Recriticality, a Key Phenomenon to Investigate in Core Disruptive Accident Scenarios of Current and Future Fast Reactor Designs

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Technical Meeting on
Impact of Fukushima event on current and future FR designs
20 - 23 March 2012
Dresden - Germany

Introduction

- March 11, 2011, 14:46 JST; Earthquake Magnitude 9
- Measured accelerations up to 26 % higher than earthquake design basis for Fukushima Daiichi
- Automatic scram, stop of power generation; decay heat level
- Start of diesel generators, transiently stable state
- Tsunami hits Fukushima plant (+ 60 min) - BDB
- Flooding of diesel generators
- Long time Station Blackout
- Common mode failure - multiple plants
- Only battery power left; loss of emergency core cooling systems, only pumps directly driven by steam turbines remain for some time
- Finally loss of all emergency core cooling systems (batteries empty and/or pump failures)
- Decreasing water level, core uncovering, first core damage and fission product release
- Core melt, hydrogen detonations, fission product release
- Loss of decay heat removal capability in fuel element storage tanks

General Comments

- **Fukushima boiling water reactors represent an old design revealing many weaknesses under severe accident conditions**
- **Modern plants, as GEN-III, GEN-III+ plants should not have ended in a core melt situation under similar conditions. Mitigative measures in case of core melt.**
- **In future fast reactor systems significantly higher passive safety features are installed, which could cope with events like Fukushima**
- **So, what lessons can be learned in a more general way from a Fukushima type event ?**
  - **Events were not expected neither in their strength nor in their consequences, leading to a common mode failure and a simultaneous meltdown of several reactors.**
  - **Overshooting of the tsunami wave. The height of the 'edge' of the tsunami protection wall literally represented a cliff edge.**
  - **The accident does not fall under the residual risk category but is related to an insufficient prevention of external events**
  - **The accident evolved in a complex nature defying any control and disproving all predictions on grid recovery potentials.**
  - **The plant showed weaknesses in design which made accident management measures difficult.**
  - **Human intervention and accident management mistakes further deteriorated plant conditions**

- **Important lesson : put a focus on rare initiators, accident routes and consequences that are neither expected nor have been observed, events that are categorized under '*black swans*'**

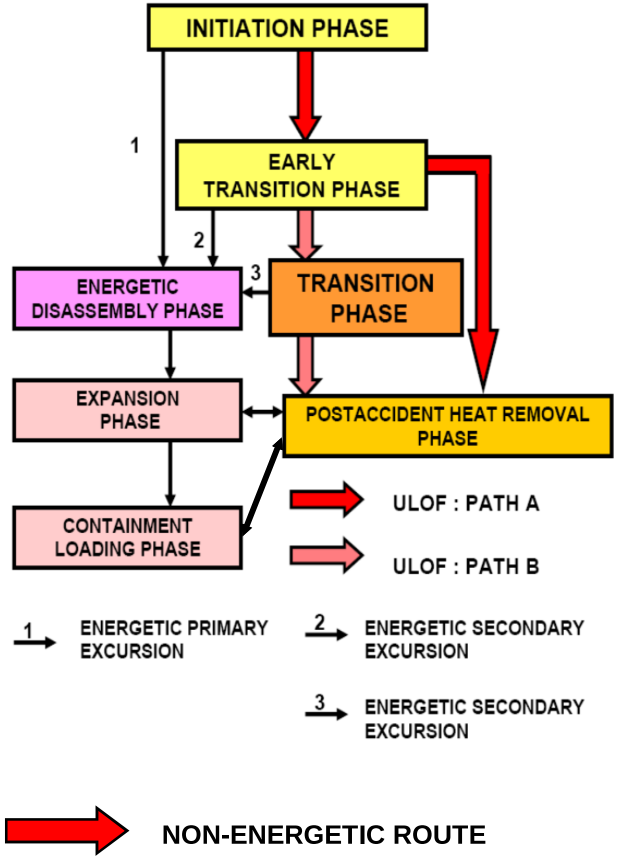
What is specific for FRs ?

- Focus on fast reactor systems, specifically the SFR
- What specific safety issues would be important for SFRs concerning severe accidents ?

➡ In fast spectrum systems as the SFR the core is not in its neutronically most reactive configuration and SFRs may be loaded with MAs for waste management

- Investigations of recriticality scenarios under severe accident conditions are a key issue of fast reactor systems:
  - Recriticalities have a high probability because of the higher enrichment levels
  - Much shorter time scales. LWRs core melting on an hours scale, FR core disruption on a second and minutes time scale.
- Future FR systems should be prepared for waste management, loading minor actinides (MAs):
  - Decay heat levels might be significantly different, if MA bearing fuel is involved
  - Nuclides generating decay heat and neutron precursors might evaporate and relocate by fuel motion impacting local decay heat loads and the neutron kinetic behavior
- Future FR systems should excel in safety requiring no emergency evacuation outside the immediate vicinity of the plant in case of severe accident
- Assessing old designs of fast reactors as the SNR-300, one can identify a much more advanced safety technology already compared to Fukushima type reactor

Safety Analyses Background



INITIATION PHASE

1

EARLY TRANSITION PHASE

2

3

ENERGETIC DISASSEMBLY PHASE

TRANSITION PHASE

EXPANSION PHASE

POSTACCIDENT HEAT REMOVAL PHASE

CONTAINMENT LOADING PHASE

ULOF : PATH A

ULOF : PATH B

1 → ENERGETIC PRIMARY EXCURSION

2 → ENERGETIC SECONDARY EXCURSION

3 → ENERGETIC SECONDARY EXCURSION

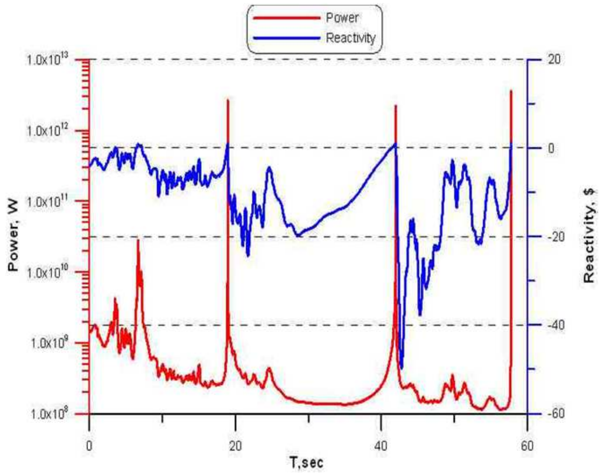
NON-ENERGETIC ROUTE

- **Phase diagram for core disruptive accidents (CDA) or Bethe-Tait accidents**
- **TRANSITION PHASE (melt & disruption phase) determines outcome of transient**
- **Route to TP : protected & unprotected transients**
- **Recriticality events take place during melt-down**
- **Complex behavior, opening of multiple event channels, increase of reactivity range scale, non-linearity, ….**
- **Important new approach : Obtain controllability of transition phase via CMR (controlled material relocation)**

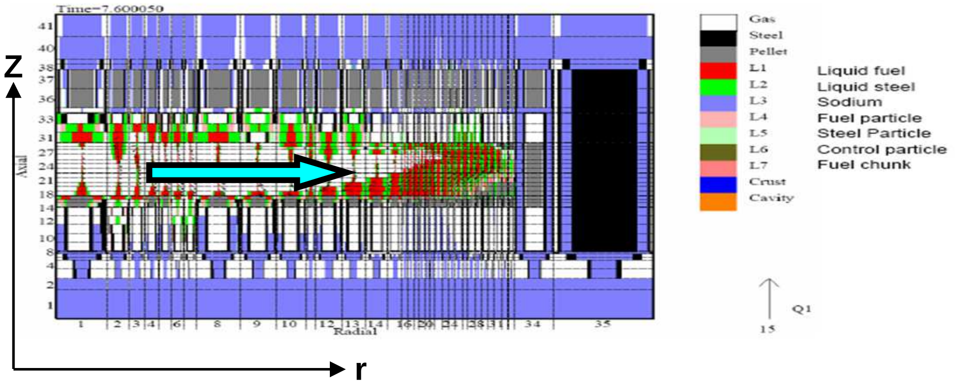
Transition Phase

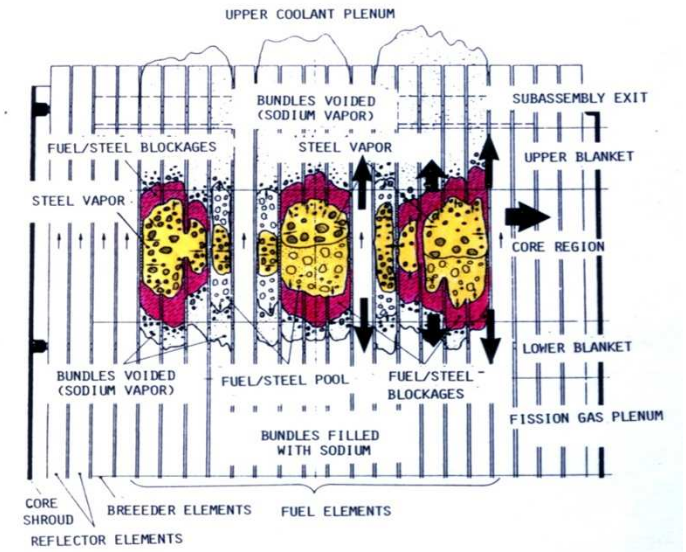
- **TRANSITION PHASE : Progression of core-melt after end of initiation phase with already disrupted but instable material configuration**
- **In case of (1) insufficient fuel release from the core and (2) coherent material motion (sloshing)**

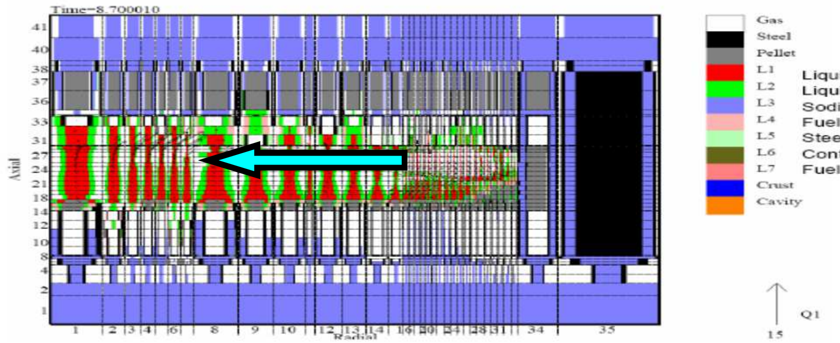
➡ potential of recriticality with energetics



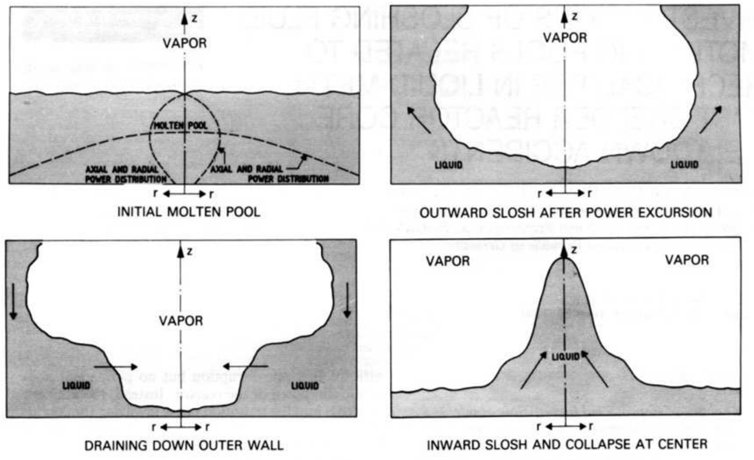
Typical nuclear power trace with multiple excursions until final core disassembly







Recriticality by Coherent Material Motion : Sloshing



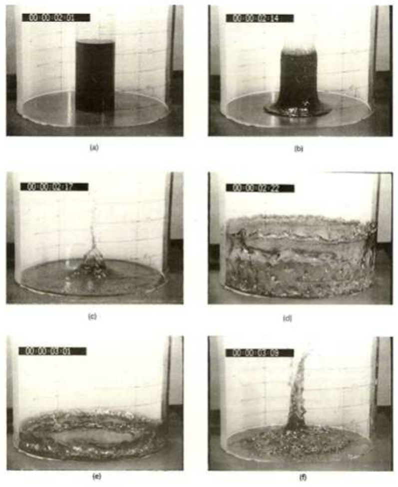
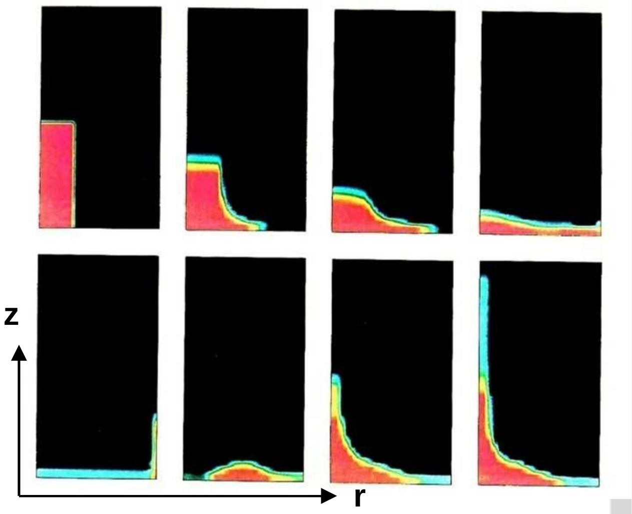


Fig. 3. Sloshing motions seen in experiment 1 (dam break).



Problem of Sloshing Phenomenon

- **Possible trigger of severe recriticality by coherent fuel motion**
- **Triggered by FCI or fuel/steel vaporization & neutronics**
- **Instability of inward slosh (Richtmeyer-Meshkov type instability) and existing structures diminish danger of coherent inward slosh**

Experiment : SLOSH

- **Material motion has to assessed with high confidence**
- **Phenomenological understanding of stability of sloshing motion**
- **Code test for numerical smearing and damping (danger of underestimation of ramp rates)**
- **Code validation**

Experiments : SNEAK 12 C Neutronics of Distorted Cores

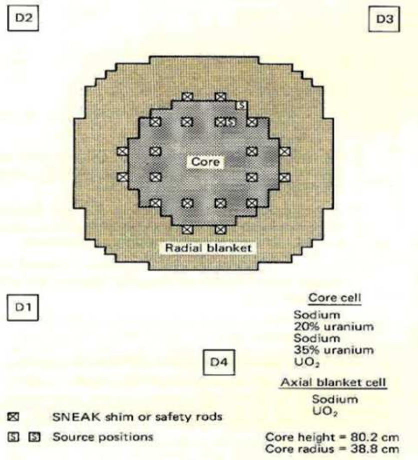


Fig. 3. Horizontal section and plate cells of SNEAK-12A. The designation "20% uranium" in the core cell means uranium metal, 20% enriched in ^{235}U. Plate thicknesses are sodium, UO_2 0.628 cm and uranium metal 0.314 cm.

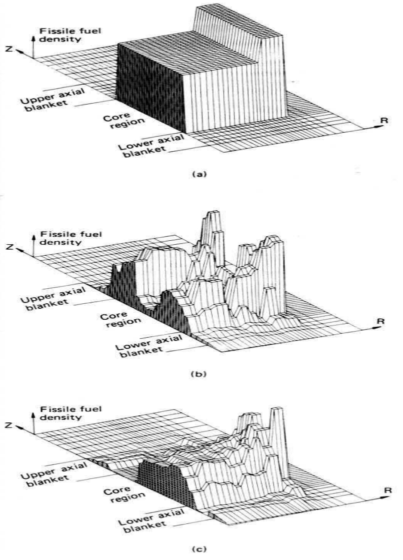


Fig. 1. Fissile fuel distributions occurring in LMFBR accident analysis: (a) undisturbed distribution, (b) slumpout configuration (calculated by SIMMER-II), and (c) slumpin configuration (calculated by SIMMER-II).

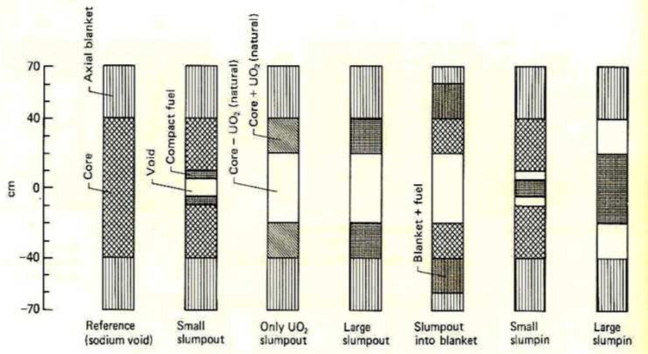


Fig. 7. Loadings for symmetrical fuel redistribution experiments.

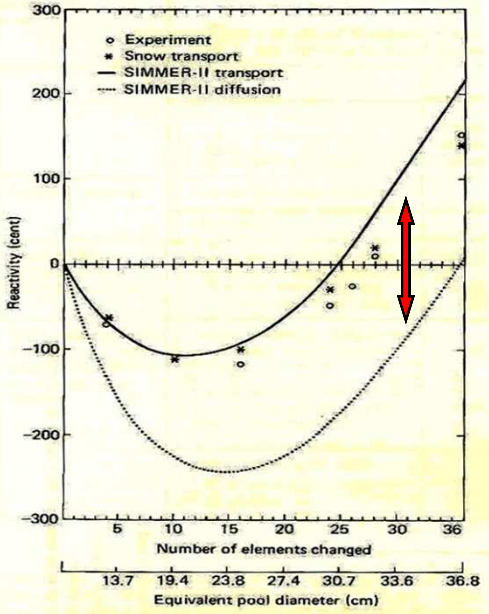


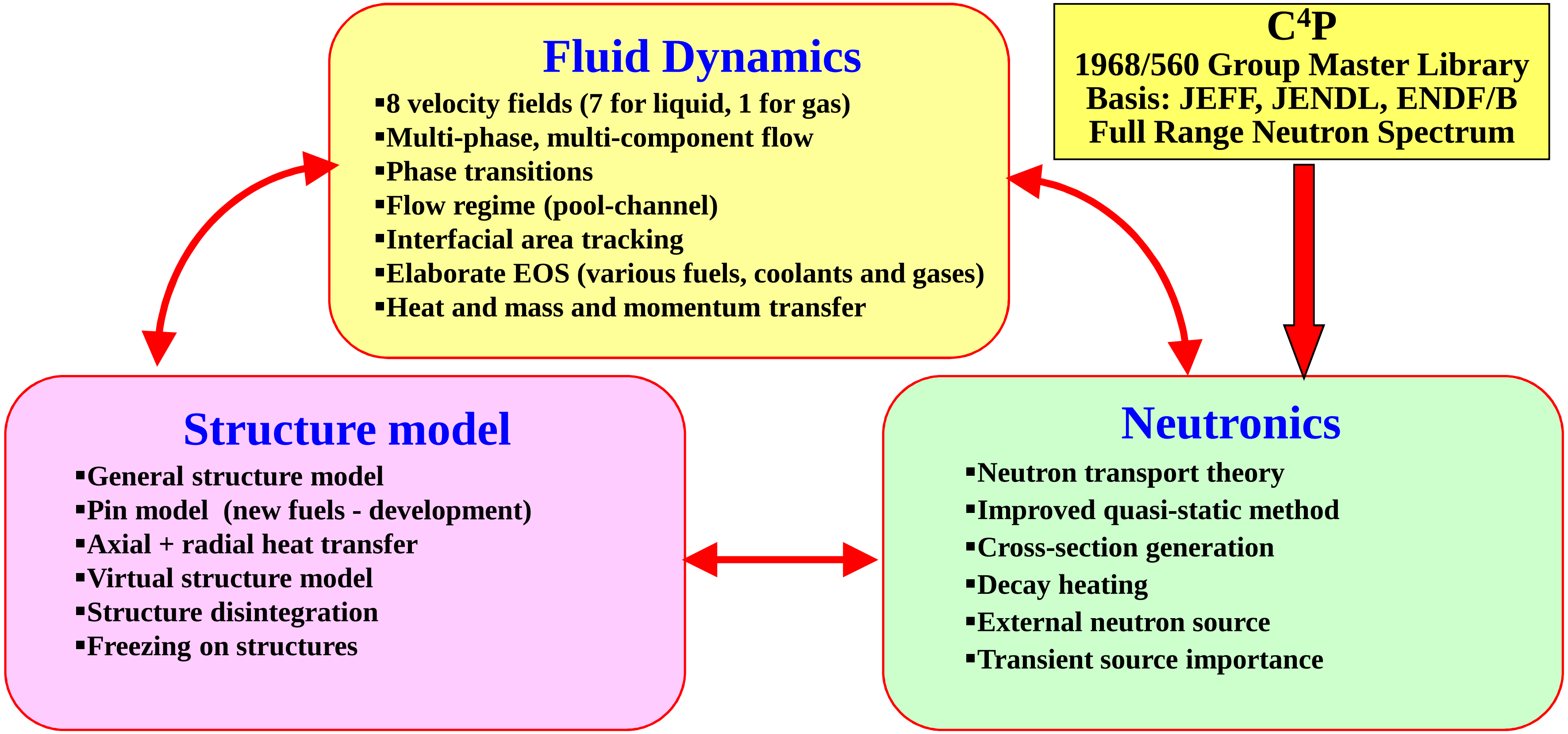
Fig. 10. Reactivity versus diameter of the simulated meltdown zone.

Critical experiments on distorted cores: SNEAK 12C & FCA

- **Simulation of material redistribution (slump-out, slump-in, pool-formation)**
- **Check of neutronics codes/modules**
- **Need for transport theory demonstrated**
- **Assessment of transient safety codes with (limits in groups, S_N order etc.)**
- **Taking into account heterogeneity effects**

SIMMER-III & SIMMER-IV

SIMMER-III and SIMMER-IV are 2D and 3D fluid dynamics codes coupled with a structure model and a space-, time- and energy-dependent neutron dynamics model



Fluid Dynamics

- 8 velocity fields (7 for liquid, 1 for gas)
- Multi-phase, multi-component flow
- Phase transitions
- Flow regime (pool-channel)
- Interfacial area tracking
- Elaborate EOS (various fuels, coolants and gases)
- Heat and mass and momentum transfer

C^4P
1968/560 Group Master Library
Basis: JEFF, JENDL, ENDF/B
Full Range Neutron Spectrum

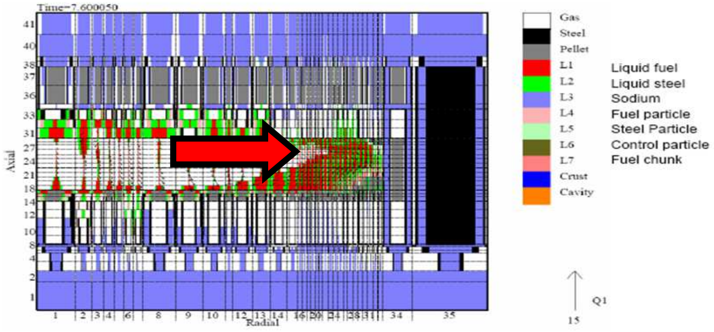
Structure model

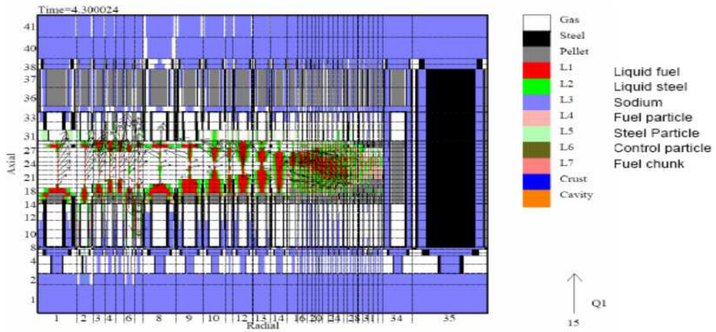
- General structure model
- Pin model (new fuels - development)
- Axial + radial heat transfer
- Virtual structure model
- Structure disintegration
- Freezing on structures

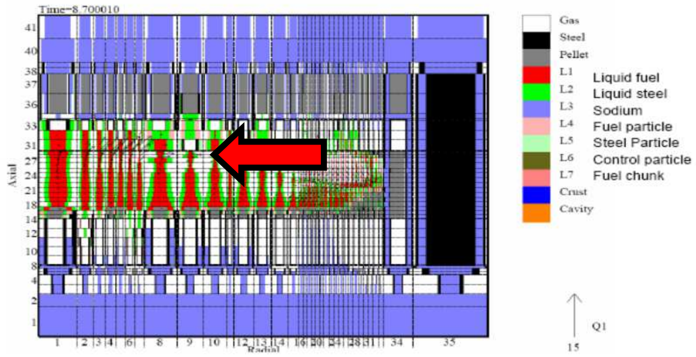
Neutronics

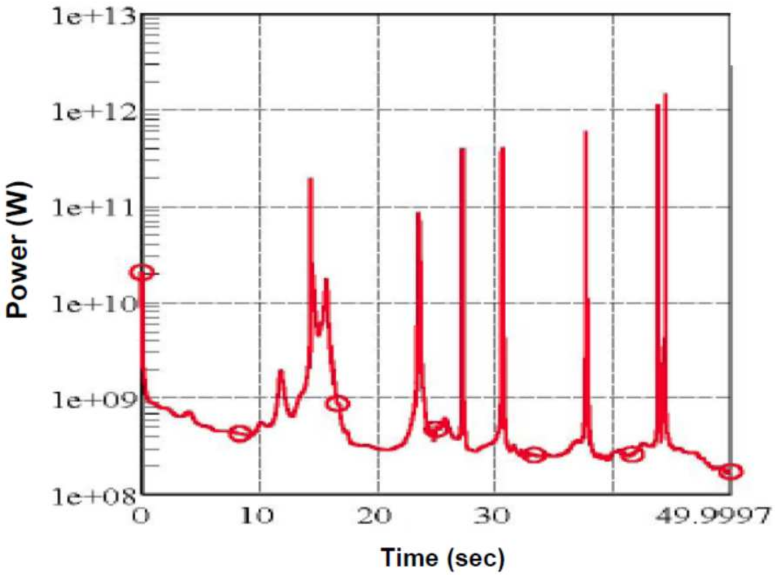
- Neutron transport theory
- Improved quasi-static method
- Cross-section generation
- Decay heating
- External neutron source
- Transient source importance

Route to Recriticality : Unprotected Accident - ULOF







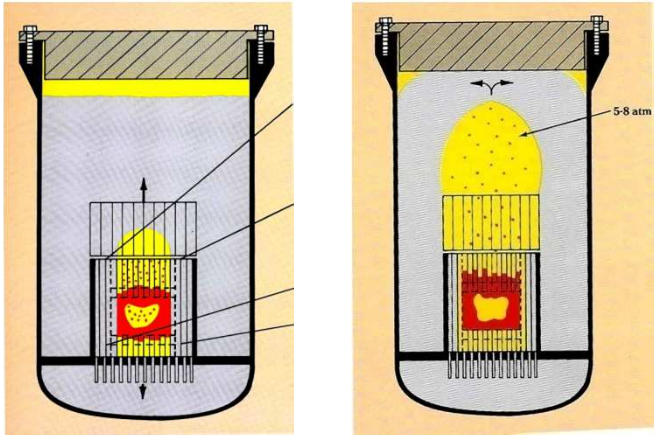


ULOF : Unprotected Loss of Flow Accident

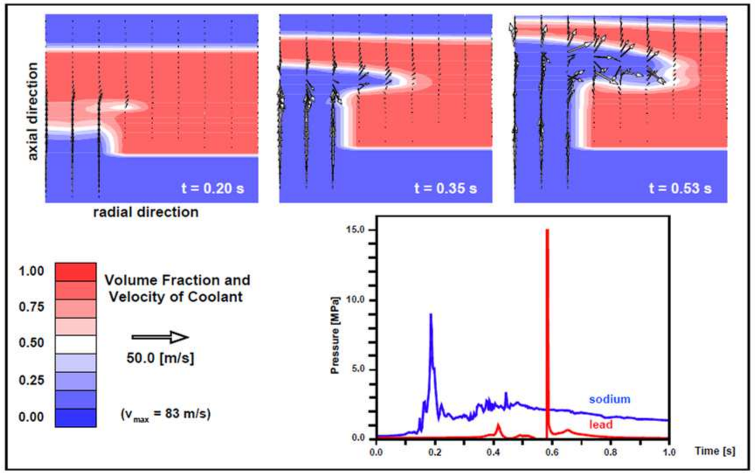
- **Pump coast down in ~ 10 sec and failure to scram**
- **Coolant boiling starts after ~ 30 sec**
- **Core melt initiation**
- **Core melt and fuel discharge after ~ 1 minute**
- **Potential for energetics and mechanical energy release**
- **Fast spectrum system : High power excursions with small half-width**

Disassembly & Expansion Phase

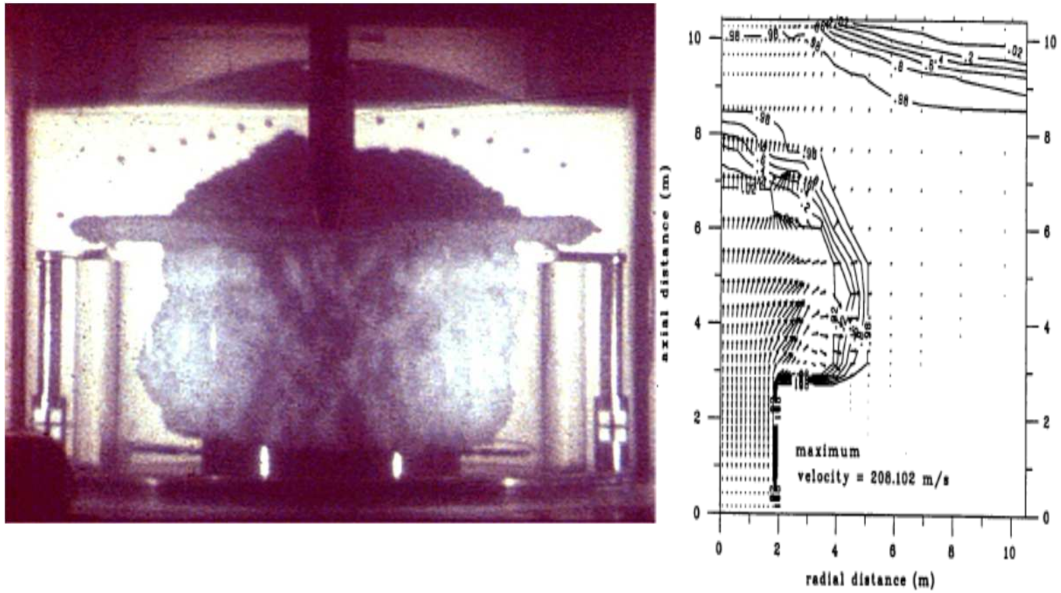
- In case of severe transient : Discharge of molten material from core and acceleration of surrounding coolant; redistribution of granulated fuel
- Important for work energy potential and mechanical structure load assessment after severe accident
- Upper core and vessel structures & behavior to be known (impact on mitigation)



Expansion phase phenomenology

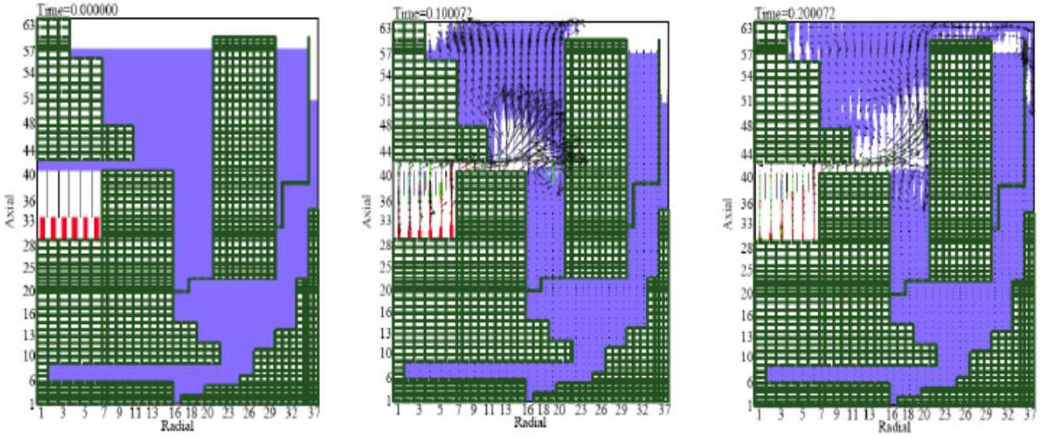


SIMMER-III void evolution (RZ) and pressure trace at vessel lid for Na and Pb coolants



SGI Experiment

Expansion Phase Calculations & Mechanical Work Energy

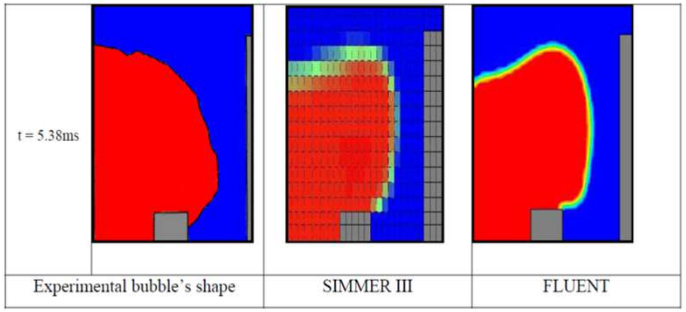


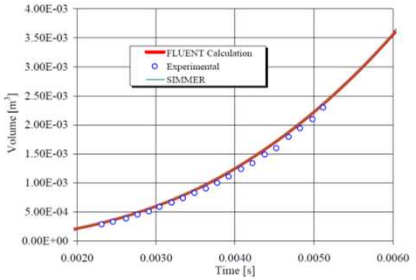
t = 0.0 sec

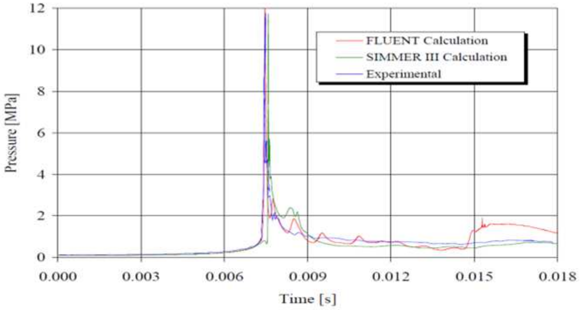
t = 0.10 sec

t = 0.20 sec

Expansion sequence and bubble pattern for an SFR and interaction of fuel/steel with coolant







The mechanical energy calculation takes into account three parts:

1. Kinetic energy of the coolant, due to the movement of the coolant itself
2. Work performed on the cover gas
3. Work due to the gravitational forces

Recalculation of SGI experiment and code benchmark (FLUENT)

Route to Recriticality : Protected Accident : PLOHS

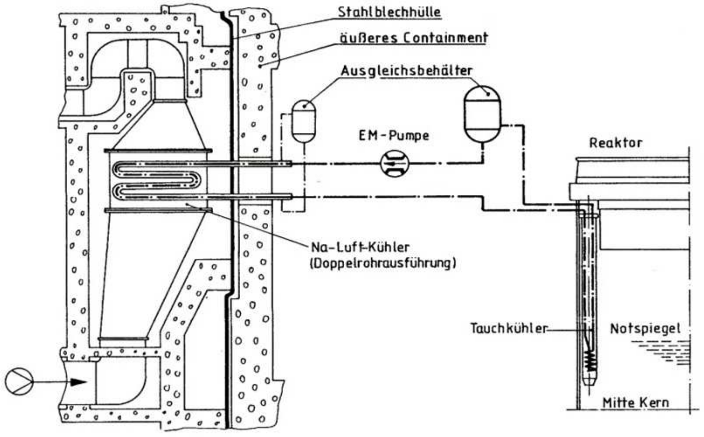


Bild 2-10:
Reaktornotkühlsystem (Übersicht)

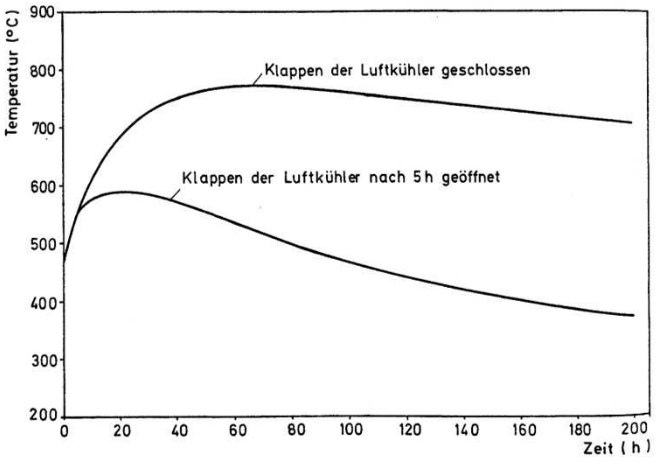
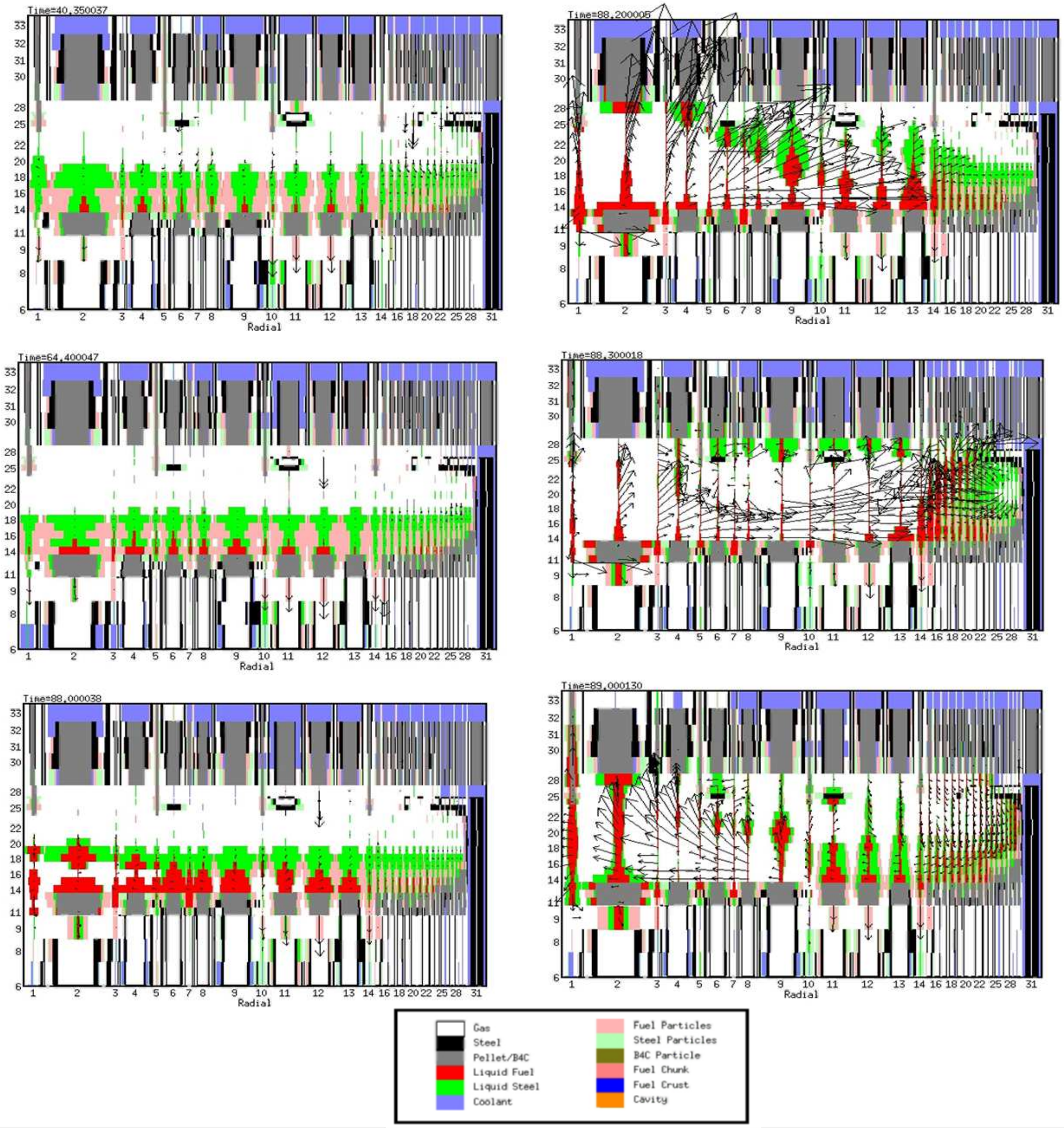


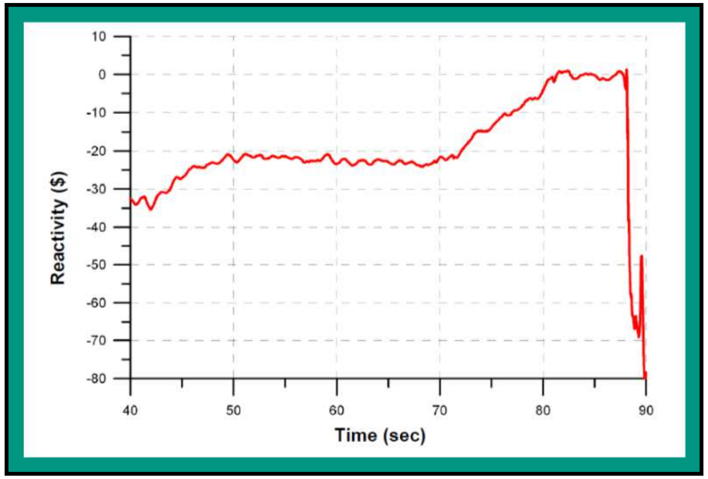
Bild 4-4:
Verlauf der mittleren Temperatur in den Na-Kreisläufen

GRS-51, ISBN 3-923875-00-2, Oktober 1982

- We refer to old German plant SNR-300
- 3 ordinary trains for decay heat removal & 6 independent immersion air coolers
- Failure of the systems does not necessarily lead to a core damage due to the natural convection capability in connection with the large heat capacity of the sodium loops and the large potential heat losses via radiation
- The passive decay heat removal can be enhanced by opening air flaps of the dip coolers
- The sodium temperatures reached depend on the timing of their opening. If all active decay heat measures have failed, the sodium temperatures reach about a peak of 840 K after 22 hours with flap opening after 5 hours
- If flaps remain closed, a peak of 1070 K is reached after 60 hours
- Elevated temperatures might lead to structural damage. Structure creep failure could lead to leaks leading to a loss of coolant, gas ingress and failure of the natural convection
- Core uncover and/or sodium boiling ending in core melting and disruption
- Important safety issue : failure of decay heat removal from fuel storage tanks. In case of failure of the active cooling, at a fully loaded vessel with a power of 0.85 MW, sodium boiling could be reached after 40 hours.

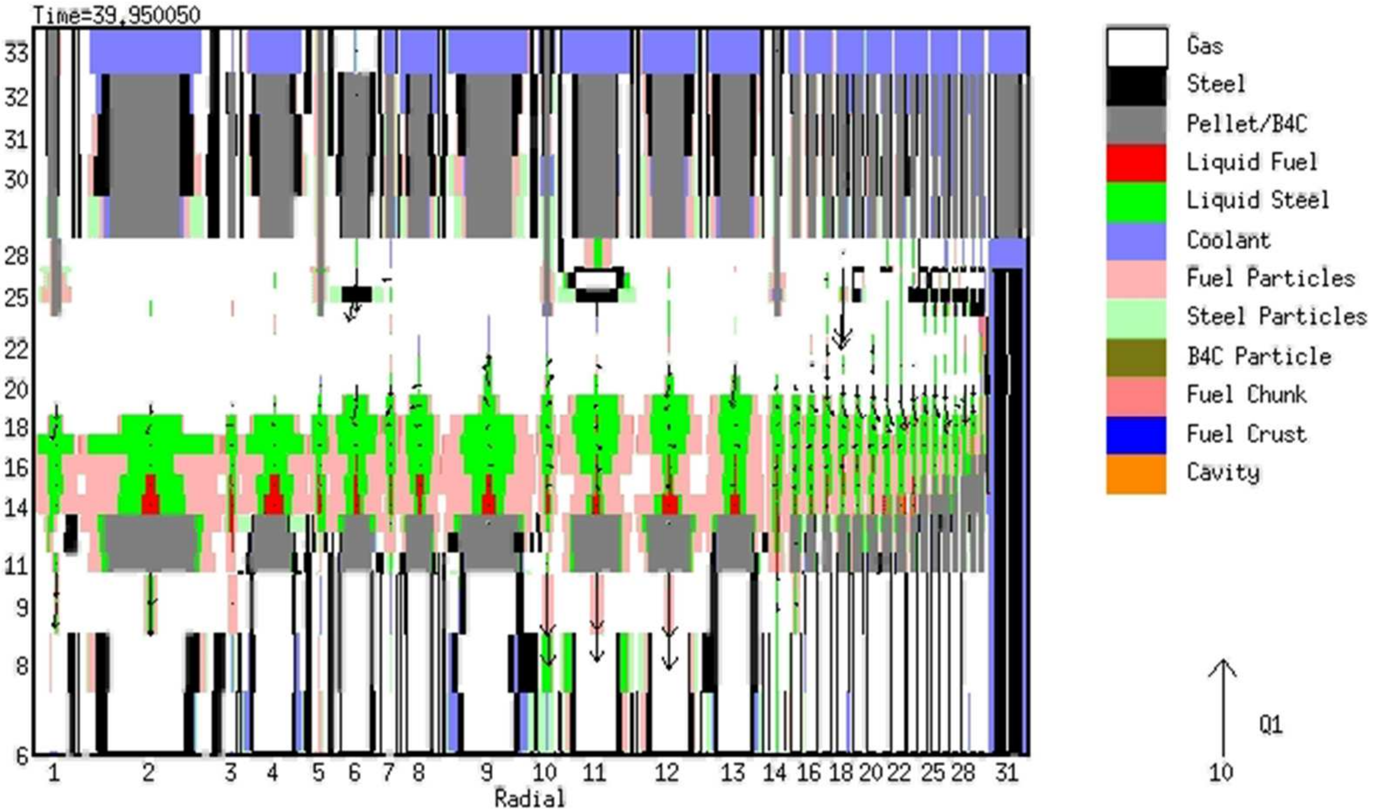
Recriticality under Protected Accident Conditions





- **CDF for protected transients dominating**
- **PLOHS**
- **Core configuration after boil-off of sodium and slow core degradation**
- **Fuel chunk/steel pool**
- **Fuel melting and separation of fuel/steel/B4C can introduce reactivity and finally trigger a recriticality**
- **Potential for energetic secondary excursion**

Sloshing Motion Initiated by F/SS/B4C Separation

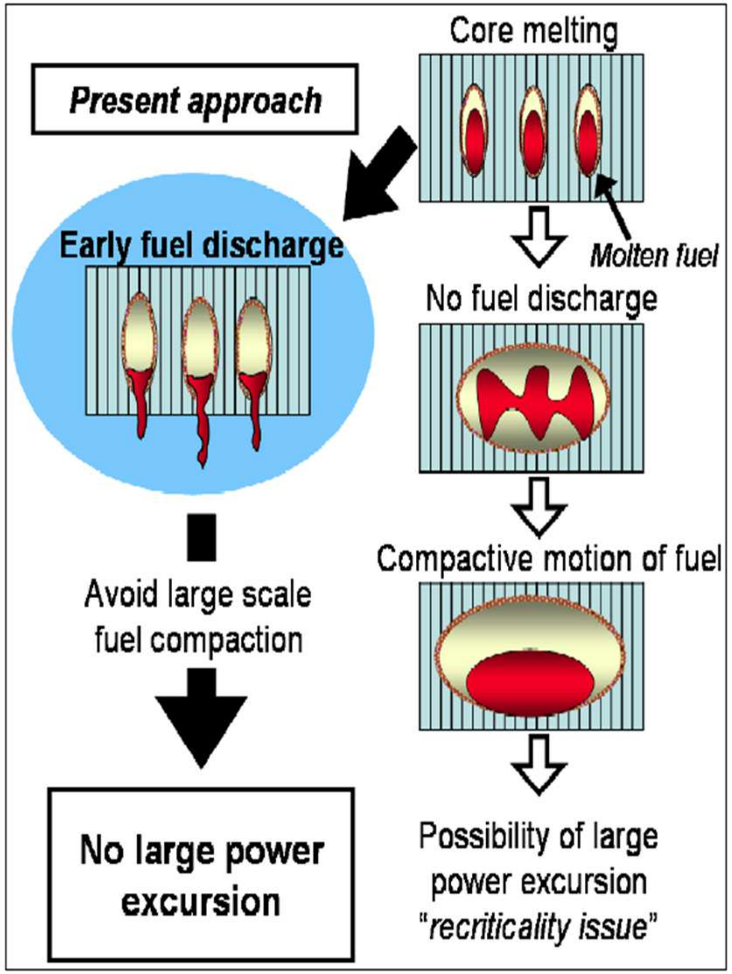


Recriticality via separation/segregation processes

New Approaches for Recriticality Prevention

- **Get control over transition phase and recriticalities**
- **Melt-down phase in a time-frame of seconds to minutes**
- **Conditions of Recriticalities :**
  - **Competition between fuel discharge from core region and prpagation to large size pools**
  - **Potential of tuning of excursions and coherent fuel compaction (sloshing motions)**
  - **Natural fuel release paths (subchannels, gap beetween hexcans, CRGT) not sufficient to guarantee nuclear shut-down**
  - **Roughly 20-30% of core fuel has to be relocated**
- **CONTROLLED MATERIAL RELOCATION (CMR)**
  - **Dedicated means to assure fast and sufficient fuel discharge**
  - **Support by SASS (self actuated shut-down system)**

JAEA Strategy



Present approach

Early fuel discharge

Avoid large scale fuel compaction

No large power excursion

Core melting

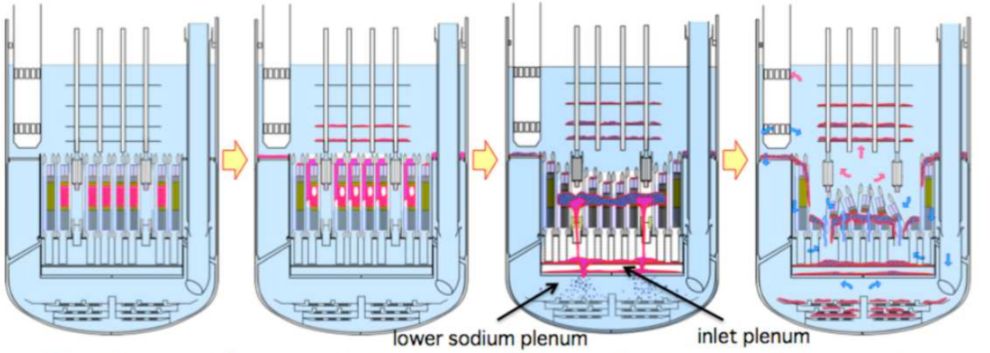
Molten fuel

No fuel discharge

Compactive motion of fuel

Possibility of large power excursion *"recriticality issue"*

I. Sato, FR'09, Dec. 7-11, Kyoto, Japan



(1) Initiating phase
Pin disruptions and fuel dispersal in SA

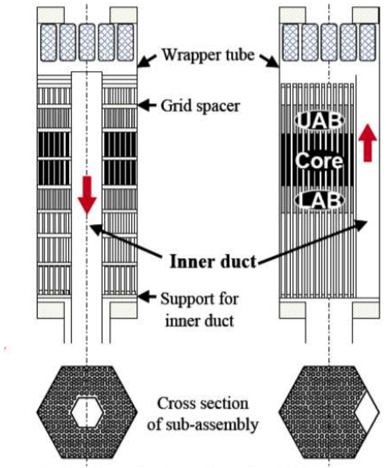
(2) Early fuel-discharge phase
Upward fuel discharge through inner duct

(3) Material-relocation phase
Fuel melting with decay heat and relocation into the lower sodium plenum

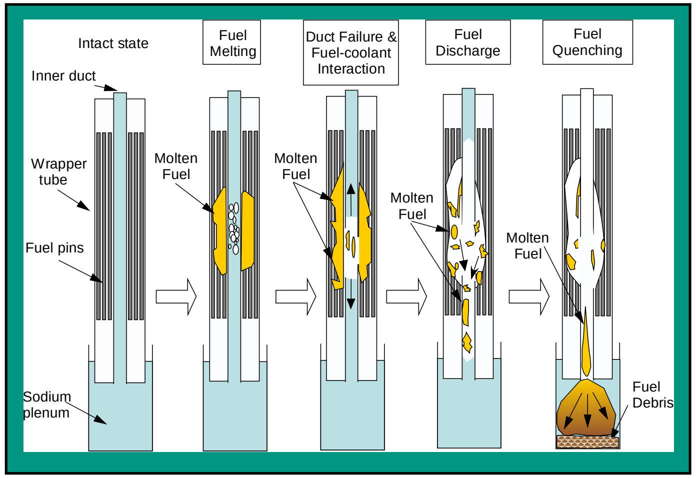
(4) In-vessel cooling phase
Stable cooling of relocated fuel

- **Means to increase fuel release from core via dedicated structures : FAIDUS**
- **Strategy: Early fuel discharge before large scale propagation**
- **Strong experimental demonstration : EAGLE**
- **Complex scenario with fuel discharge (with reversing directions), SASS action, upper structure collapse, transport into core catcher**

FAIDUS-Concept & EAGLE Program

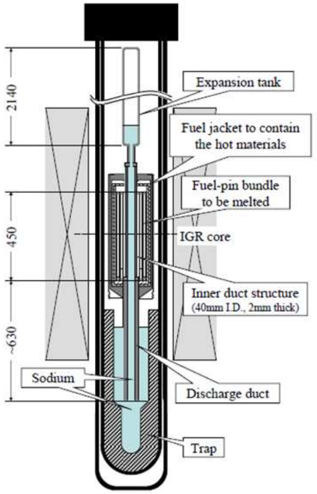


SA Designs Enhancing Fuel Discharge

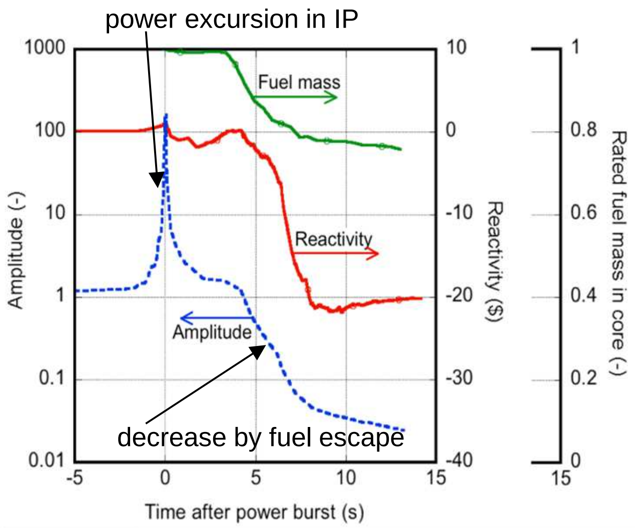


- **JAEA - EAGLE :** Experimental Program to demonstrate FAIDUS principle
- Out-of-pile and in-pile tests (IGR reactor)
- Tests ID1 and ID2
- Experimental demonstration of relevant phenomena

In-pile Tests in IGR



Test Section EAGLE ID1



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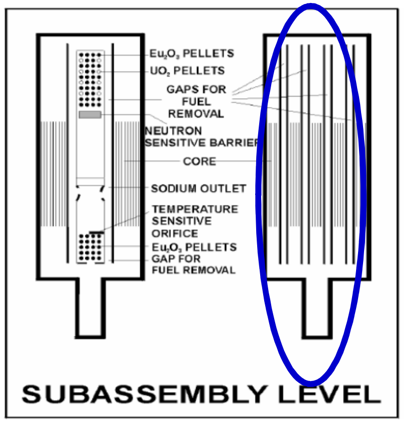
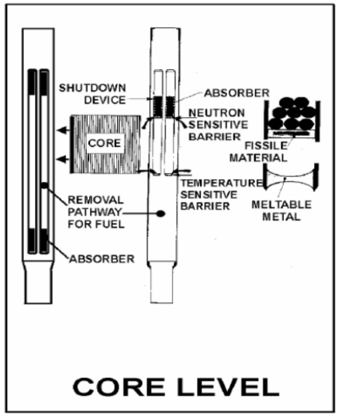
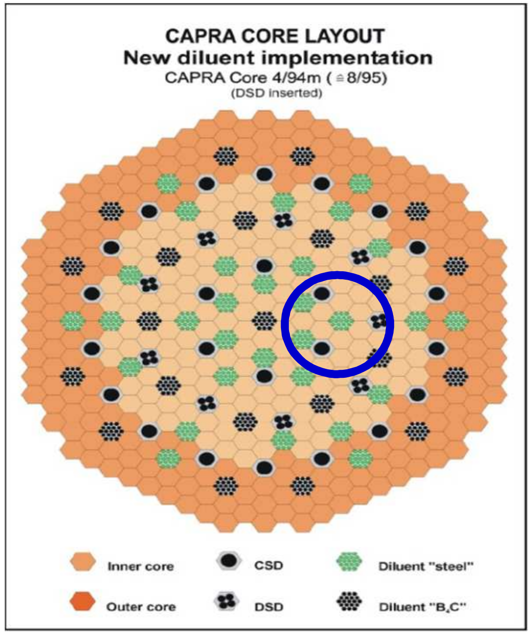
CAPRA/CADRA Strategy

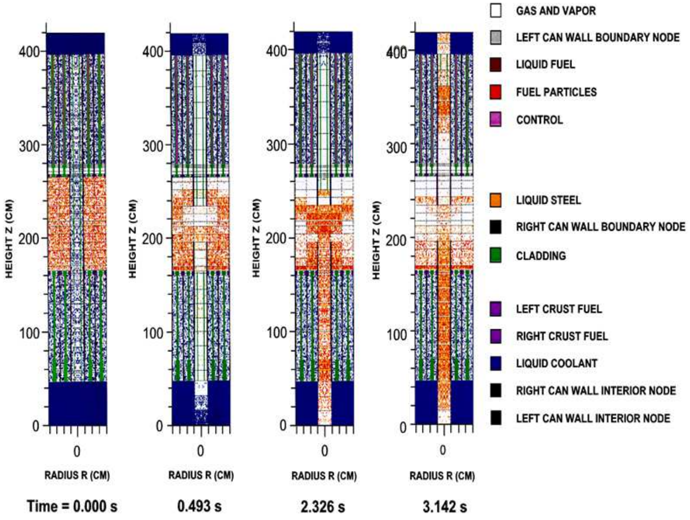
CAPRA/CADRA Cores

- **High Pu enrichment (up to 45 %)**
- **Strategy : Acceptance of damage propagation and pool growth into neighbouring diluent subassemblies and CR**
- **Fuel release via specially designed diluents – large hollow pins with minimized sodium inventory in diluent**









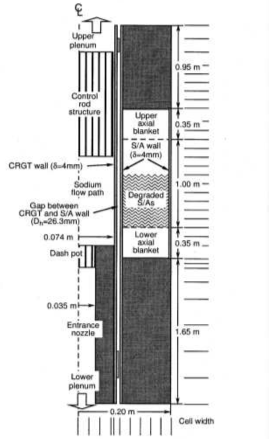
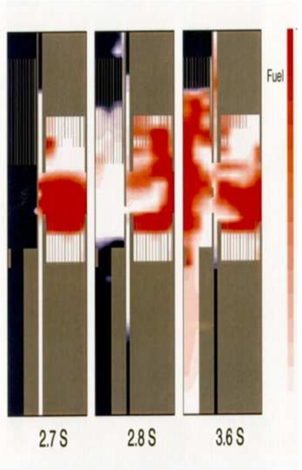
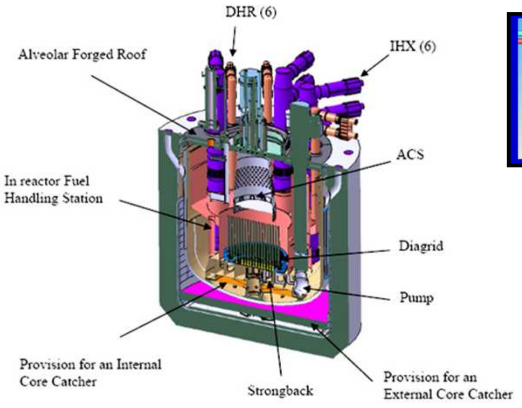


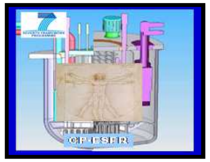
Fig. 1. Geometric model for analysis of fuel removal through CRGT channel.



Fuel relocation from core via diluents and CRGT

Example of SFR Project : CP-ESFR





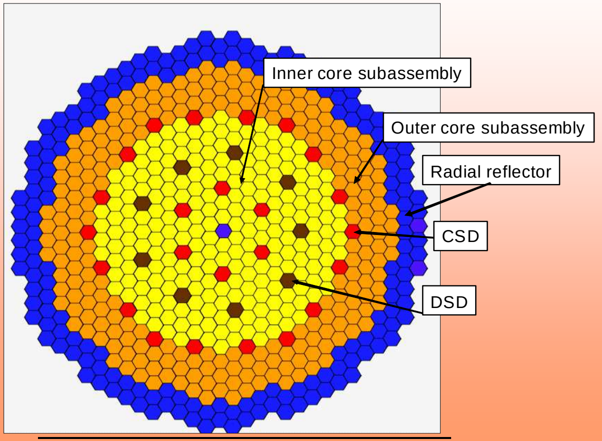
ESFR Pool Option

Reactor power	3600 MWth
Core inlet temperature	395°C
Core outlet temperature	545°C
Avg core structure temperature	470°C
Average fuel temperature	1227°C
429 fuel sub-assemblies	(207 / 222)
24 CSD, 10 DSD	
Pu enrichment	14.5% / 17.0%
Power density	218 W/cm3
Max Lin Pow	450 W/cm
Avg BU ~ 100 GWd/t	~2000 JEPP

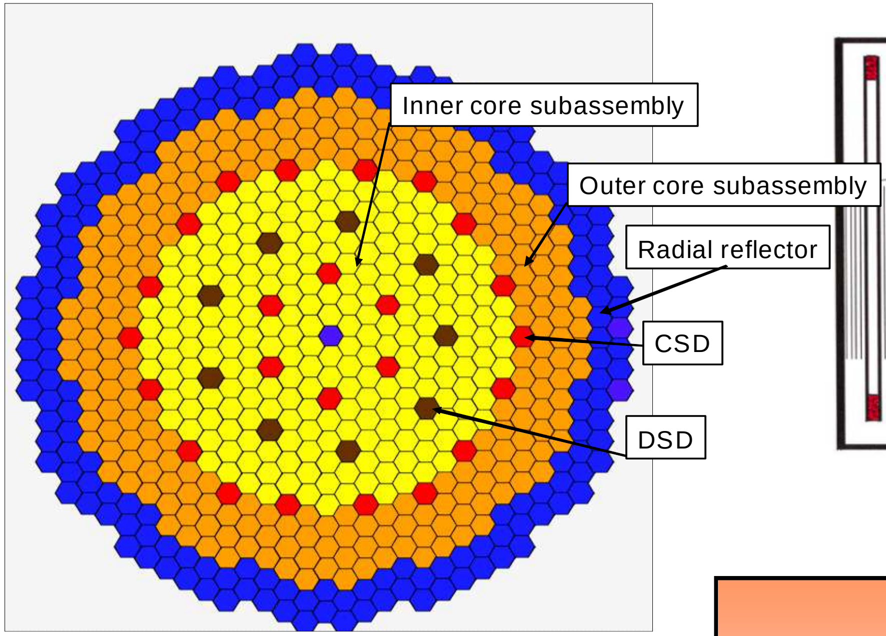
ESFR Oxide Core Nominal Conditions

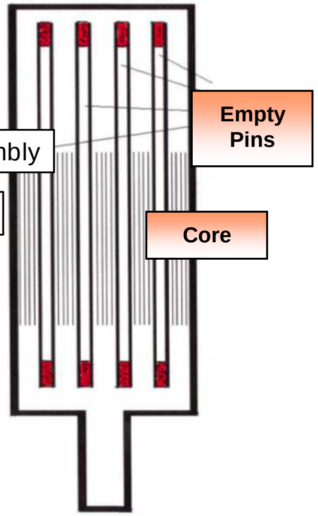
G.L. Fiorini, FISA 2009, 22-24 June, Prague, Czech Republic

- **CP-ESFR : Collaborative Project European Sodium Fast Reactor – 7th FP of EU**
- **Goals: Support SFR development, rebuild expertise in Europe, R&D activities launched within the international context, ….**
- **Pool and loop design investigated**
- **Oxide and carbide option**
- **Investigations on safety optimizations - e.g. void reduction & recriticality prevention**



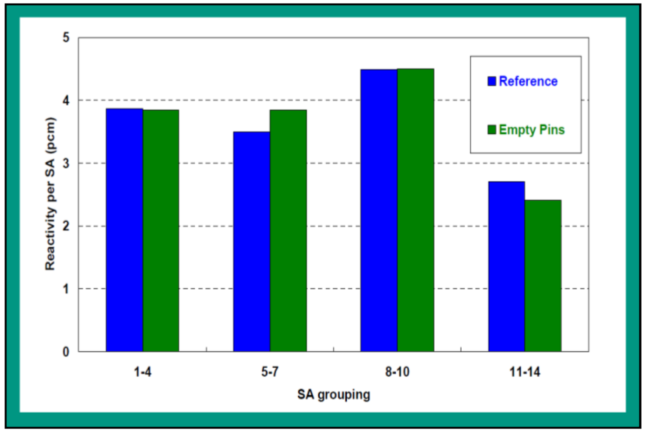
Proposal for CMR Measure (ESFR Core)





Core Region	Δρ(pcm)	K_D(pcm)
Inner core	923	-1073
Inner + Outer core	1510	
Original Inner core	867	-1050
Original Inner + Outer core	1494	

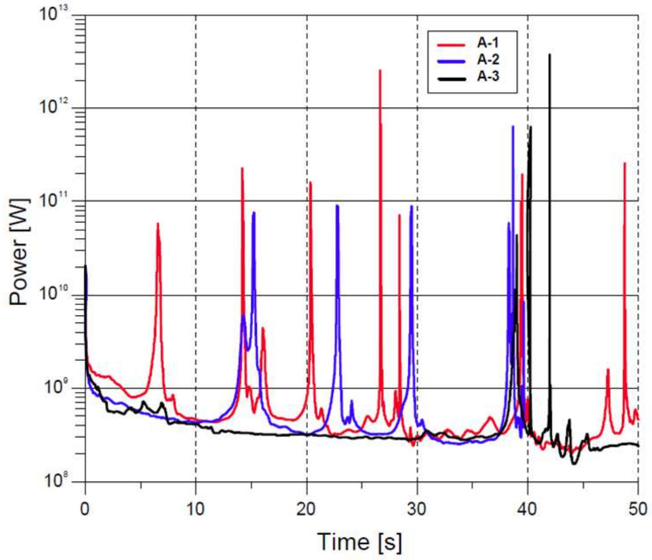
Coolant void and Doppler constant for the configuration with fuel sub-assemblies loading empty pins

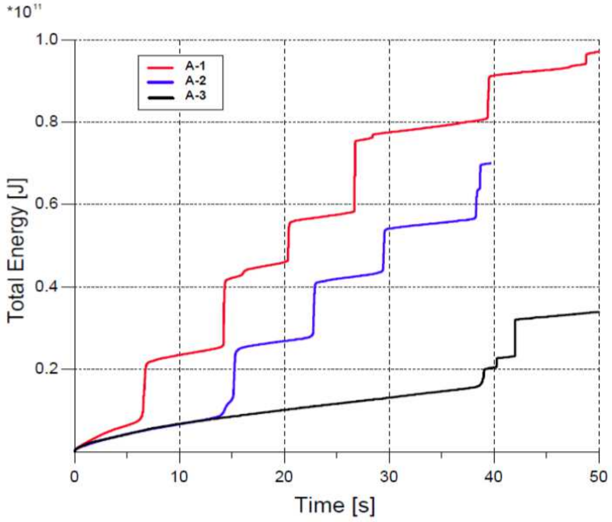


Results of void worth optimization

- ESFR- type core with 19 empty pins/subassembly
- CMR : Relocation through additional 19 empty pins & CRGT
- Strategy : Mitigation of recriticalities - propagation and pool formation accepted
- Important : Minimal impact on subassembly design

SIMMER Simulations Assessing Impact of CMR Strategy





SIMMER-III Analyses for ULOF :

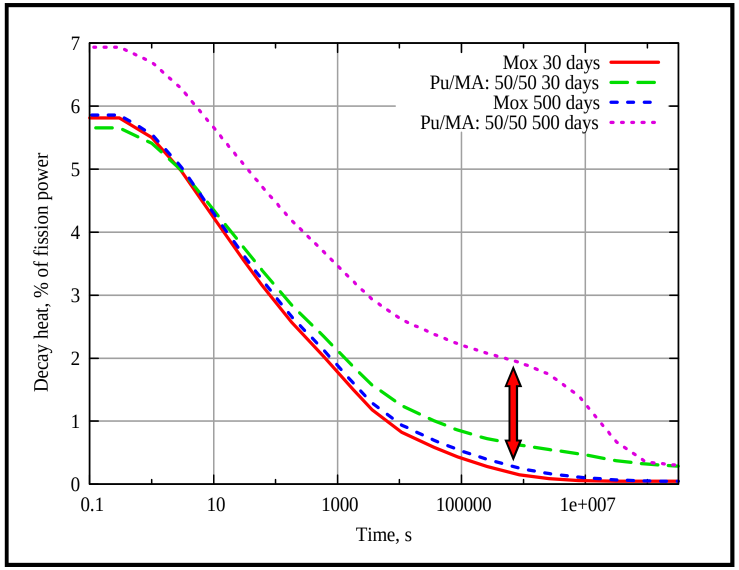
Case A-1 : Reference simulation

Case A-2 : 19 empty pins/subassembly

Case A-3 : 19 empty pins/subassembly +CR modelling

- **Energetics reduced but no complete prevention**
- **Improve design by measures for prevention and/or mitigation of recriticalities**
- **High reliability of simulations required for proof**
- **Assessment of fuel relocated on peripheral structures**
- **Further optimization needed**

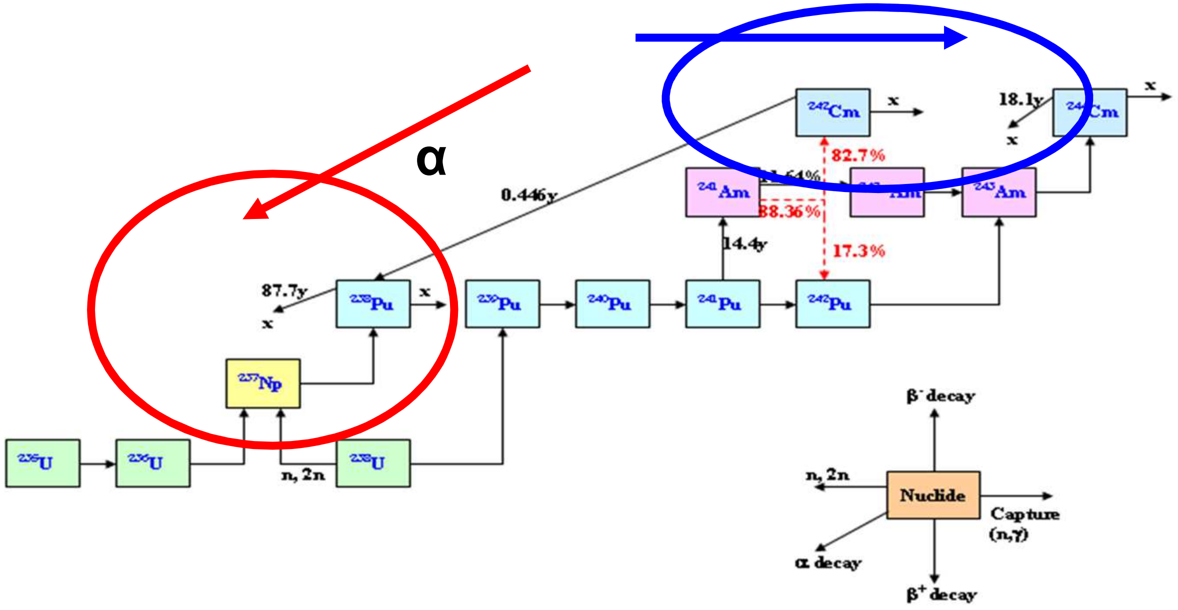
Decay Heat in SFR with Minor Actinide Load



Decay heat for the MOX and Pu/MA: 50/50 fuels after 30 and 500 days of irradiation (decay heat values obtained for all fuel cases in this study are relative to the fission power at operating conditions, this power being lower than the total reactor power by a value of the order of 10%)

- **The failure of decay heat removal was the key issue in the Fukushima. To manage the decay heat problem the natural convection paths have to be guaranteed and also the decay heat levels have to be well known**
- **Of special importance if SFRs should manage waste and burn Minor Actinides (MAs)**
- **Results of a benchmark exercise. Fuel options considered : MOX fuel and ADS-EFIT-type fuel with high, 50% fraction of MAs**
- **The decay heat includes mainly two components: FPs and actinides decay heat**
- **The actinides decay heat is sensitive to the irradiation time and isotopic content of the fuel mainly due to the production of Cm242**
- **For long cooling times the decay heat in fuels with MAs may be several times higher than in MA-free fuels**
- **Decay heat determination after an excursion history & influence on temperature level of the pool and potential for vaporization of fission products and MAs and their redistribution.**

Decay Heat in SFR with MAs



- MA bearing fuels : α-decay and generation of He in the fuel pins. Fission gas pressure build-up will cease after stop of fission process, decay will go on and lead to a pressurization of the pins.
- In-pin pressure will increase under a temperature transient in the core and also in the storage vessel under insufficient coolant conditions. Decay heat and in-pin pressure are thus a strong function of burn-up.

Fig.:infcis.iaea.org/NFCSS/NFCSSMain.asp?RightP=Mo..

- Design has to take into account possible increased heat load by MAs
- Impact of neutron & decay heat precursor redistribution
- Impact of FG & He release in fuel storage pools
- Fuel storage pool instrumentation

Final Comments and Conclusions

- **Modern plants, should have performed better under Fukushima type event**
- **In future fast reactor systems significantly higher active and passive safety features are installed, which should cope with events like Fukushima**
- **One important lesson: put a focus on rare initiators, accident routes and consequences that are neither expected nor have been observed, events that are categorized under '*black swans*'**
- **Importance of severe accident research demonstrated - both analytically and experimentally for assessing and interpreting accident scenarios and developments. Precondition for developing preventive & mitigative safety measures. Passive safety measures are in the focus of advanced design options and must work under conditions of multiple loads and aggravating events**

Final Comments and Conclusions

- **Fast reactor systems behavior as the SFR under severe accident conditions :**
  - **In fast spectrum systems as the SFR the core is not in its neutronically most reactive configuration and SFRs may be loaded with MAs for waste management**
  - **Recriticalities have a high probability because of the higher enrichment levels**
  - **Short time scales have to be envisioned for core melt-down**
  - **Decay heat levels might be significantly higher, if MA bearing fuel is involved**

- **Improve design by measures for prevention and/or mitigation of recriticalities**
- **High reliability of simulations required for proof**
- **Assessment of fuel relocated on peripheral structures**
- **Preventive/mitigating measures should not replace containment measures**