Transition Phase and Expansion Phase Analysis

ESFR-SMART Spring School

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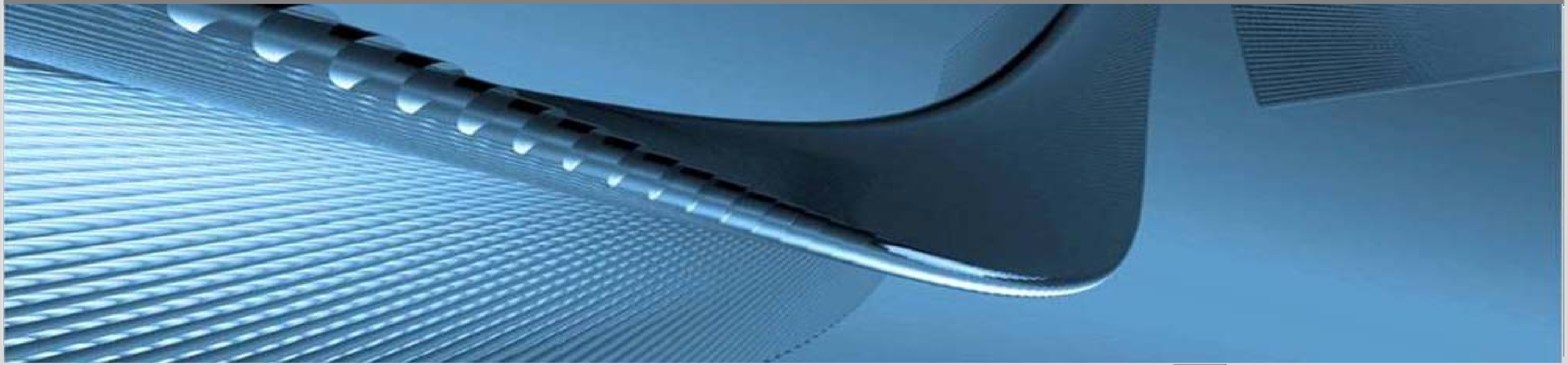
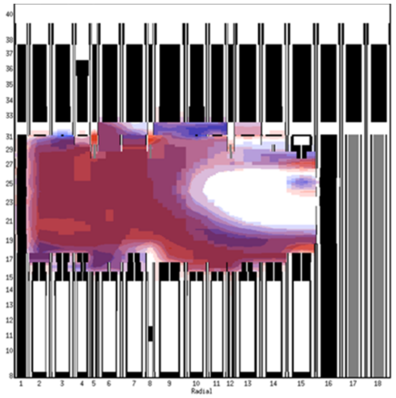
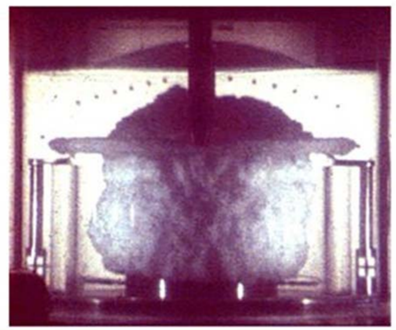
Institute for Nuclear and Energy Technologies



Outline

- Phases of severe accidents in SFR
- SIMMER code family
- Transition Phase simulation results for ESFR-SMART
- Core material prior to EP
- Phenomena during EP
- Assessment of work potential
- Expansion Phase simulation results (example)
- Outlook
- Summary





Phases of Severe Accidents in SFR (1/2)

Why sub-divide an accident into different phases?

- Focus on dominant phenomena of the event
- Assessment of phases by specialized codes
- Uncertainties related to branching into different phases
- Former lack of codes capable of describing the whole sequence

Phases of a severe accident

- Initiation Phase (primary phase)
- Transition Phase (secondary phase)
- Expansion Phase (post disassembly expansion phase)
- Post-accident heat removal phase etc

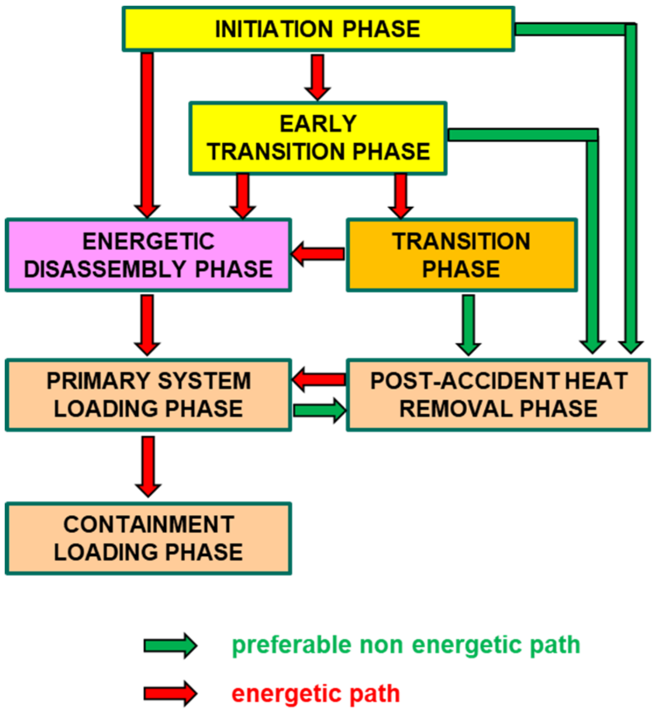


Fig. Phases of a severe accident

Phases of Severe Accidents in SFR (2/2)

Initiation Phase (IP) – *SAS: multi-1D code; point-kinetics*

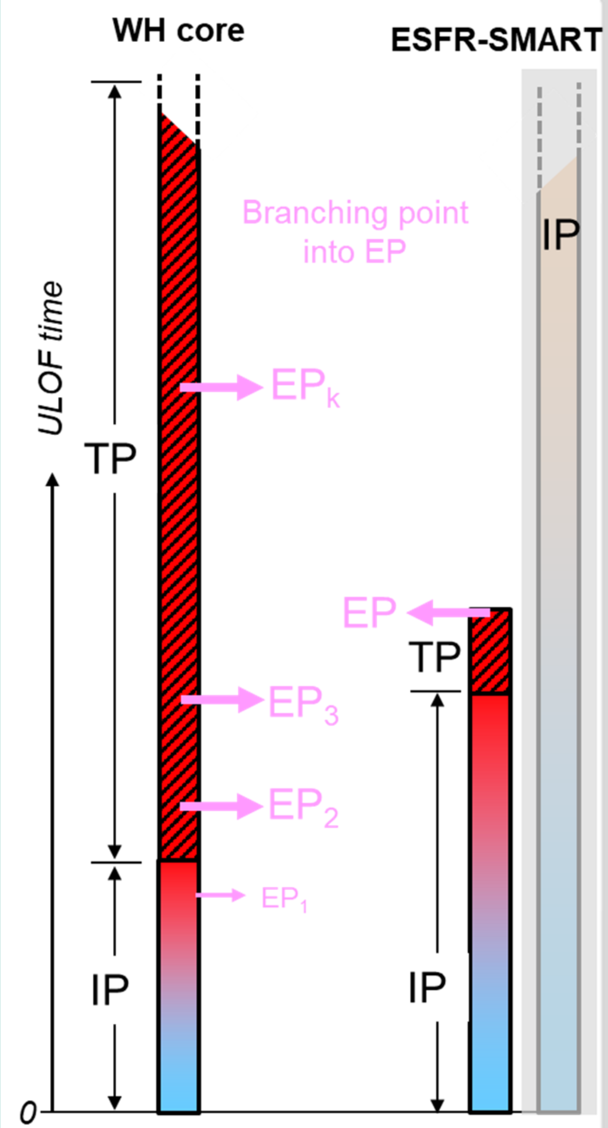
- Accident initiation until CW failure:
- Potentially primary power excursion

Transition Phase (TP) – *SIMMER: 2D/3D code, space-time kinetics*

- Power profile according to fuel redistribution
- Risk of large pool formation & fuel compaction
- Risk of secondary power excursions with high energy release

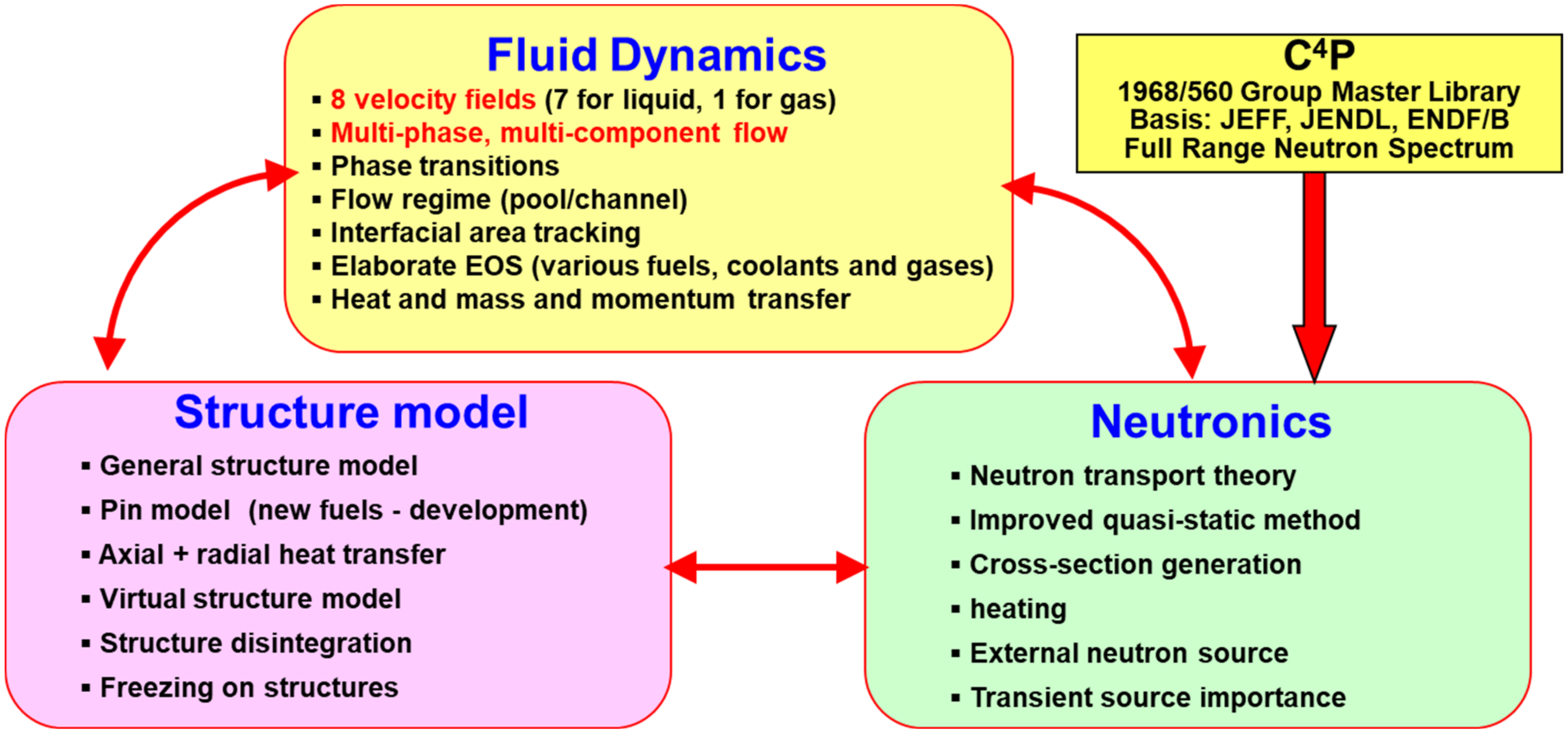
Expansion Phase (EP) – *FD codes: multi-phase, multi-component*

- Final outcome of the energetic path leading to core dissassembly
- Conversion of thermal into mechanical energy
- Potential challenge for PV (sodium slug/pressurization)



SIMMER Code Family

2D / 3D fluid-dynamics code coupled with a ***structure module*** and a
space-time and energy dependent neutron dynamics model

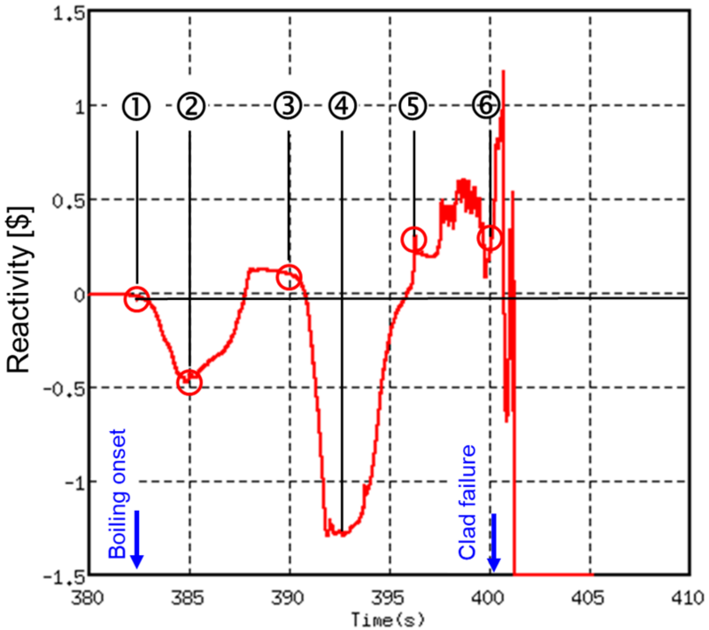


TP: space-time kinetics is a *major requirement* (fuel arrangement creates its own power-profile)

EP: neutronics may be *neglected; rigid structure concept – no failure under load in SIMMER*

Transition Phase simulation result for ESFR-SMART (1/2)

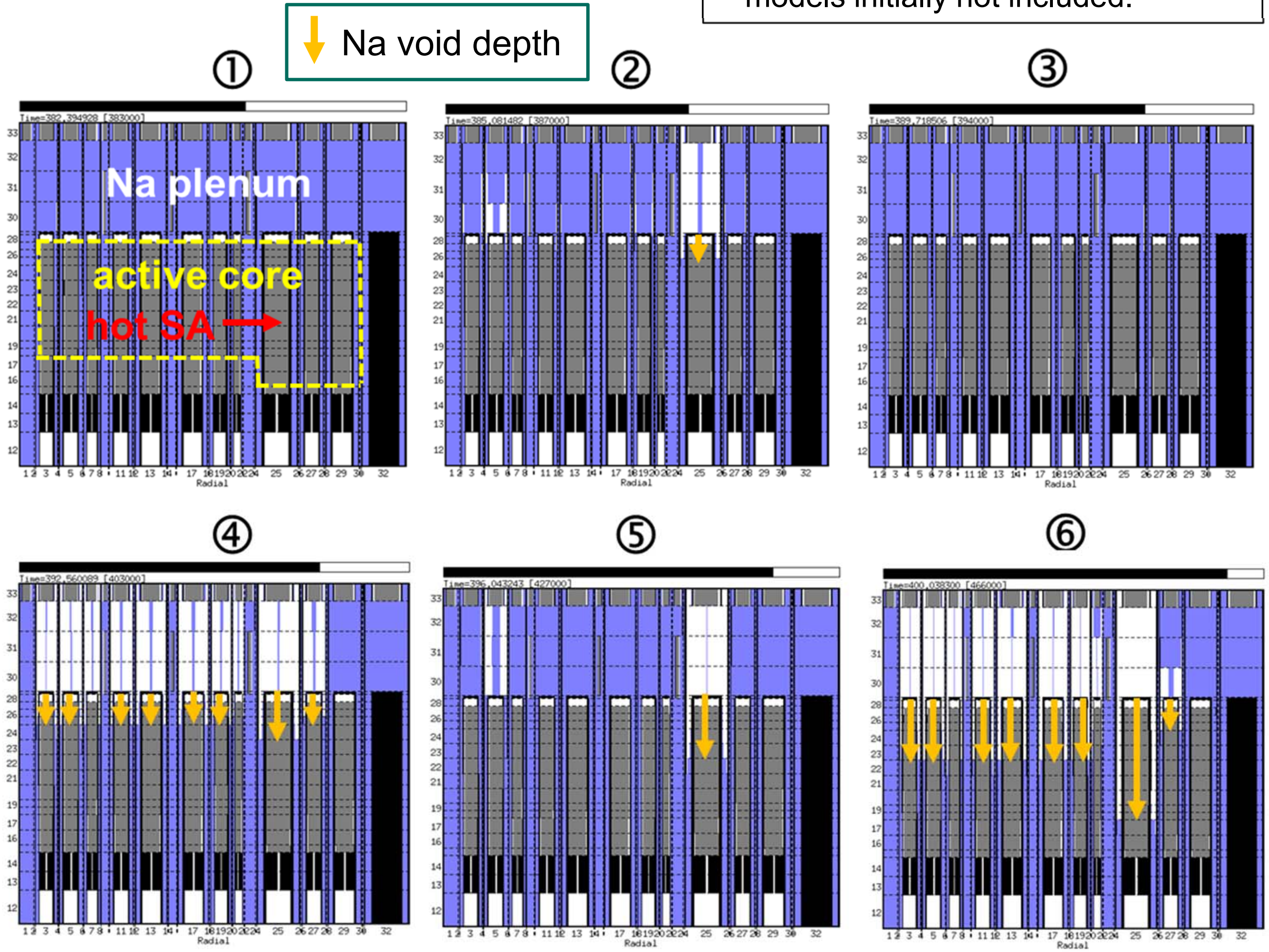
350 s	0 s	ULOF onset
382 s	32 s	boiling onset
400 s	50 s	clad failure
401 s	51 s	power peak



- Slow voiding/rewetting cycles
- Overshooting after rewetting
- Void front dives into positive SVRE area …

➔ Void driven power excursion

Material distribution snap-shots



Conservative evaluation result*

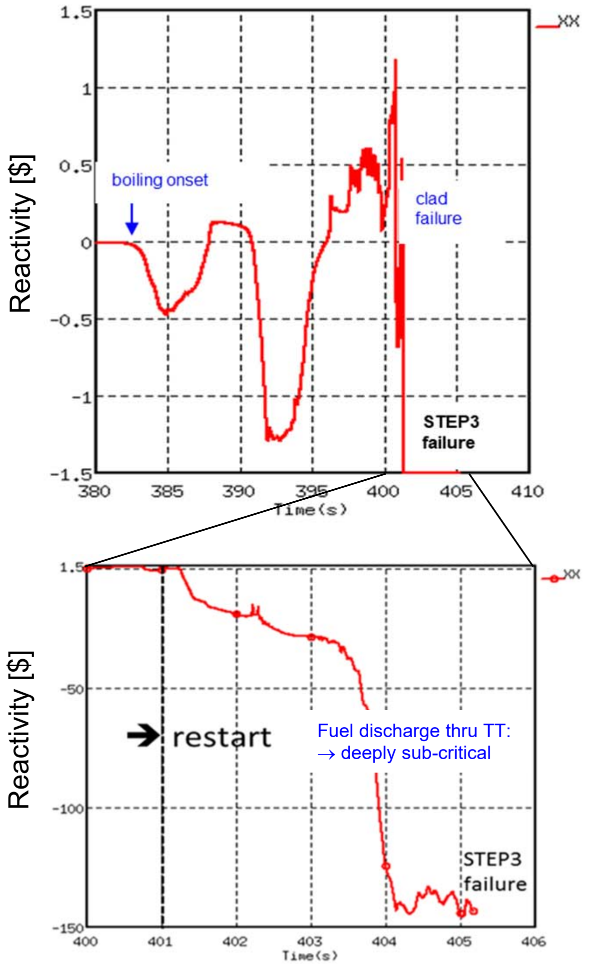
* CRDL & core thermal exp. feedback models initially not included.

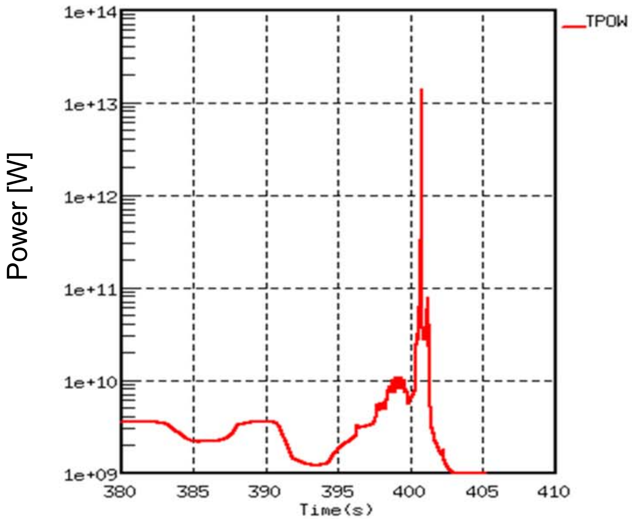
Transition Phase simulation result for ESFR-SMART (2/2)

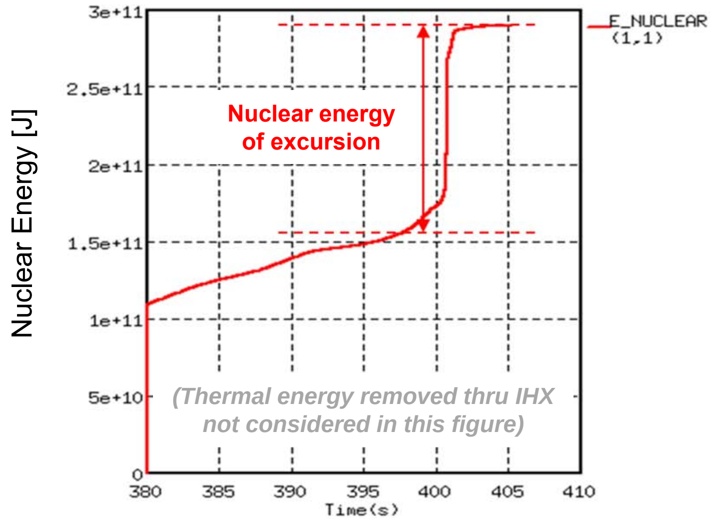
Conservative evaluation result*

* CRDL & core thermal exp. feedback models initially not included.

Accident history







Results of KIT simulation:

	t (s)	Δt (s)
Start of ULOF	**350.0**	**0.0**
Boiling onset	**382.4**	**32.4**
Clad failure	400.2	50.2
Liquid fuel	400.7	50.7
Power peak	**400.8**	**50.8**
CW failure	401.1	51.1
TT CW failure	**401.5**	**51.5**
Calculation terminated	405.2	55.2

Power peak ~ **3.900 P0**

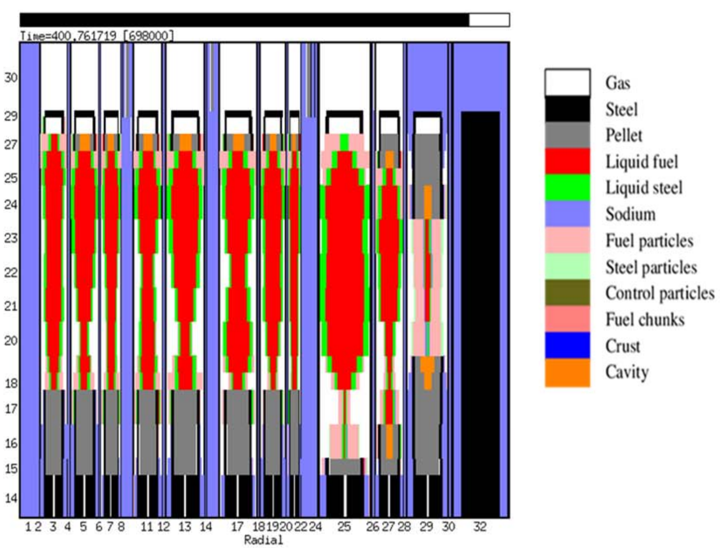
$E_{nuclear}$ ~ **116 GJ**

Relatively mild power excursion but ***surprisingly large energy deposit*** … caused by double hump (broad pulse).

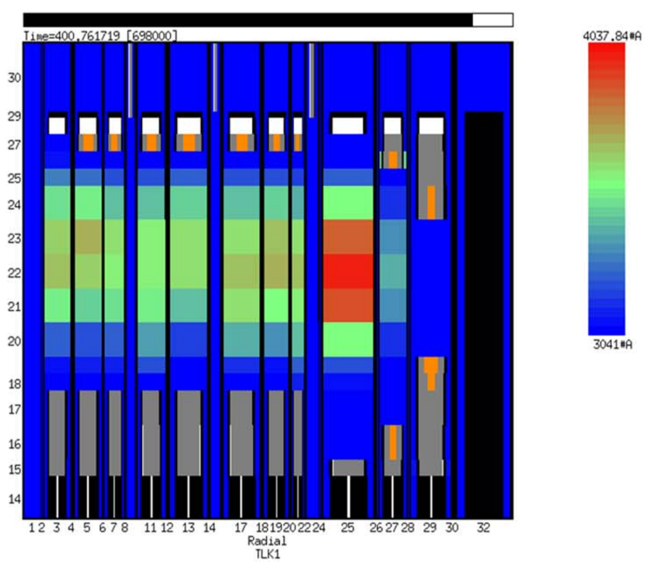
Nuclear shutdown shortly after peak due to ***fuel relocation through transfer tubes*** (TT).

Core material prior to expansion phase

Material distribution



Fuel temperature distribution



melt component	mass	temperature range	average temp	pressure
Liquid fuel	~ 44 to	3041 … 4450 K	**~ 3500 K**	**~ 0.03 MPa**
Fuel particles	~ 17 to	…	…	…
Liquid steel	~ 13 to	1750 … 4150 K	**~ 3300 K**	**~ 0.40 MPa**
Steel particles	~ 0.2 to	…	…	…
Liquid sodium	---			
Sum mobile	***~ 75 to***			
Na vapor	~ 350 kg	…	**~ 2600 K**	**~ 15 MPa**
Gas/vapor total	~ 1100 kg	…	**~ 3300 K**	…

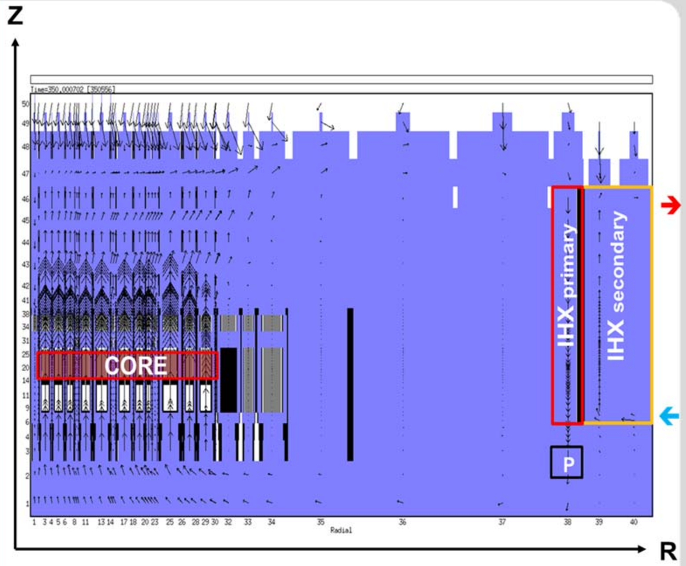


Fig. SIMMER model of ESFR_SMART

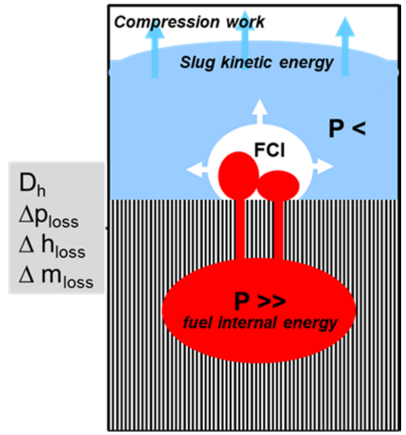


Fig. Schematics of EP event

Important Phenomena during EP

EP *as a pure FD event:*

- quickly sub-critical; quickly finished (decay heat neglected)

Core material liquefied during power excursion

High core temperatures (~ 3000 … ~ 4450 K), local distribution
High core pressure (~ 15 MPa)

Melt relocation due to large Δp between core & cold/hot plena.

Mostly upwards due to frozen plugs at the core bottom..

Flow paths: sub-channels, interwrapper gaps or ripped-off UCS parts.

Rapid expansion of melt with dispersel and vaporization. Thermal fuel-coolant interaction (***FCI***) between melt and liquid sodium. Fast ***vaporization of sodium*** (up to vaper explosion) with ***pressure build-up***. Feedback on melt discharge.

Expansion and rising of bubble: sodium entrainment at liquid-vapor interface due to FD instabilities.

Displacement of liquid sodium and ***acceleration of sodium slug***.

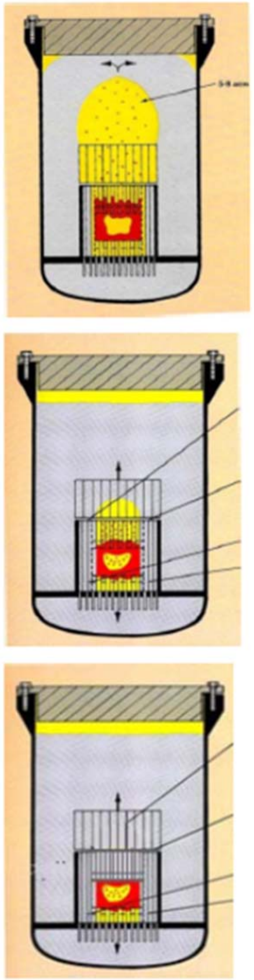


Fig. Schematic of expansion phase

Assessment of Mechanical Energy Potential: Classical approaches

TNT equivalent (damage picture)

Empirical correlation (vapor explosion):

1 kg $UO2_{EP\_cond}$ ≈ 0.5 kg TNT

Isentropic expansion (of liquid fuel):

Thermodynamic conception of „working cycle":

➔ max. mechanical energy for given internal energy

$$W_{mech} = -\int_1^2 pdv = U_1 - U_2$$

$$ds = \frac{du + pdv}{T} = 0$$

Hicks- and Menzies (liquid fuel and Na vaporization):

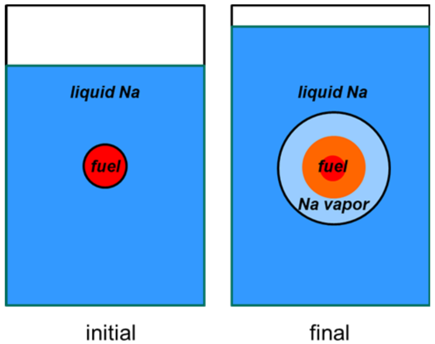
Thermodynamic conception:

Choose fluid to optimize efficiency of working cycle:

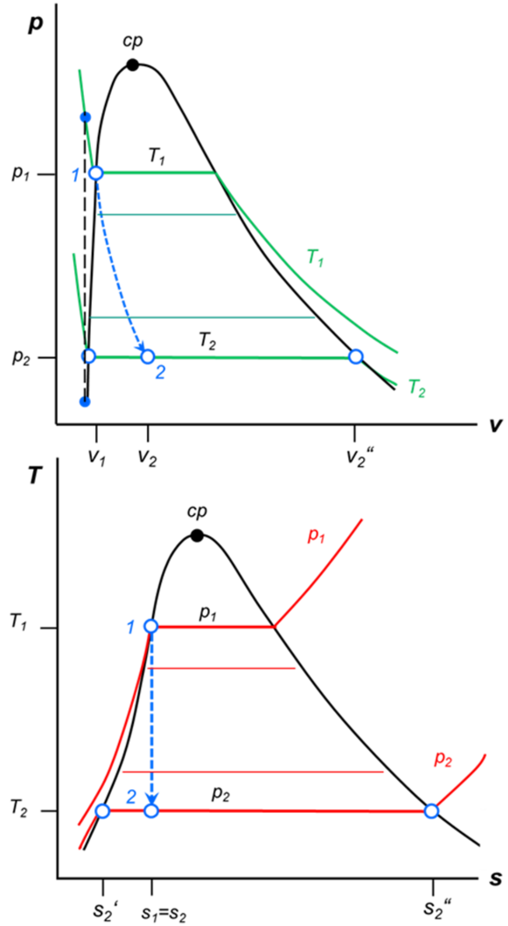
➔ tranfer of fuel energy to coolant – only coolant expands

$$\varepsilon_{conversion} = \frac{E_{mech}}{E_{core,thermal}}$$ *Thermal-to-mechanical conversion ratio*

➔ *„energy conversion rate":* very small but high numbers for large reactors



Result contains no dynamic of process



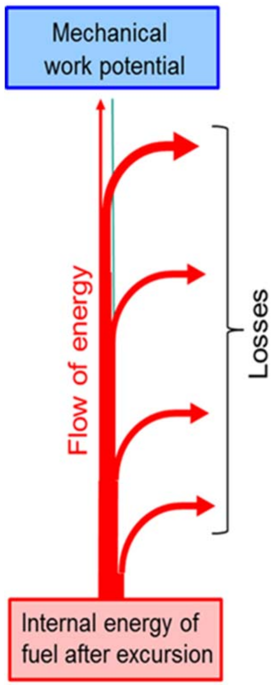
Expansion till specified V_2 or p_2

Fig. Isentropic expansion scheme

Assessment of Mechanical Energy Potential: Mechanistic approach

Mechanistic: Loss terms inherently considered in FD models

Loss of mass, momentum & energy of ***mobile*** material components



Upper Na plenum

Fuel expansion / particle release
FCI ➔ Na as major working fluid
Coolant vaporization / condensation
Coolant redirection (friction, vortices)

Discharge through UCS:

Mass losses (freezing)
Momentum losses (friction)
Energy losses (heat conduction)

In hot pool:

Mixing of fuel with steel components
Freezing in LAB and radial blankets

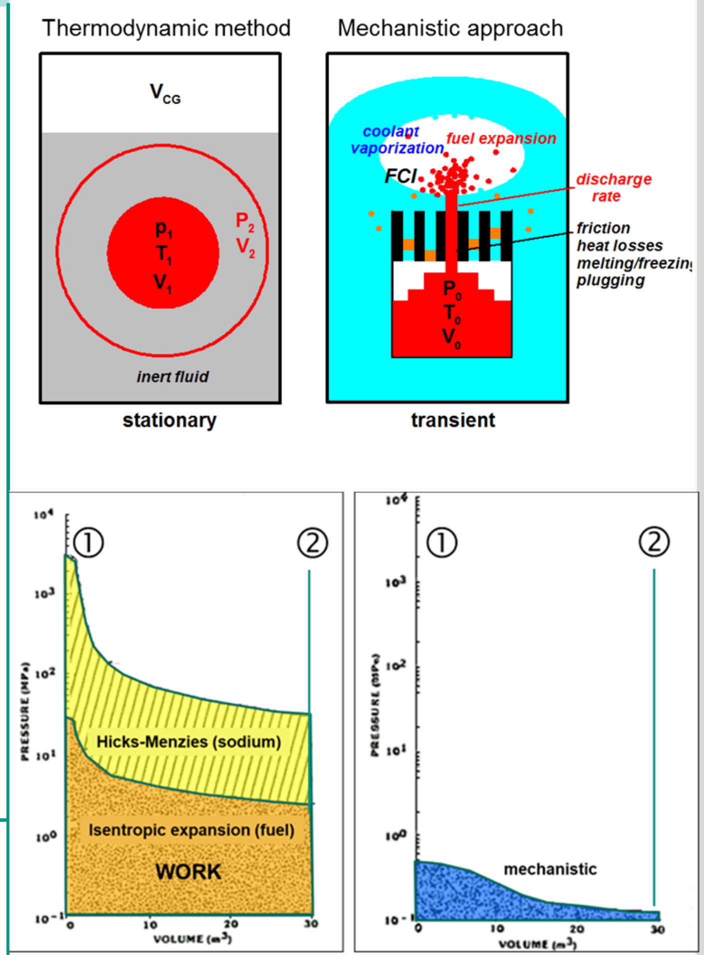


Fig. Comparison of work potential evaluated with different approaches

Examples for other European codes used for this task:

EUROPLEXUS for simulation of fast transient fluid-structure interaction problems. Co-owned by JRC and CEA.

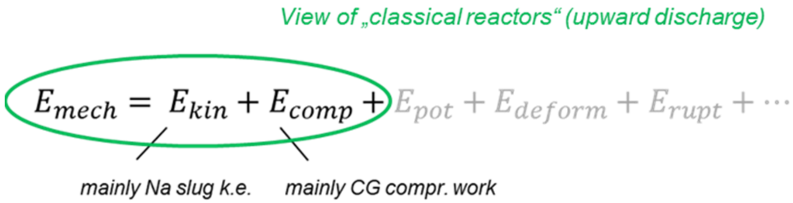
ASTEC, MC3D (IRSN). Material-structure interaction codes.

SIMMER EP Model and Assessment of Work Potential

No direct continuation of TP simulation because of …

- Mesh refinement in energy conversion region (hot plenum & CG)
- Neutronics not necessary (speed up)
- Models missing for material failure due to force load ($\rightarrow$ user)
- Condition of UCS with large impact ($\rightarrow$ parametric variations)
- Chance for parametric modifications (deeper insight)

Evaluation of work potential by postprocessing of FD quantities:



Components of mechanical energy

$$E_{kin,slug} = M_{Na}\frac{v_{Na}^2}{2}, \quad E_{compr,CG} = W_{compr} = -\int_i^f (pdV)_{CG}$$

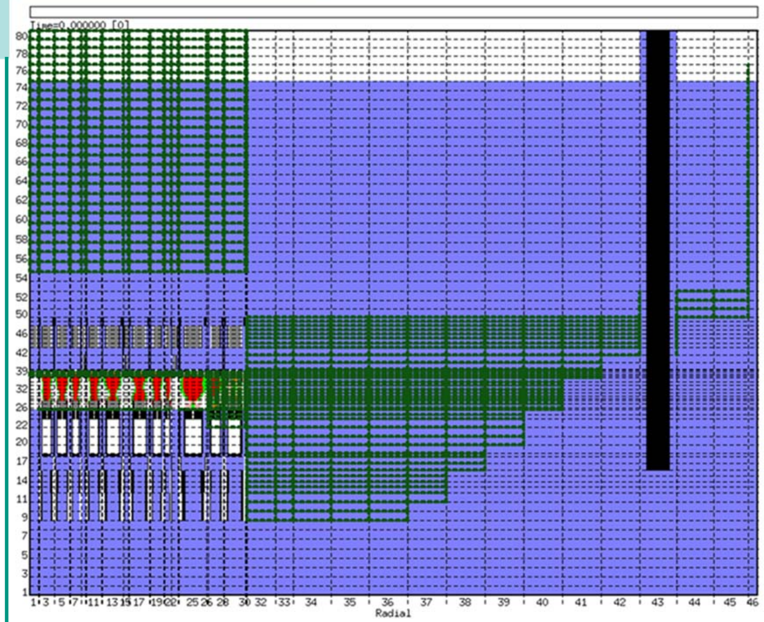


Fig. SIMMER EP simulation model

$$W_{kin,ax} = \sum_{ij} m_{Na} v_{Na}^2$$

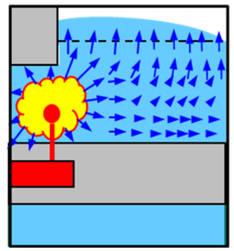


Fig. Kinetic energy

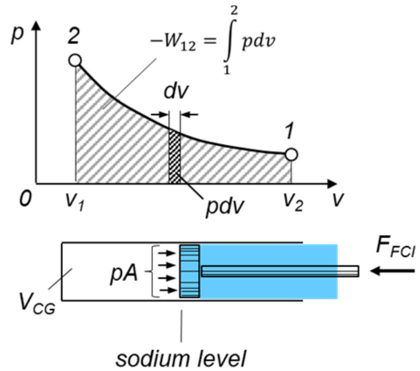


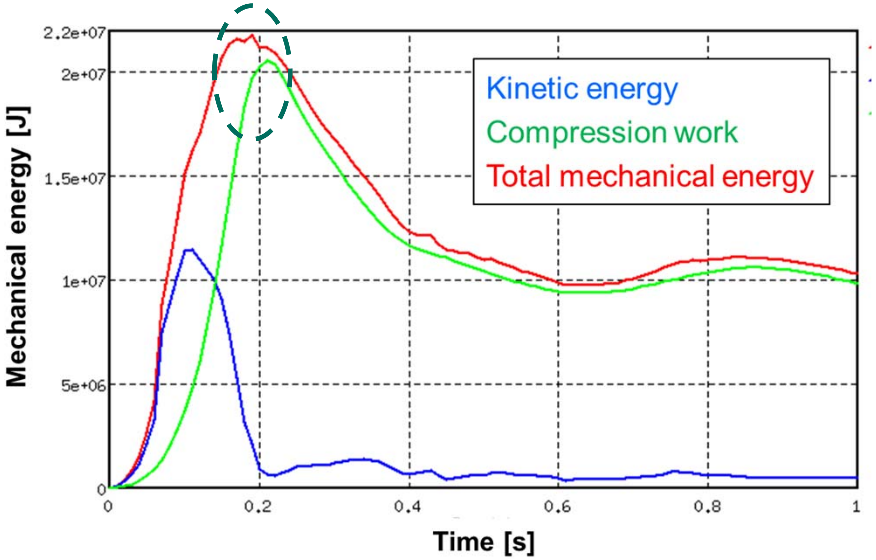
Fig. Cover gas compression

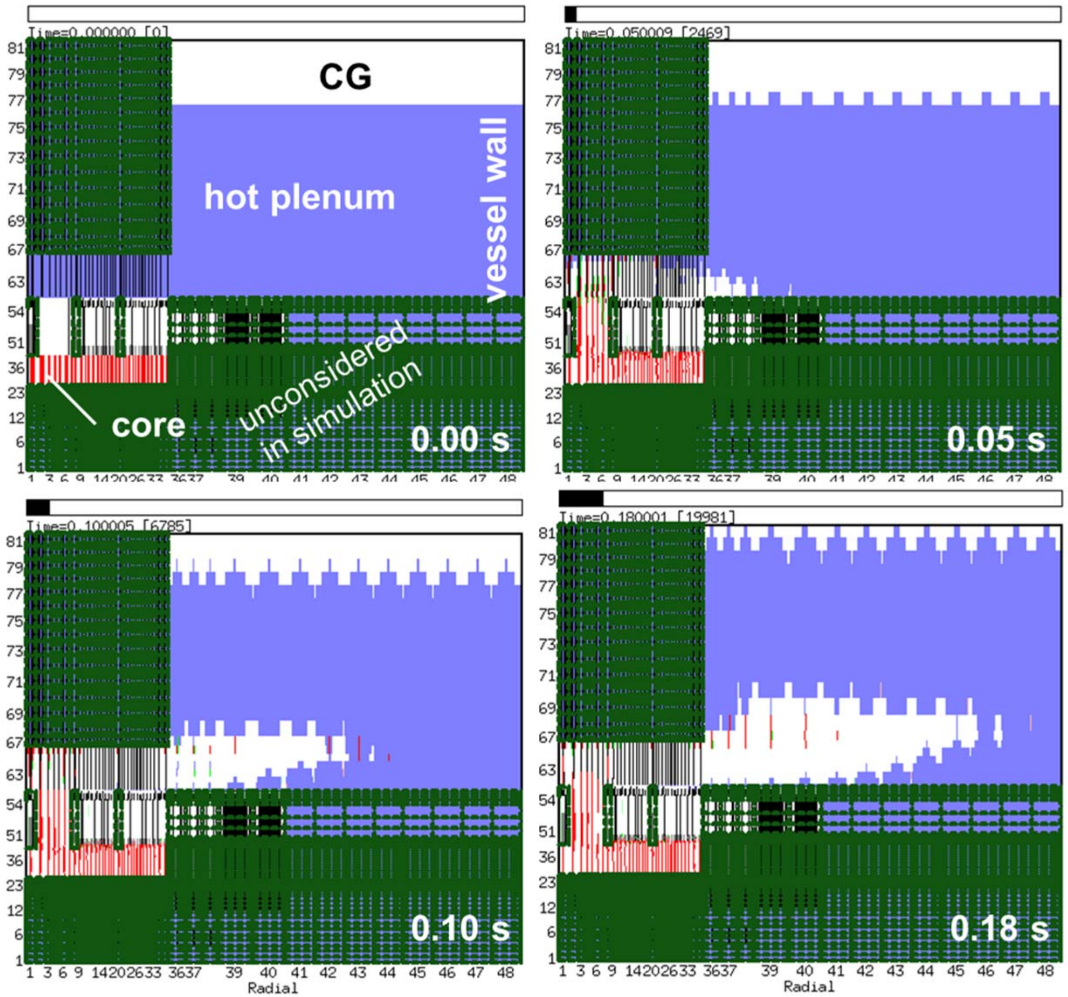
SIMMER-III EP Simulation: Example for SFR Model Case

EP simulations for ESFR-SMART in delay …

… therefore, ***example*** for an EP simulaton:

- Small reactor; T_{fuel} = 5500 K; p_{core} = 9.0 MPa
- ***Upward directed*** discharge path
- Three inner rings assumed thermally eroded





➔ CG compressed to 20 % of initial volume

➔ no Na slug impact experienced

➔ Energy conversion rate: ~ **0.15 %**

Outlook

Completion of SIMMER-III EP simulations for ESFR-SMART (KIT, EdF)

Parametric variations:

- Different direction: upward; downward; <u>combined</u>
- Impact of different model parameters
- Reference values for WH core for comparison

MC3D EP simulations for ESFR-SMART (IRSN)

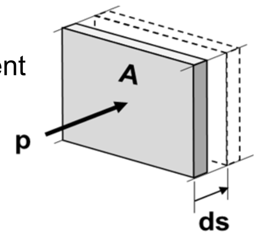
Evaluation of work potential (corium state taken from SIMMER)

Real wall behavior model in MC3D / limited number of melt components

Work evaluation at downward discharge?

SIMMER-III: rigid wall - problem

MC3D: flexible wall - no issue



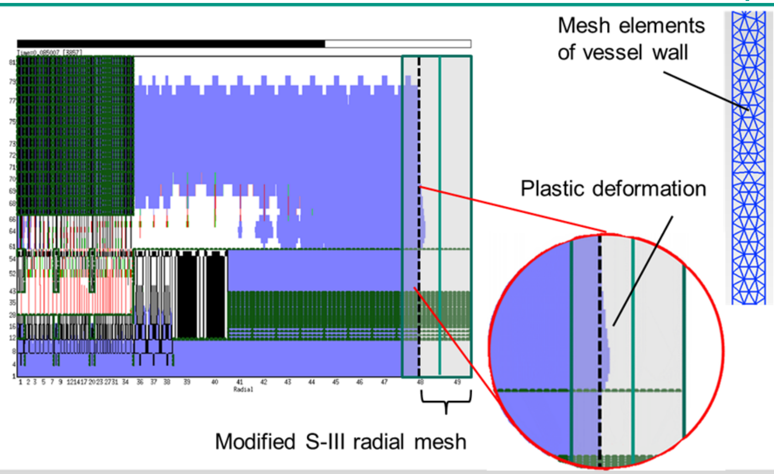
$$dW = pA\underbrace{ds}_{0 \text{ for rigid wall}} = pdV$$

Ongoing model development:

Coupling of SIMMER with an external structure code*:

* Presently limited to radial deformation.

M. Hartig, Numerical Simulation of Fluid Structure-Interaction during the Expansion Phase in Sodium Cooled Fast Reactors, PhD, KIT (2019).



Long-term plan: extend application also for structures inside vessel.

Summary

The ***transient behavior of the ESFR-SMART*** core during ***IP and TP*** is presented based on SIMMER-III for a ULOF initiator.

Leaving some neutronic feedbacks unconsidered, a ***conservative result*** is achieved. In this case SIMMER predicts sodium boiling followed by a ***void driven power excursion*** ~50 s after ULOF start. A primary power excursion occures with a magnitude of ~ 3.900 x P_0 and a broad pulse width. Shortly after the excursion, ***the transfer tube ducts open*** and corium is discharged towards the core catcher. This newly introduced saftey feature looks very promising in breaking the cycle of recriticalities formerly experienced during TP.

At present understanding, the reactor is at the edge of stability, if all feedback models are included.

Yet, the conservative result is very useful supporting other tasks of the project, e.g. EP simulations.

For ***Expansion Phase***, important phenomena are briefly described and ***theoretical and mechanistic approaches*** are explained for evaluating the work potential and the energy conversion rate.

Due to a ***delay of EP simulations for ESFR-SMART*** only a general example for an EP simulation could be presented.

The mainly downward directed melt discharge during EP suggests a new consideration of the work evaluation due to the rigid wall formulation in SIMMER. An extension of the code towards mechanical fluid-structure interaction has been started at KIT.