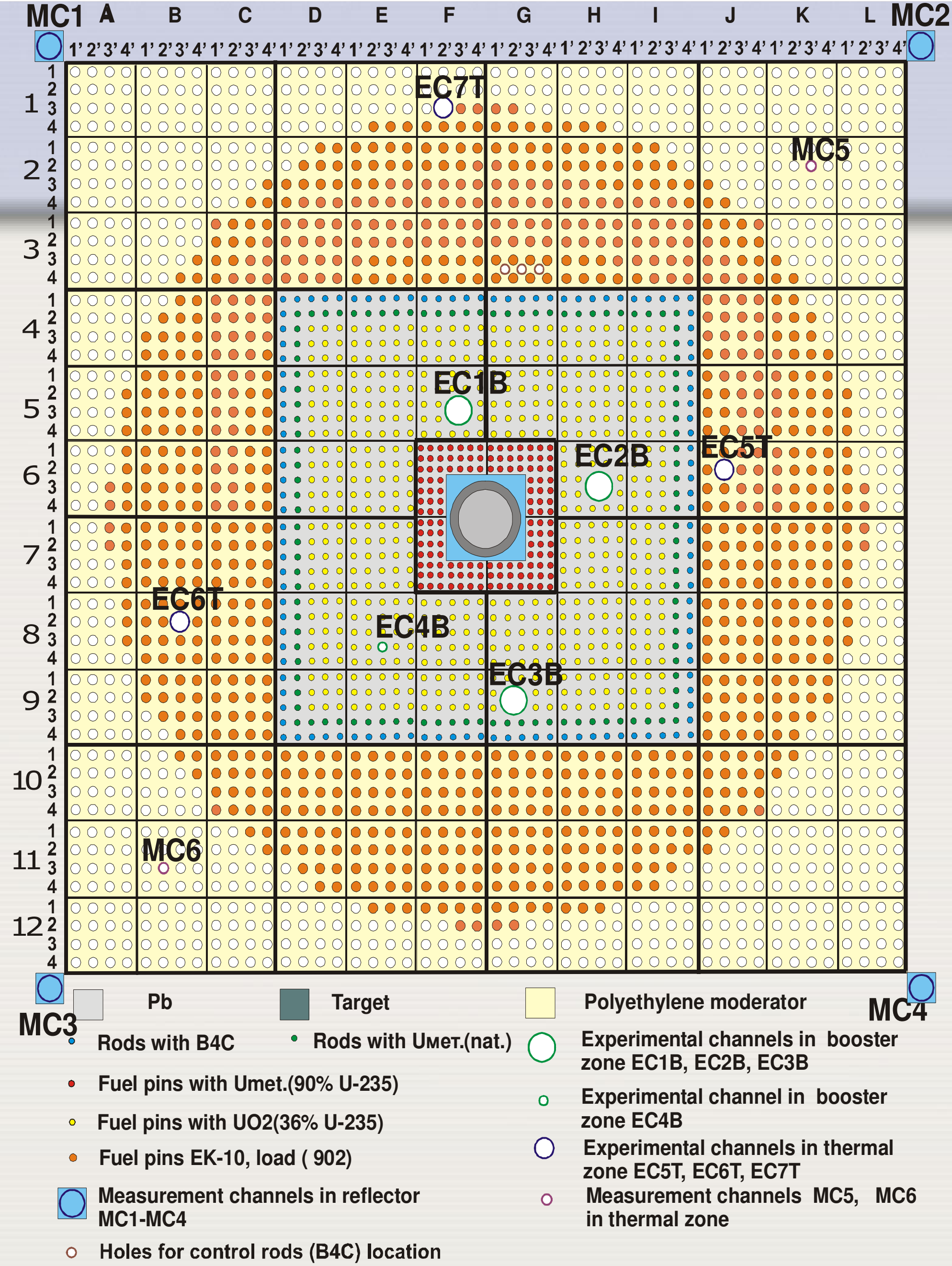
(3) sub-critical assembly; (4) γ-spectrometer



YALINA-Booster Benchmark Specifications

Two sub-critical configurations differing in thermal zone loading

Configuration #1: 902 Al clad UO_2 and MgO rods, 10% ^{235}U)



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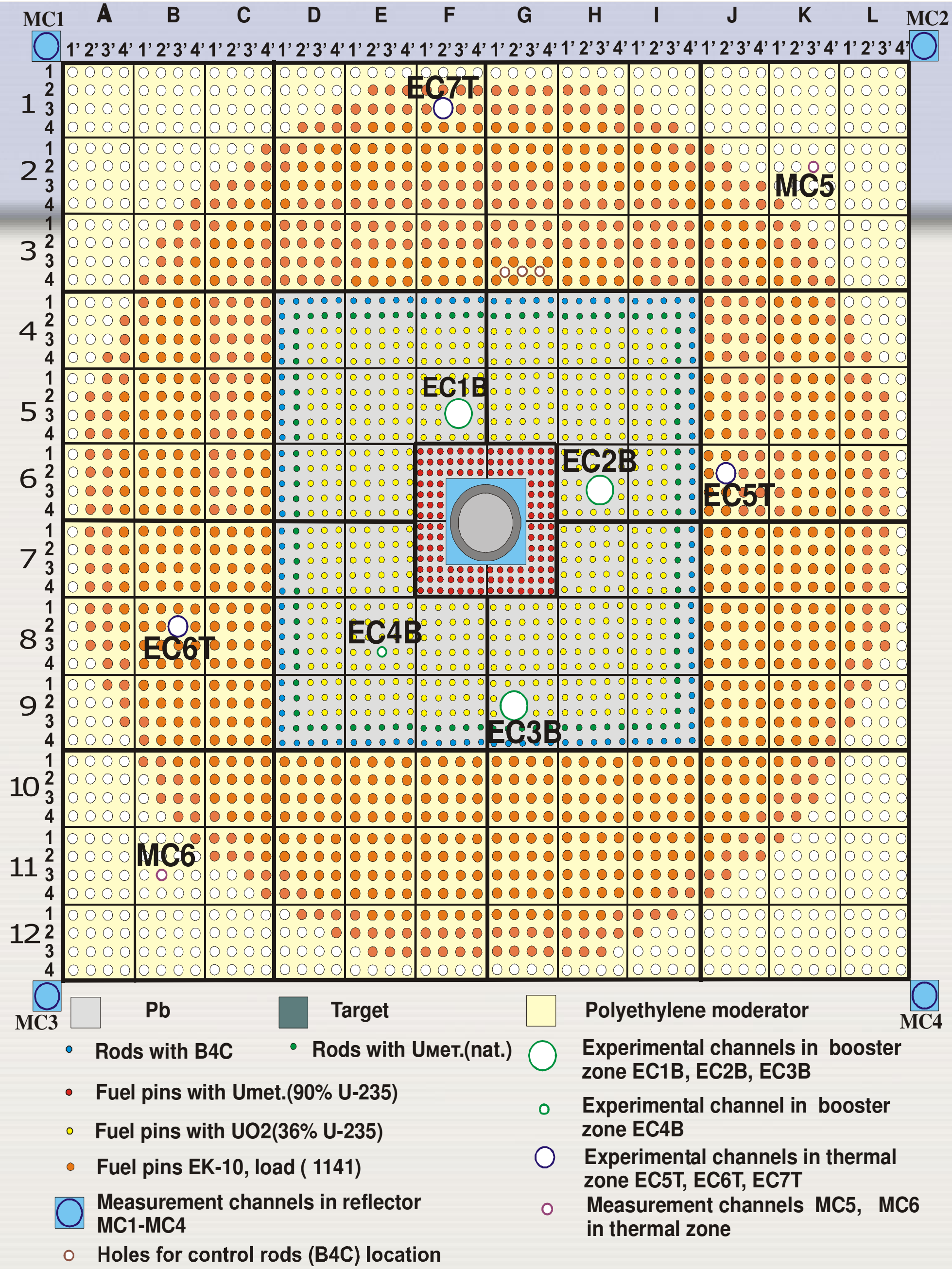
YALINA-Booster Benchmark Specifications

Two sub-critical configurations differing in thermal zone loading

Configuration #2: 1141 Al clad UO_2 and MgO rods, 10% ^{235}U)



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YALINA-Booster Benchmark Analyses

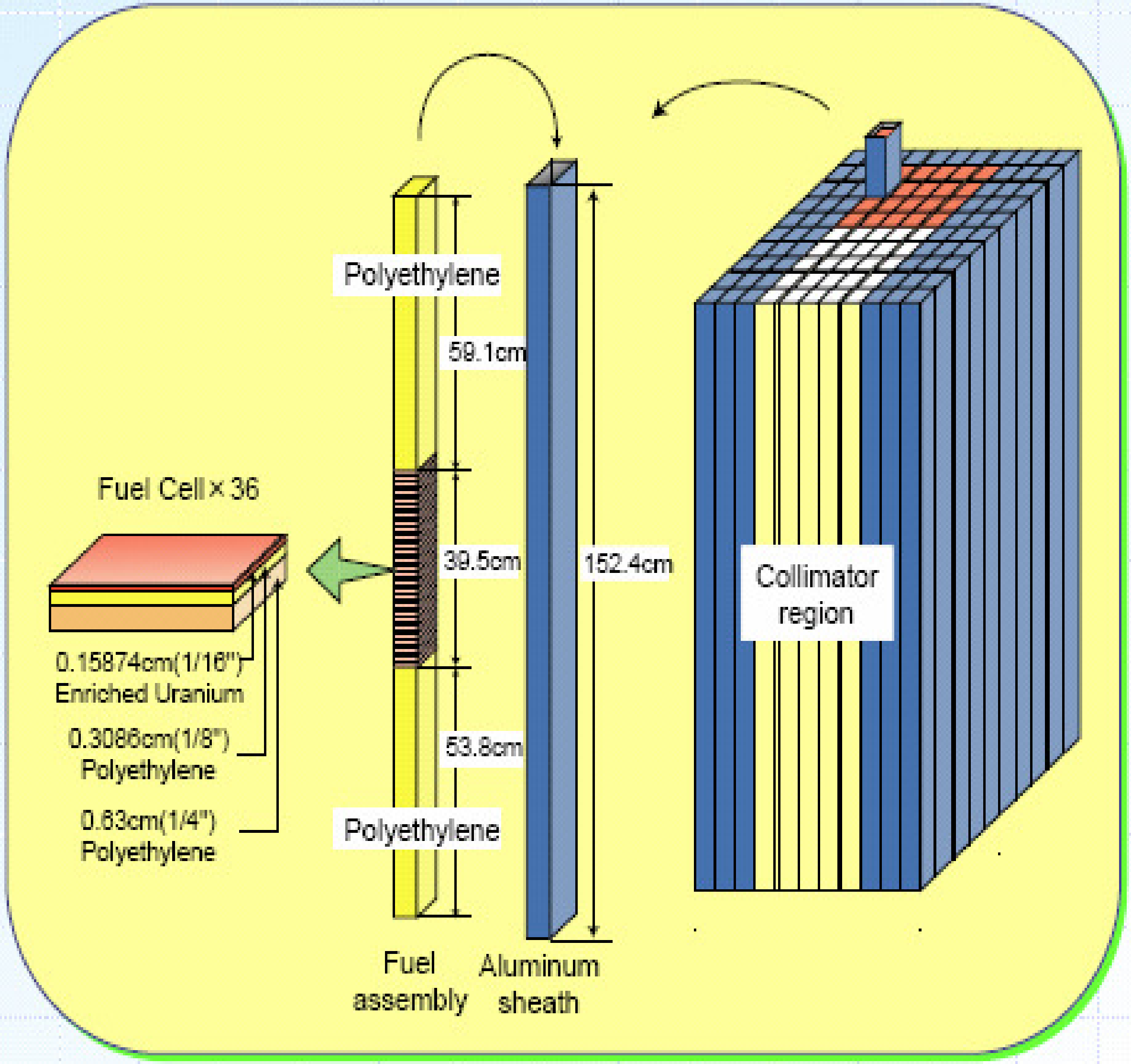
Axial and radial reaction rate distributions (detector locations)

Reaction Rate	Axial Distribution	Radial Distribution
$^{3}He(n,p)$	EC6T	–
$^{235}U(n,f)$	EC2B, EC6T	–
$^{115}In(n,\gamma)$	EC2B, EC5T, EC6T, EC7T	EC10R
$^{197}Au(n,\gamma)$	EC2B, EC6T	–
$^{55}Mn(n,\gamma)$	EC2B, EC6T	–

YALINA-Booster Benchmark Analyses

- Neutron spectra
- Neutron flux
- Effective (k_{eff}) and source (k_s) multiplication factor
- Mean neutron generation time (Λ)
- Prompt (l_p) and mean (l) neutron lifetime
- Effective delayed neutron fraction (β_{eff})

KUCA Sub-Critical Benchmark

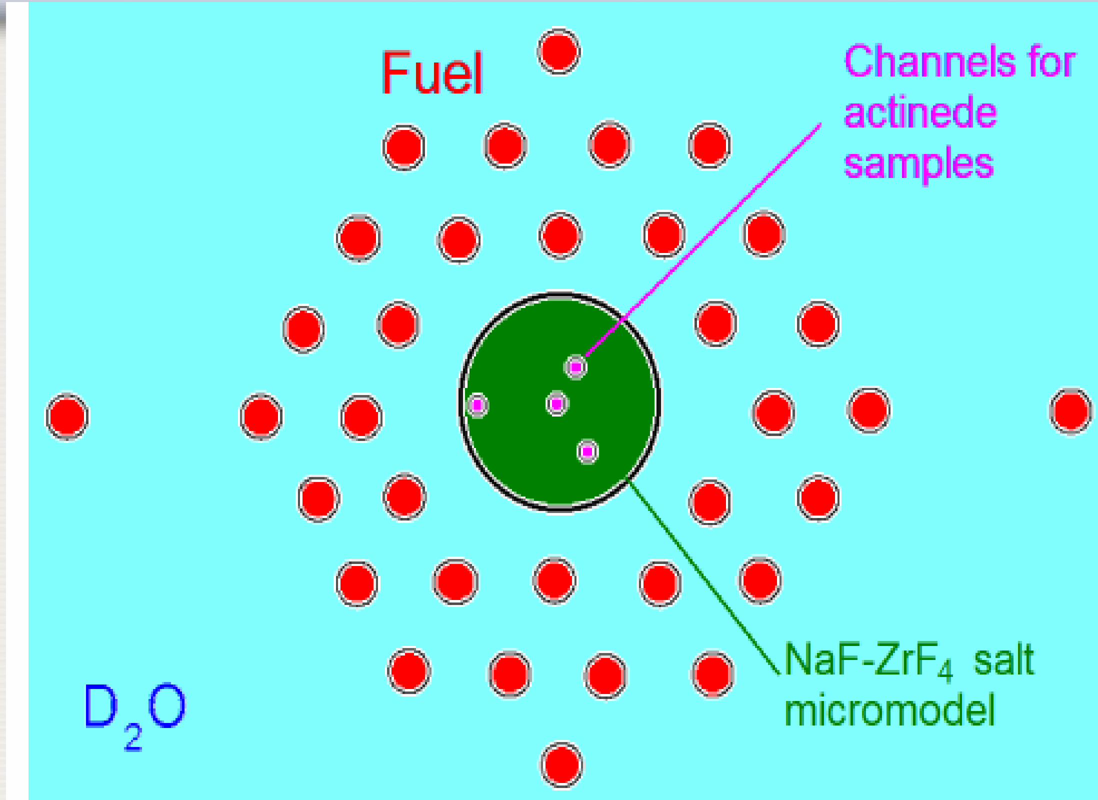


Three stages:

- Static neutronics in sub-critical KUCA with (D,T) neutron source
- Kinetics benchmarks focusing on the sub-criticality measurement methods using the (D,T) neutron source
- Static and dynamic spallation target KUCA experimental program (150 MeV FFAG proton accelerator)

Actinides Cross Sections

Actinides Integral Fission XS Measurements in ITEP's MAKET Heavy-Water Critical Facility

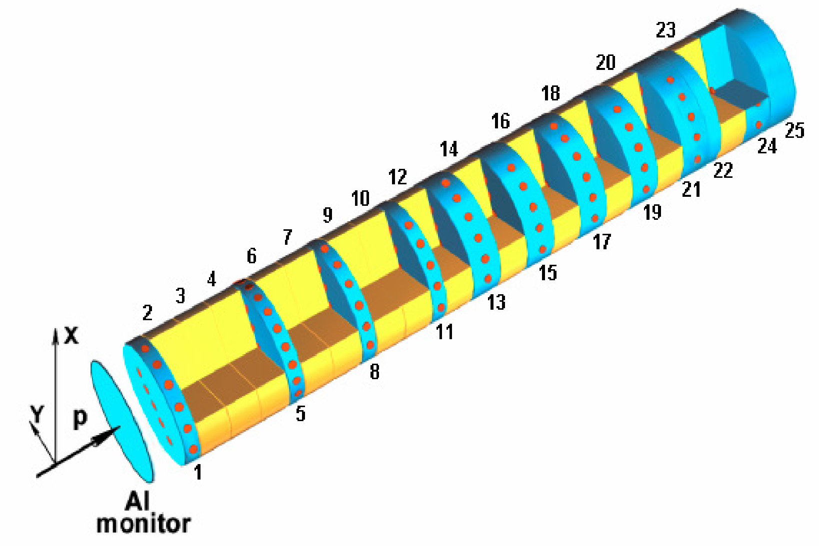


Actinide samples placed into special channels inside $0.52NaF+0.48ZrF_4$ solid Salt melt Blanket "Micro-modules" (SBM)

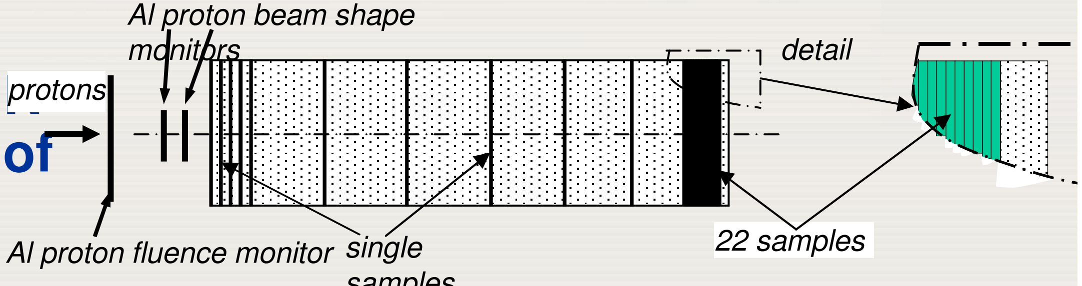
^{235}U, ^{239}Pu, ^{237}Np, ^{238}Pu, ^{240}Pu, ^{241}Pu, ^{242m}Am, ^{243}Cm, ^{245}Cm, ^{247}Cm

Spallation Target Studies

- Production rates of residual activation reaction products
  - Tungsten and sodium target
    - 800 MeV protons at ITEP U-10 synchrotron
    - Irradiated samples ^{209}Bi, ^{197}Au, ^{181}Ta, ^{169}Tm, ^{115}In, ^{93}Nb, ^{65}Cu, ^{63}Cu, ^{64}Zn, ^{59}Co, ^{27}Al, ^{19}F, ^{12}C

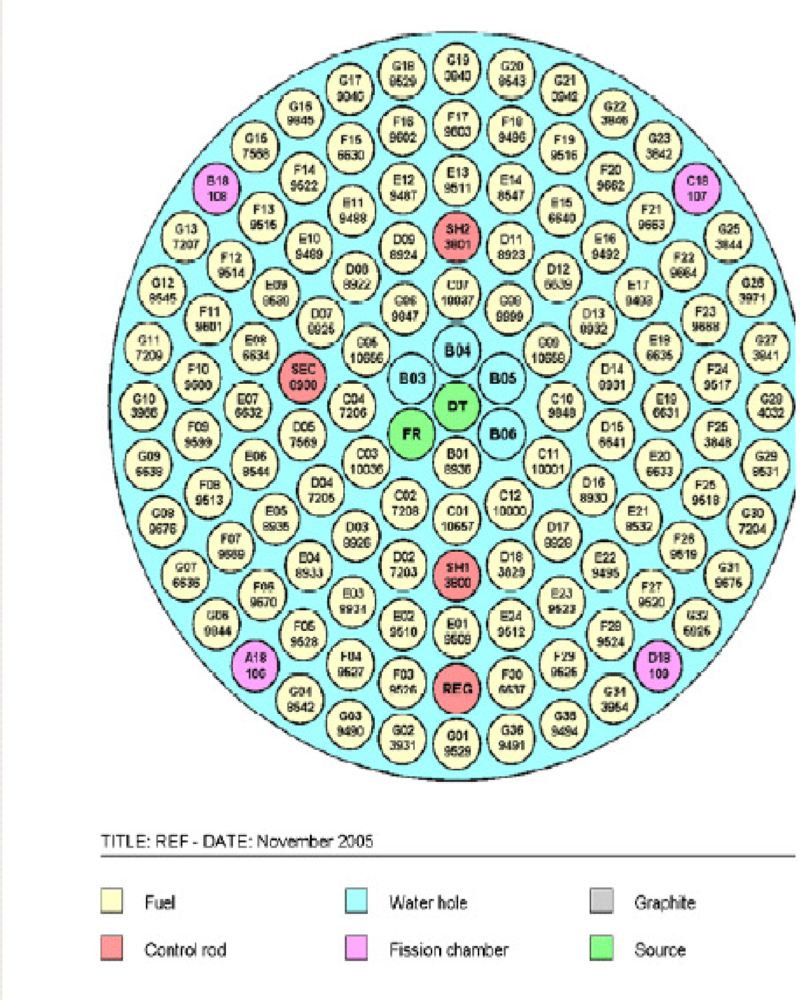


  - Lead Target
    - 800 MeV protons at ITEP U-10 synchrotron
    - 660 MeV protons at JINR Dubna, Dzhelepov Lab of Nuclear Problems



Pre-TRADE Experiments

- **TRIGA RC-1 Pre-TRADE sub-critical reactivity measurements (-500, -2500, -5000pcm)**
- **Understanding the spatial/energy correction factors with different experimental sub-criticality measurement techniques:**
  - **MSM (MSA) [^{252}Cf source in B02]**
  - **"PNS Area-ratio" [(D,T) neutron generator]**



ADS Kinetics and Dynamics Analytical Benchmarks

- Definition of several benchmarks for ADS neutron kinetics and dynamics problems amenable to
  - Exact analytical solutions
  - Highly accurate numerical solutions
- Definition of benchmarks comprises
  - Identification of physical problems (e.g. type of transient, pulsed/oscillated experiment, etc)
  - Definition of physical configurations (e.g. geometry, source, etc) with increasing degree of complication
  - Definition of physical quantities of interest (e.g. neutron fluxes/currents, integral parameters, etc)
  - Choice of physical models to be adopted (transport/diffusion)
- CRP participants are
  - Solving the benchmark problems (exact solutions for analytically solvable problems, and numerical solution with the help of available codes in other instances)
  - Performing error evaluations

http://www.iaea.org/inisnkm/nkm/aws/fnss/index.html

Thank You !

…Atoms for Peace