Evolution and Assessment of Core Disruptive Accident Scenarios in SFR: From PFBR to CFBR

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Possible severe accident initiators in PFBR

- Loss of flow followed by failure of both the shutdown systems (ULOF)
  - Battery power to Primary sodium pumps
  - 2 independent & diverse shutdown systems
- Uncontrolled withdrawal of one Control rod followed by failure of both the shutdown systems (UTOP)
- ULOF and UTOP events are analyzed for PFBR

Various Phases of Accident Progression in PFBR

Pre-disassembly Phase

In this phase, the phenomena occurring are sodium boiling, fuel-clad melting and fuel slumping. This phase ends when the peak fuel temperature in the highest rated subassembly reaches boiling point. This phase lasts from a few tens of seconds to a few minutes.

Transition Phase

At the end of the pre disassembly phase, the reactor can become sub critical if there are sufficient negative reactivity feedbacks. If the negative feedbacks are insufficient, melting of fuel-clad will continue to form a molten pool. This is known as transition phase, since the fuel attains gradual transition from solid to liquid phase.

Disassembly Phase

In this phase, the core has lost its integrity & whole core is taken as fluid and fuel starts dispersing. Fuel displacement feedback dominates & time scales are short (~milliseconds) and all other reactivity feedbacks except the Doppler are insignificant. This phase lasts till the reactor attains sub criticality due to fuel dispersal.

Tools used for analysis of pre-disassembly phase

The initial analysis of CDA was done using **Bethe & Tait** model, which assumes gravity driven collapse of the core and hydrodynamic core disassembly.

- **PREDIS**
  - In house developed 2D axi-symmetric point kinetics code for reactor core
  - Models for coolant boiling and fuel melting
  - Feedback reactivity models for Doppler, core expansion, coolant expansion, control rod drive expansion, coolant voiding, fuel melting and slumping
  - Validation against International benchmark data.
- **DYANA-P**
  - In house developed 1D system dynamics code for whole plant
  - Hydraulic models of primary and secondary sodium systems and thermal models for core, IHX, pipe lines, pools and steam generator
  - Validated against FBTR experiments and PHENIX end of life test
- Iterations performed between PREDIS and DYANA-P to obtain consistent reactor inlet temperature and thermal balance.

Tools used for analysis of disassembly phase

At the end of the pre disassembly phase, the reactor can become sub critical if there are sufficient negative reactivity feedbacks. If the negative feedbacks are insufficient, melting of fuel-clad will continue to form a molten pool. This **transition phase** is highly complex and is accounted by conservative assumption.

- **VENUS II**
  - ANL developed 2D coupled neutronics and hydrodynamics code
  - Point kinetics used for power calculations
  - Calculates core dynamics during prompt critical disassembly excursion
  - Feedback reactivity models for material displacement and Doppler effects
  - Validated against Kiwi-TNT, SNAPTRAN-2 and SNAPTRAN-3 reactor disassembly experiments
- Calculations performed for the pre-disassembly phase provides input for the disassembly phase calculation
- Mechanical energy release of the event is predicted by **MERC** subroutine attached to the Venus code
- Mechanical consequences of the event are predicted subsequently.

Parametric Studies on Various Fuels

Fuels considered: Mixed Oxide, Mixed Carbide & Metallic Fuel

Event Scenario considered: ULOFA with fast flow coating (2 s flow halving time)

Results of the pre-disassembly phase

Parameter	Oxide	Carbide	Metal
Thermal power (W)	6.9×10^{10}	1.3×10^{11}	2.8×10^{12}
Reactivity ($)	0.96	0.97	1.02
Coolant void fraction	0.32	0.34	0.39
Molten fuel fraction	0.53	0.79	1.00
Coolant void react($/s)	<1	<1	<1
Fuel slumping reactivity rate ($/s)	8	16	28
Reactivity addition rate due to FCI ($/s)	35	70	4
Phase duration (s)	7.574	8.400	21.428

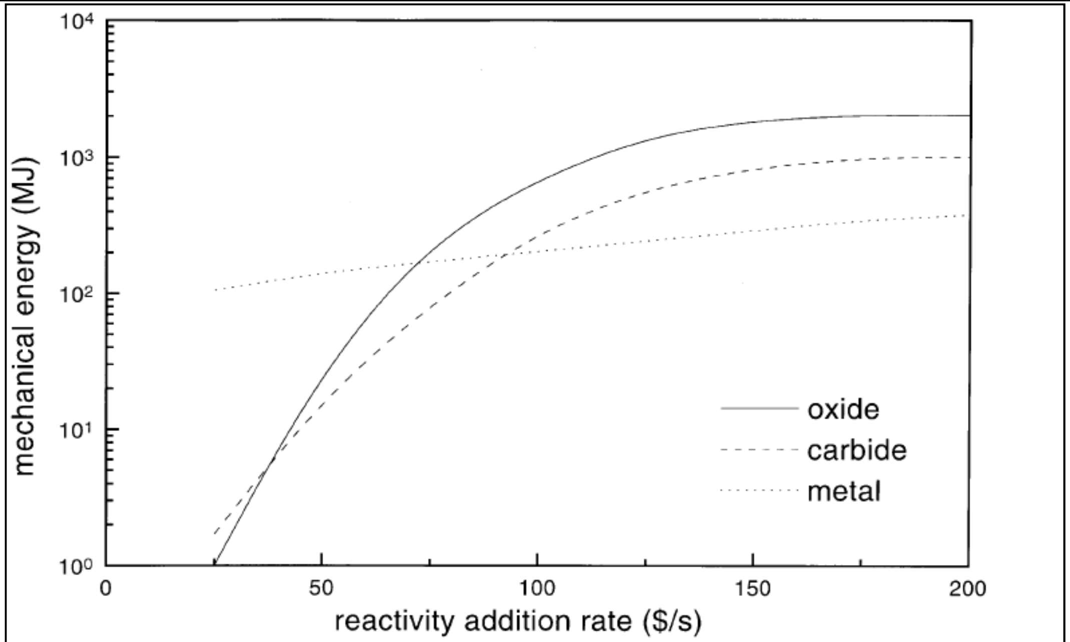
Ref: Om Pal Singh, R. Harish, 'Energetics of core disruptive accident for different fuels for a medium sized fast reactor', Annals of Nuclear Energy 29 (2002) 673–683.

Results of the disassembly phase calculations

Parameter	Oxide	Carbide	Metal
Reactivity ramp rate ($/s)	50	75	50
Thermal energy release (MJ)	2130	3074	2748
Mechan. work-potential (MJ)	23	87	140
Max. fuel temperature (K)	4274	5342	5854
Max. fuel vapor pres. (atm)	10	15	48
Fuel vapor fraction	0.21	0.25	0.40
Phase duration (ms)	13.3	9.6	3.6

Ref: Om Pal Singh, R. Harish, 'Energetics of core disruptive accident for different fuels for a medium sized fast reactor', Annals of Nuclear Energy 29 (2002) 673–683.

Major Findings of the Parametric Study



. Energy release for different reactivity addition rates for oxide, carbide and metal fuels.

- The energy release is seen to stabilize at 1000 MJ beyond a reactivity insertion rate of 100 $/s.
- Revised estimate of reactivity insertion rate based on realistic scenarios based on TREAT & CABRI tests indicated a value of < 50 $/s and the associated energy release is 23 MJ, using the CV2M Crosss-section data
- A few fundamental experiments on molten fuel – coolant interaction, carried out at IGCAR (to be presented in a companion paper) indicated that MFCI effects are insignificant.
- However, an energy potential of 100 MJ is pessimistically assumed for PFBR. Through backward calculations, it is estimated that the reactivity addition rate to achieve 100 MJ energy is 66 $/s.

Ref.: SC.Chetal and P.Chellapandi, 'Severe Accident Assessment for PFBR: Designer's Perspective', Economic times.

Reference Analysis

Analysis of UTOPA

Following cases of uncontrolled withdrawal of one control rod (CSR) have been considered

- BOL fresh core - conservative
- BOL fresh core - nominal
- BOEC core – conservative

Plant under normal operation

Initiating event :

Withdrawal of one CSR

Several SCRAM parameters (ρ, Power & Temp.) evolve

Shutdown system fails

Power in fuel pin increases due to reactivity ddition by CSR

Fuel pin temperature increases

Fuel pin melting starts from its centre

Clad remains intact due to availability of cooling

Due to the release of cover gas from the molten fuel, pressure builds up and pushes the molten fuel upwards and downwards (fuel squirting)

Large negative reactivity inserted due to movement of fuel from most active region (core centre) to less active region (top and bottom)

Reactor power reduces and new stable steady power condition achieved

Does not result in CDA

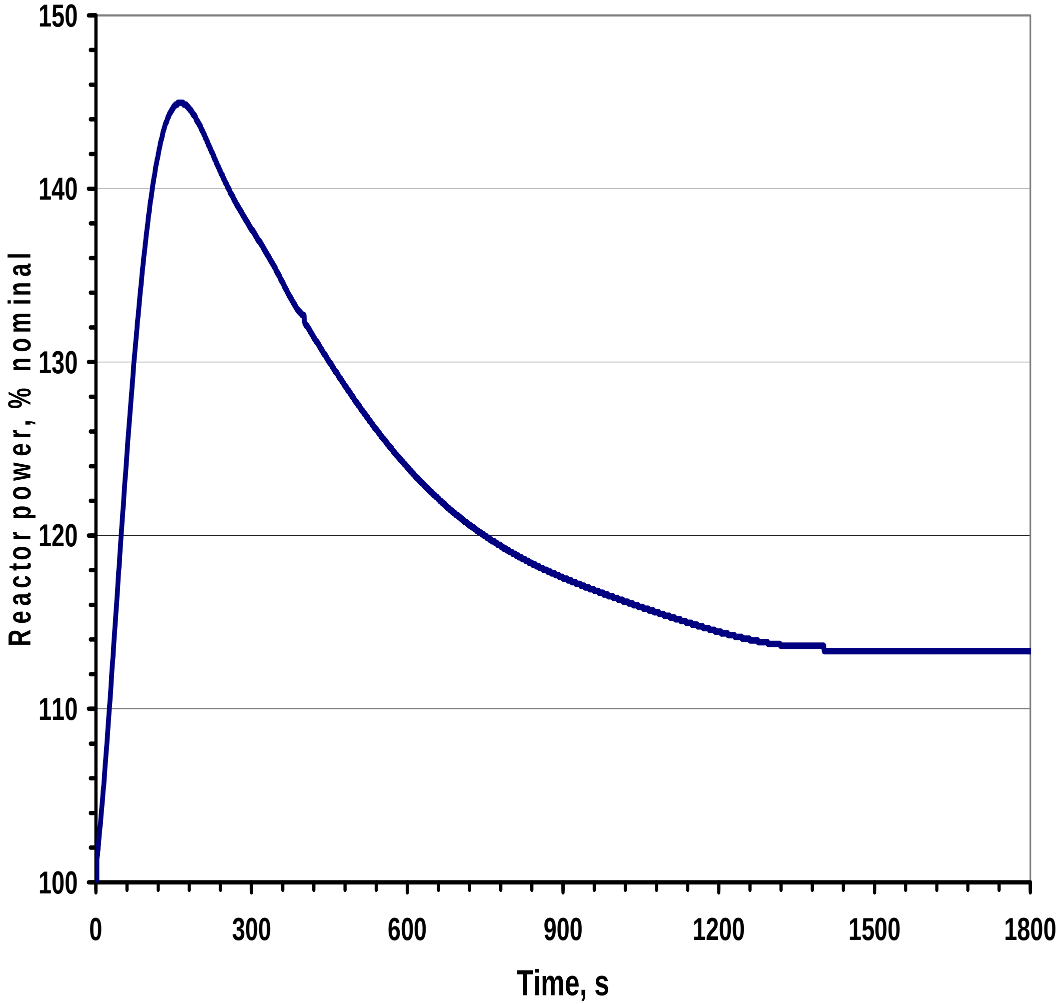
Analysis of UTOPA - continued

- **Modeling of fuel-squirting**
  - In-pin fuel motion of melted fuel is considered in the analysis after CSR withdrawal is complete (250 s)
  - Only 7 % of melted fuel is shifted to axial blanket regions
  - But 15-25 % movement of melted fuel was observed in experiments
- **Conclusion of HUT 52 A Experiments**
  - Full length heated pins and annular pellets enhance in-pin fuel motion
- **Conclusion of TREAT Experiments**
  - Full length pins with 22 % PuO_2 tested in TREAT reactor
  - TOPA simulated with an external reactivity addition rate of 5 c/s
  - Pre failure movement of 25 % of melted fuel was observed even with solid fuel pellets
- CABRI experiments also confirm central hole formation during a simulated TOPA

UTOPA – Fresh core – Nominal analysis

- **Length of CSR withdrawal = 40 cm**
- **Time for CSR withdrawal = 200 s**
- **Net reactivity added = 317 pcm**
- **Non-uniform power profile & low pellet-clad gap conductance**

- **The power reaches 145%.**
- **No fuel melting**
- **Feedback reactivity (Doppler, Core radial & Fuel axial expansions, Control rod drive expansion) arrests the transient**
- **Reactor power stabilises at ~ 115 %**



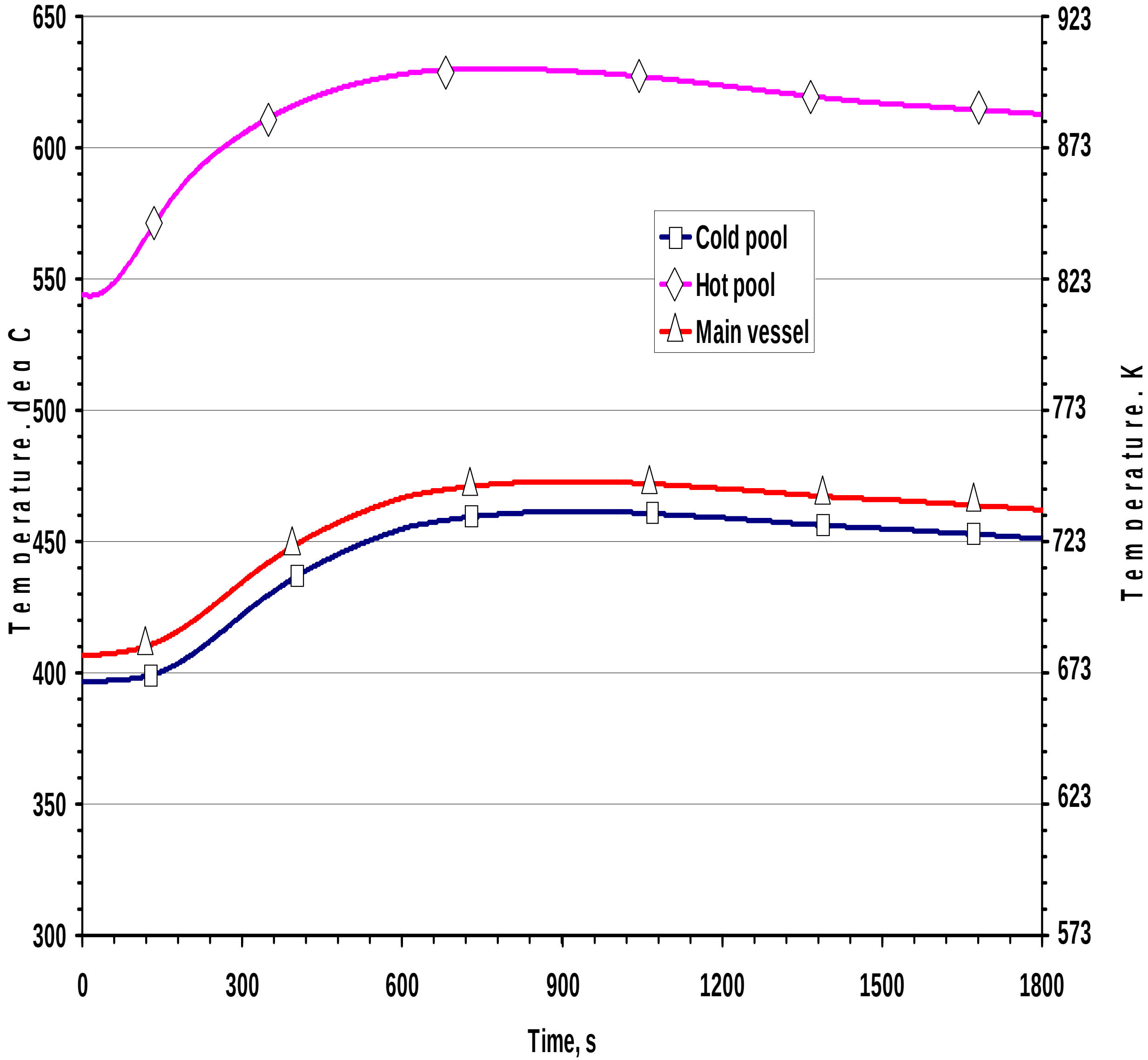
Predicted power evolution

UTOPA – Fresh core – Nominal analysis

- **Max. Hot pool temperature : 630 ^{0}C**

- **Max. cold pool temperature : 460 ^{0}C**

- **Max. main vessel temperature : 473 ^{0}C**

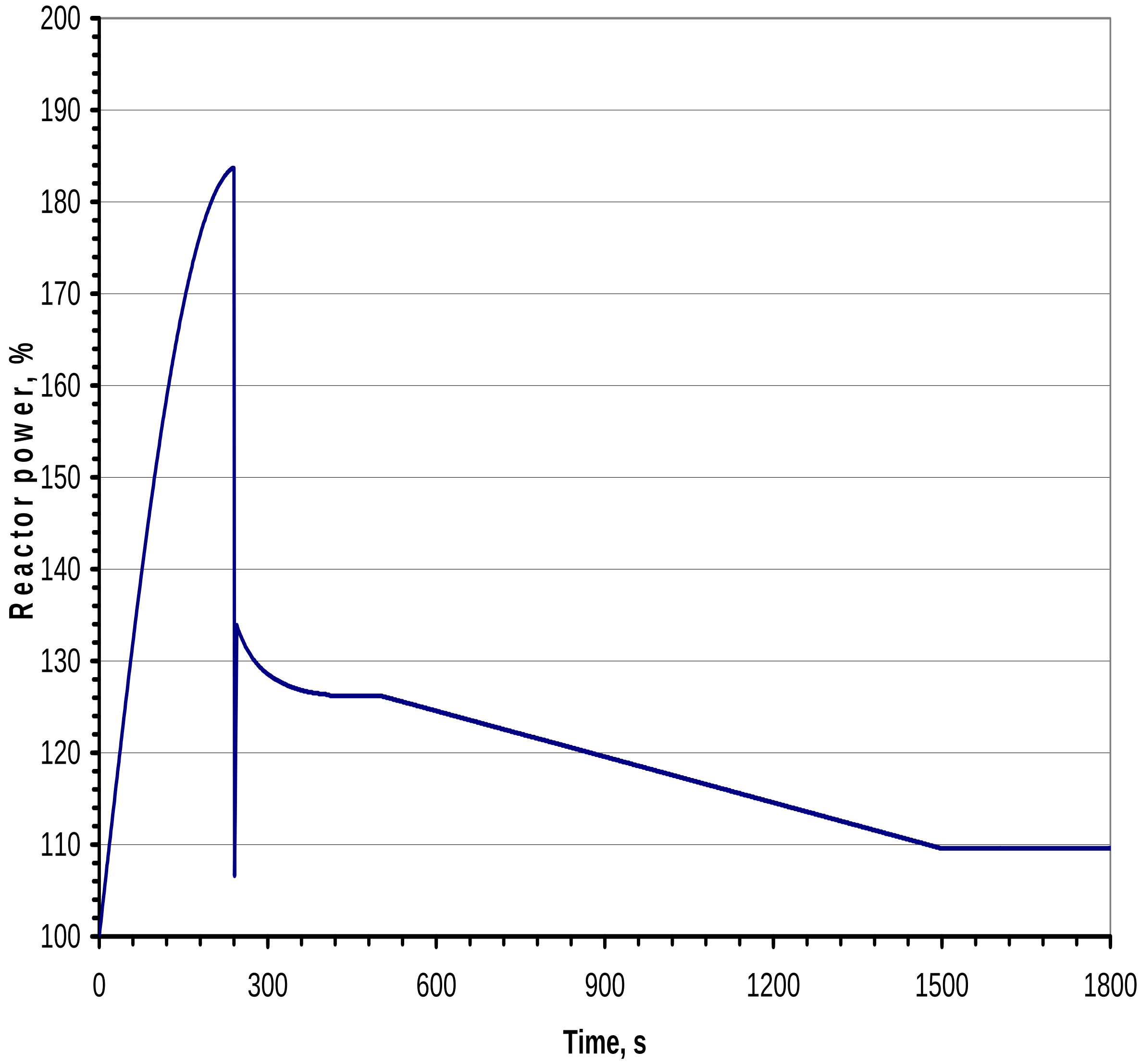


Predicted pool temperature evolution

UTOPA – Fresh core – Conservative analysis

- **Length of CSR withdrawal = 50 cm**
- **Time for CSR withdrawal = 250 s**
- **Net reactivity added = 479 pcm**

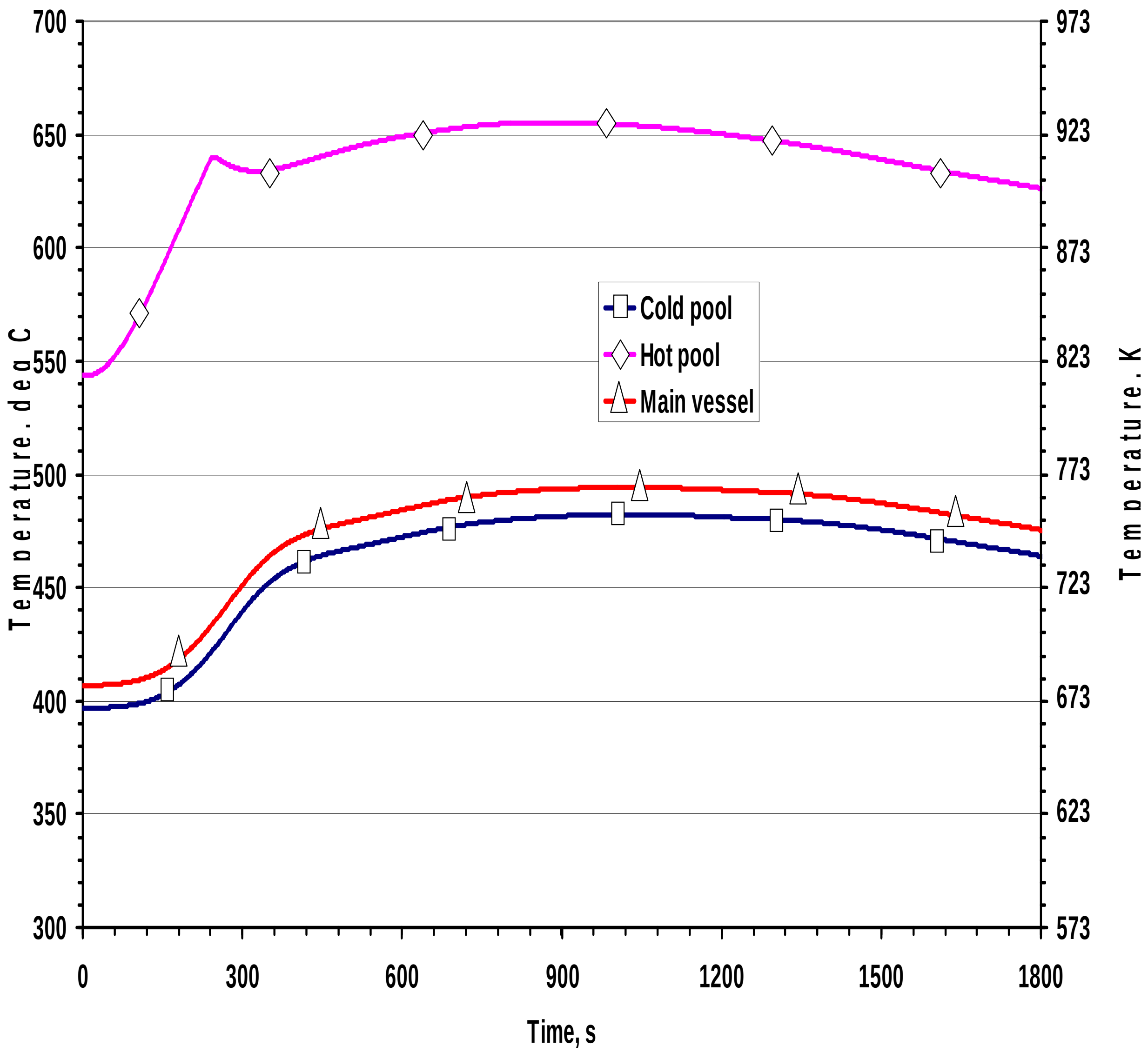
- **Fuel melting starts at 128 s & at 240s the melt fraction reached is 28 %**
- **Fuel squirting considered**
- **Power reduces and stabilises at ~ 110 %**



Predicted power evolution

UTOPA – Fresh core – Conservative analysis

- **Max. Hot pool temperature : 655 ^{0}C**
- **Max. cold pool temperature : 482 ^{0}C**
- **Max. main vessel temperature : 494 ^{0}C**

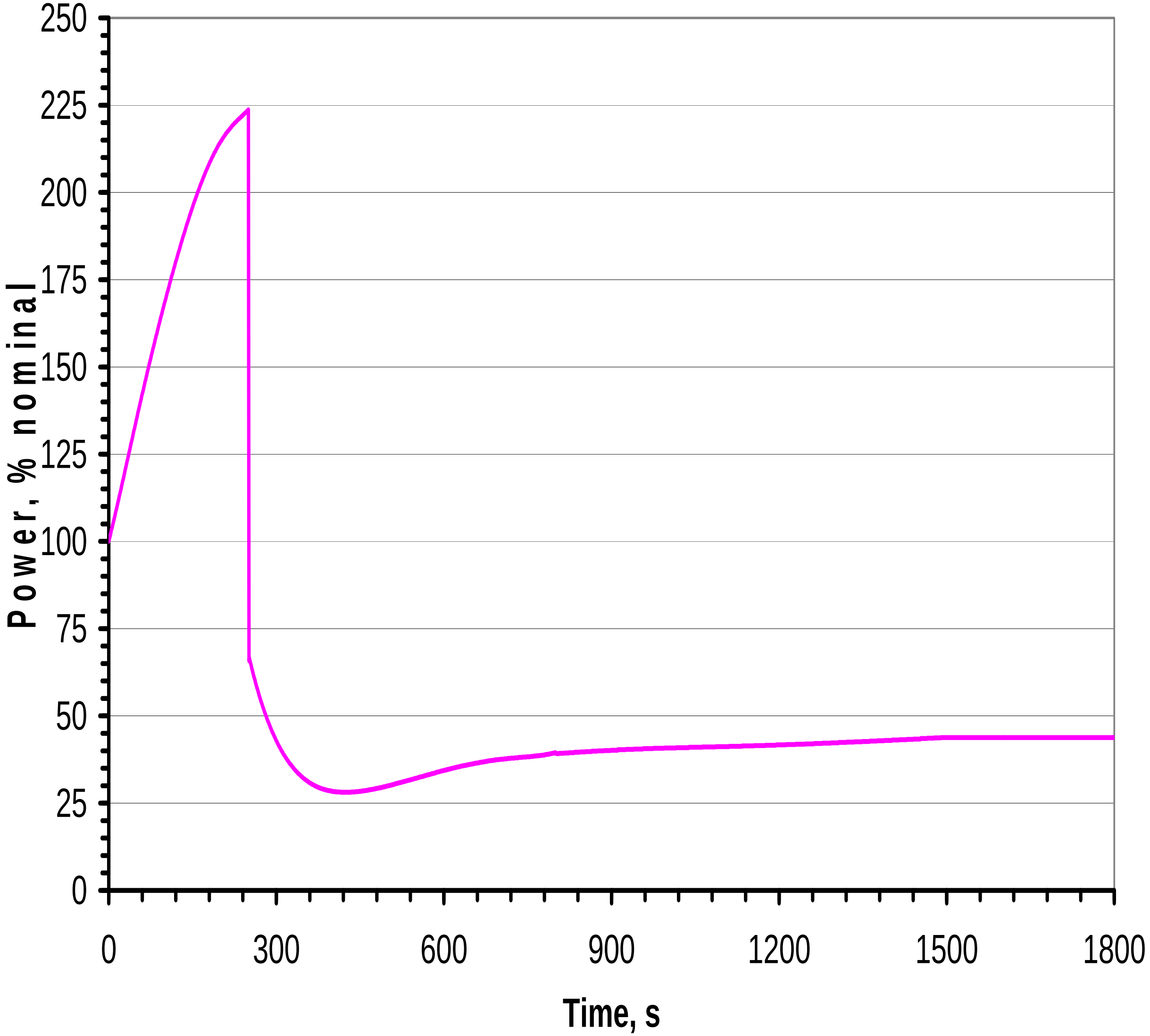


Predicted pool temperature evolution

UTOPA – BOEC core – Conservative analysis

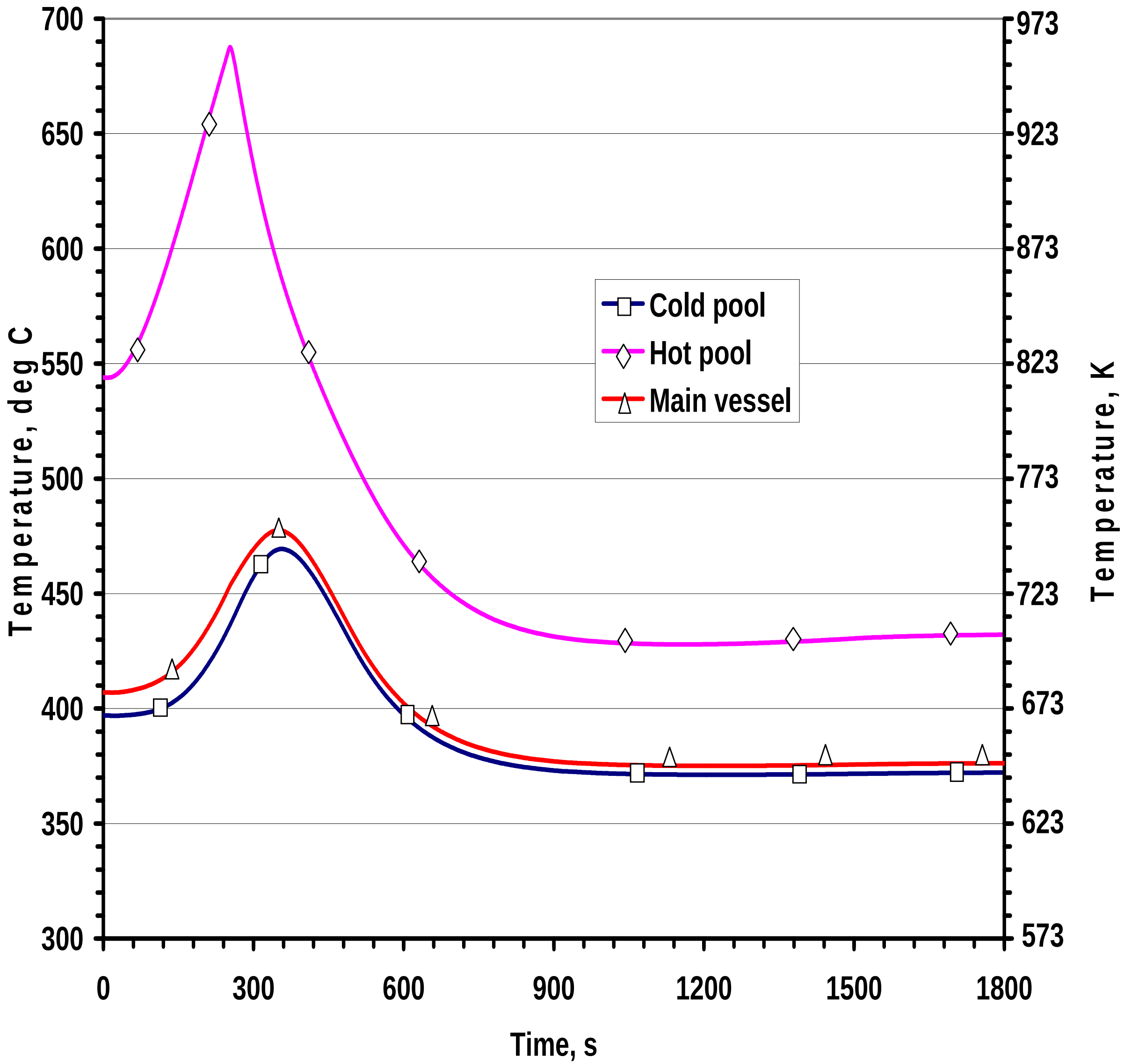
- Length of CSR withdrawal = 50 cm
- Time for CSR withdrawal = 250 s
- More uniform power profile & high pellet-clad gap conductance

- Fuel melting starts at 133 s & at 250 s, the melt fraction reached is 28 %
- Fuel squirting occurs
- Power reduces and stabilises at ~ 45 %



Predicted power evolution

UTOP – BOEC core – Conservative analysis



- **Max. Hot pool temperature : 687 ^{0}C**
- **Max. cold pool temperature : 470 ^{0}C**
- **Max. main vessel temperature : 478 ^{0}C**

Predicted Pool temperature evolution

Summary of UTOPA Studies

Case description	Maximum temperatures of various parts of the primary circuit reached, ^0C			Minimum cover gas volume reached, % nominal
	Hot pool	Cold pool	Main vessel	
Fresh core – Nominal	630	460	473	83
Fresh core – Conservative	655	482	494	77
BOEC core - Conservative	687	470	478	70

Analysis of ULOFA

Initiating event

- This transient is initiated due to the loss of power supply in the plant at full power operating conditions
- Alternate power sources to drive pony motors are also not available
- Primary and secondary sodium pumps coast down naturally governed by the inertia of their respective drive system
- Steam water system is also considered to be lost due to power failure
- Shutdown systems fail to trip the plant in-spite of the availability of several SCRAM parameters

Scenario of ULOFA – Pre-disassembly phase

Reactor under normal operating conditions

↓

<u>Initiating event</u>

Failure of all power sources

(i) Primary sodium pumps coast down by inertia (pony motors do not take over)

(ii) Secondary sodium pumps coast down by inertia

(iii) Steam water system becomes unavailable

↓

Several SCRAM parameters (speed, P/Q & Temp.) evolve

Shutdown systems fail to act

↓

Core flow reduces

Coolant boiling starts from top

(- ve reactivity feedback)

↓

Coolant boiling propagates to middle of the core

(+ ve reactivity feedback)

↓

Coolant dryout and clad & fuel melting

↓

Molten fuel slumps down

Large positive reactivity insertion

↓

Fuel temperature reaches boiling point

Core integrity lost

↓

Disassembly phase

Scenario of ULOFA – Disassembly phase

Coolant flow completely stopped

Power generated is deposited within core

↓

Reactivity insertion due to fuel slumping

Super prompt power excursion initiated with associated Doppler feedback

↓

Core bubble gets pressurised due to heat generation

Governed by equation of state of fuel

↓

Core bubble expands due to pressure gradient

-ve reactivity feedback evolves due to Doppler and fuel displacement

↓

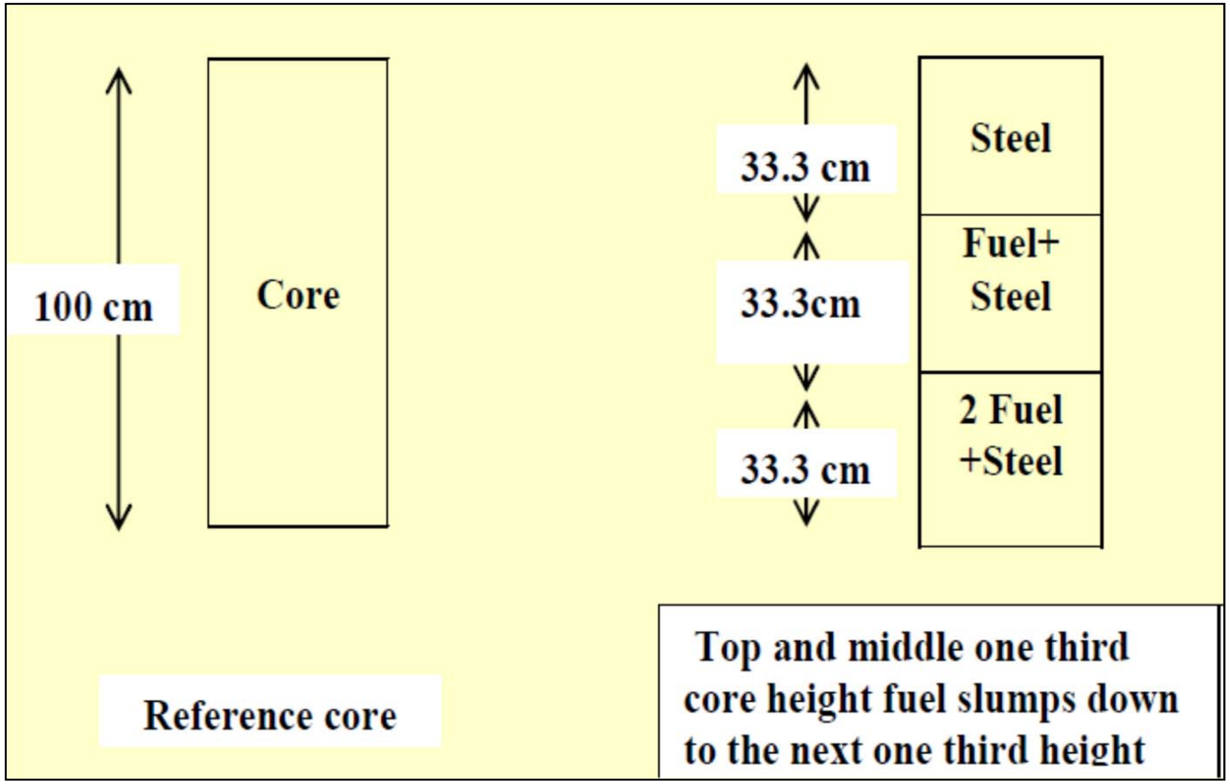
Keff becomes less than 1

End of disassembly phase

↓

Core bubble expands isentropically and exerts mechanical loading

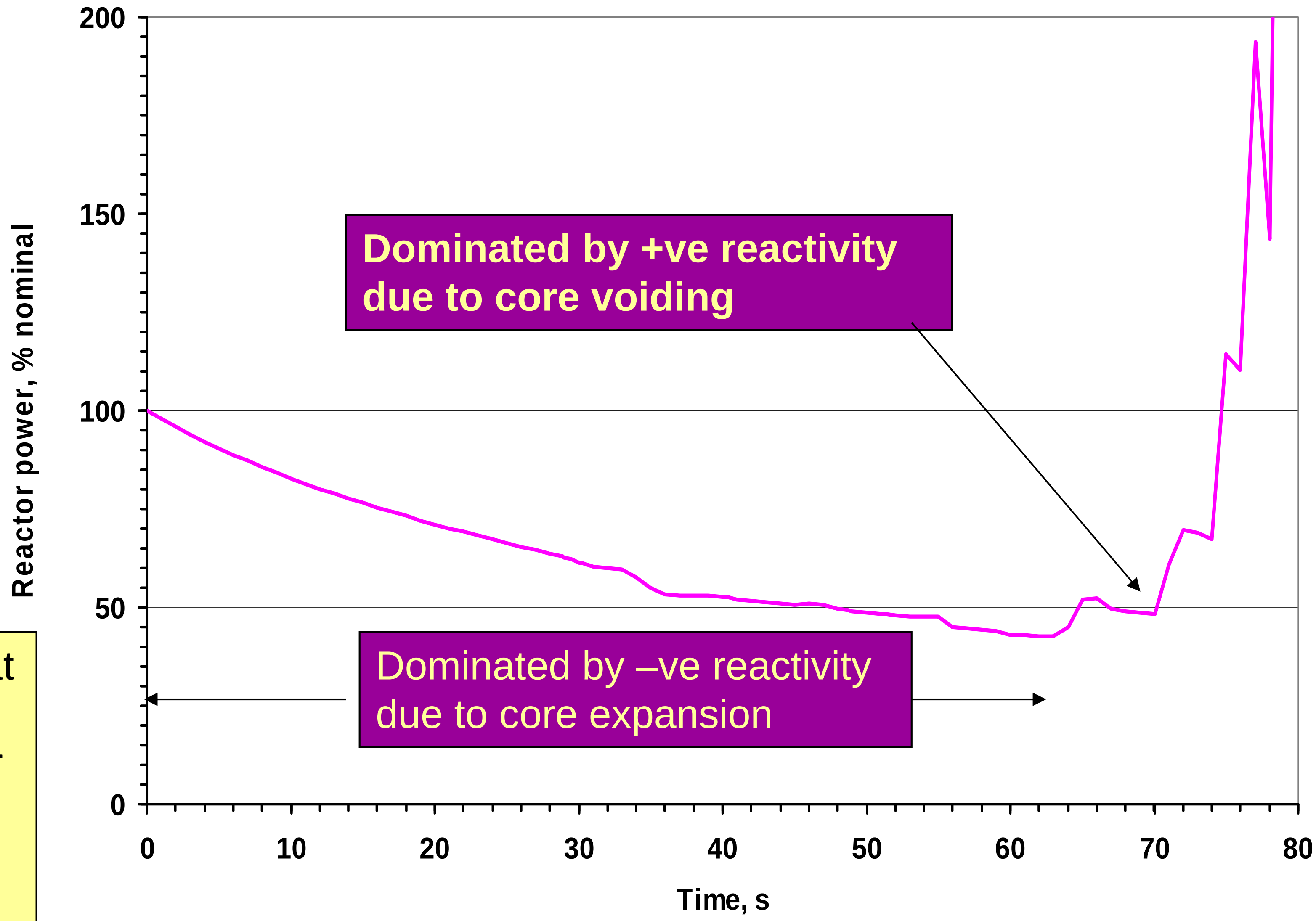
ULOFA : Fuel Slumping Model



Conservative slumping model

ABBN-93 Cross Section Data are used instead of CV2M Cross Section Data

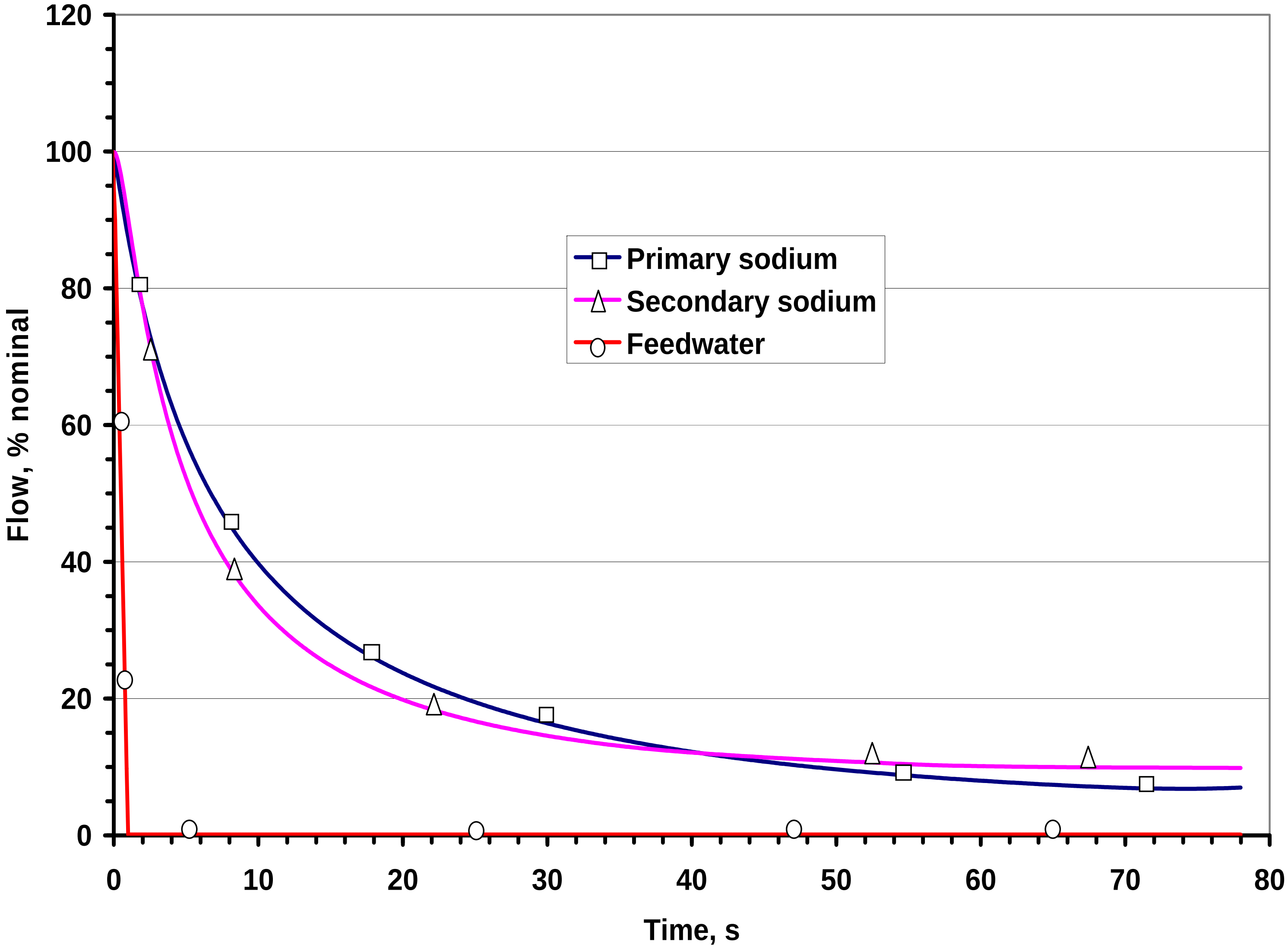
Analysis of ULOFA



Fuel melts at 77s and slumps after 78 s leading to core disruptive accident (CDA)

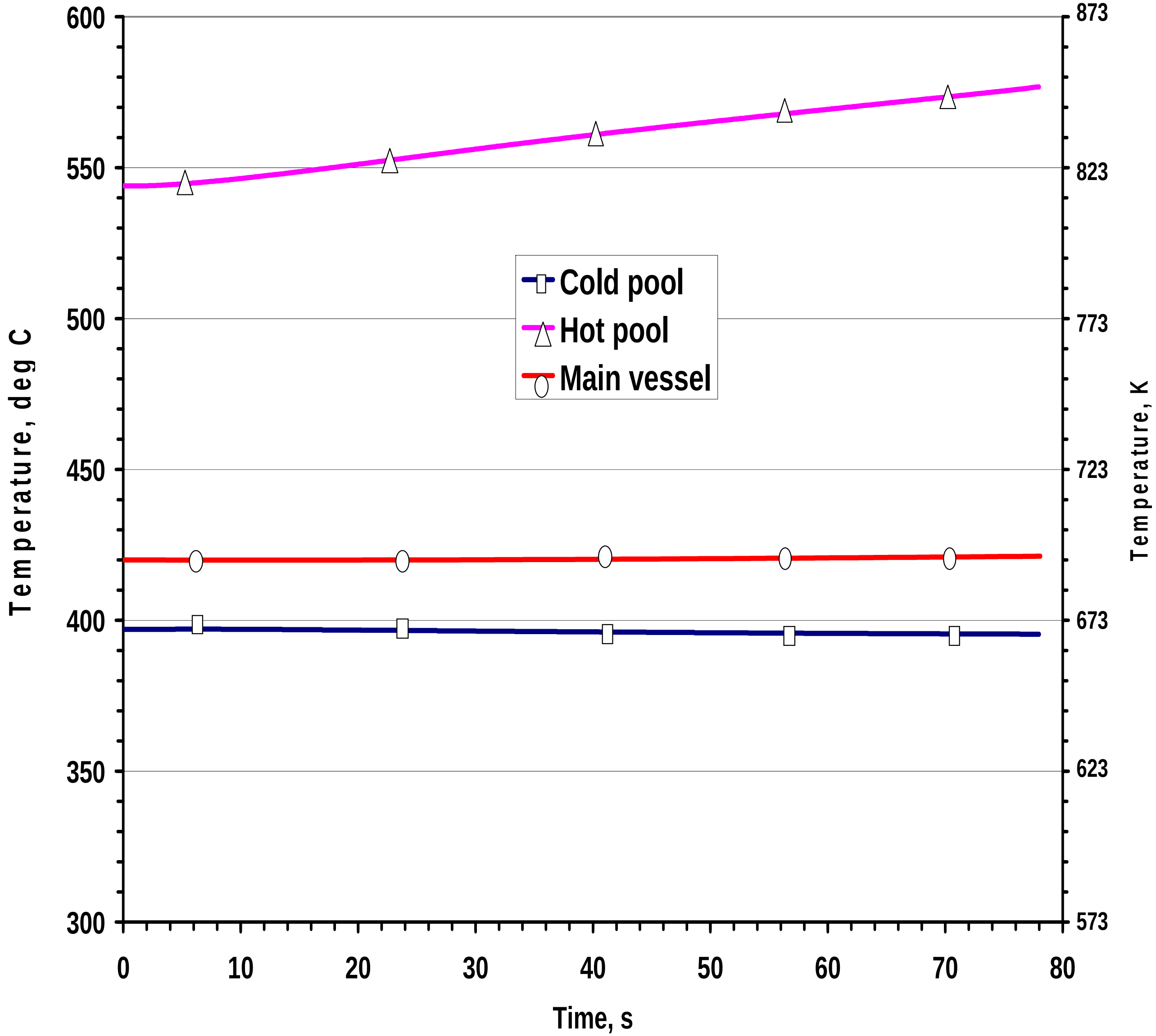
Predicted power evolution

Analysis of ULOFA



Predicted flow evolution in the plant

Analysis of ULOFA



- Max. Hot pool temperature : 580 ^{0}C
- Max. main vessel temperature : 410 ^{0}C

Predicted pool temperature evolution

End of pre-disassembly and disassembly phases

End of pre-disassembly phase

1.	Power (MWt)	0.15×10^5
2.	Reactivity ($)	0.88
3.	Phase duration (s)	78.83
4.	Reactivity addition rate due to fuel slumping ($/s)	10.4
5.	Reactivity addition rate from sodium boiling/FCI ($/s)	0.07

End of disassembly phase

- Thermal energy released : 298.8 MJ
- **Mechanical energy released : 0.02 MJ**
- Peak temperature at the end of disassembly : 3734 K
- Peak pressure : 0.14 MPa
- Phase duration : 42.2 ms

Parametric study on energy release Vs reactivity addition

Reactivity Addition Rates ($/s)	Mechanical Energy Release (MJ)
10.5 (Nominal)	0.02
25	0.08
40	14.7
50	34
65.7	100
75	156
100	344

- 100 MJ mechanical energy release has been considered for the evaluation of mechanical consequences
- Reactivity addition rate for this is 65.7 $/s
- Reactor containment is designed for 100 MJ of mechanical energy release

Future Directions

Future R&D in the domain of Severe Accident will be directed towards development of

(i) Transition phase modeling and

(ii) an **integrated Computer code** for severe accident analysis incorporating models for reactor physics, thermal hydraulics and structural dynamics, on the lines of SIMMER.

The R & D studies being performed at IGCAR towards these goals will be presented by **Dr.P.Chellapandi**, Director, Reactor Design Group, in a companion paper.

Thank You for your kind attention !