Analyses of Severe Unprotected Accidents in PFBR

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Possible Initiating Events

- **Transient Undercooling Event**
  - Loss of Flow

    Power failure to the pumps – flow halving time of 8 s
  - Loss of Ultimate Heat Sink (LOHS)
    - Failure of Decay Heat Removal System
- **Transient Overpower Event**
  - Uncontrolled withdrawal of Control Rod
  - Sudden structural failure

Followed by failure of both shutdown systems

Events Considered

- **Loss of Flow (LOF) followed by full failure of both shut down sysems called ULOF**
- **One CSR uncontrolled withdrawal with both shut down systems failure. Unprotected Transient Over Power (UTOP)**
- **Events higher than SSE only can cause structural failure and are considered in residual risk category**
- **Loss of Heat Sink followed by full failure of both shut down systems (ULOHS)– consequences less than that of ULOF due to very slow transient**

PFBR Core Parameters

Parameter	Value
Pu inventory (t)	2 t
Number of core SA Absorber Rods (CSR/DSR)	85/96 9/3
Core enrichments (%)	21/28
Number of pins per SA	217
Pin diameter /clad thickness (mm)	6.6/0.45
Pellet inner diameter	1.8 mm

Steady State Analysis

- ABBN-93 data
- 2-D Diffusion theory modeling
- Reactivity worth by perturbation theory
- Power distributions and kinetic parameters also estimated
- Fresh core and equilibrium core cases considered
- Equilibrium core reached by 3-D core burn-up computations

Kinetic Parameters

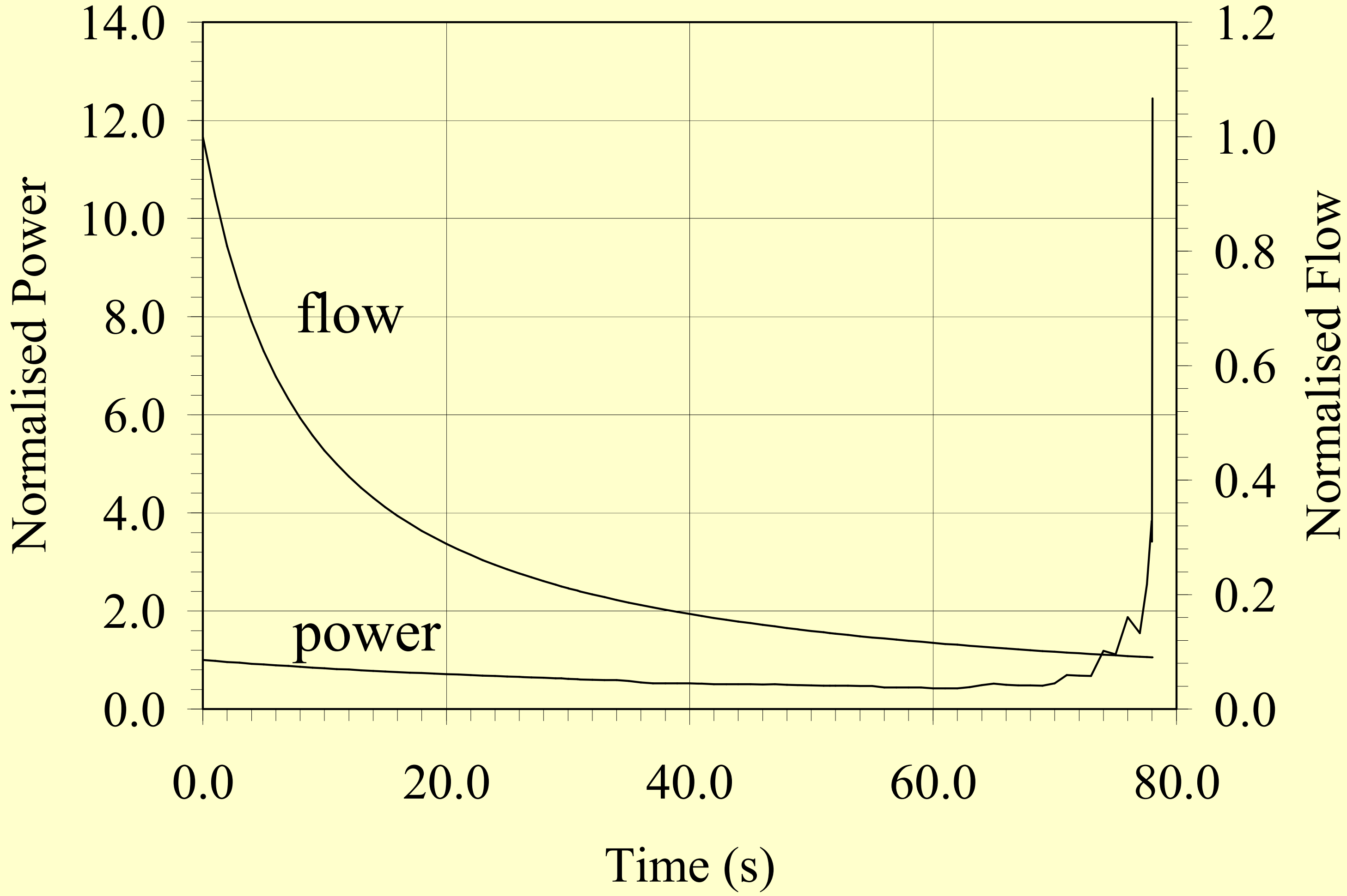
Parameter	Value
Delayed neutron fraction-β (pcm)	355
Doppler constant - 200 C to 973 C (pcm)	-748
Steel addition worth (pcm)	3181
Na void worth – core and axial blankets (pcm)	738

Compared to U fuelled LWRs, the reduced β and positive coolant worth are relevant in severe accidents

Computer Codes and Models Used for Transient Analysis

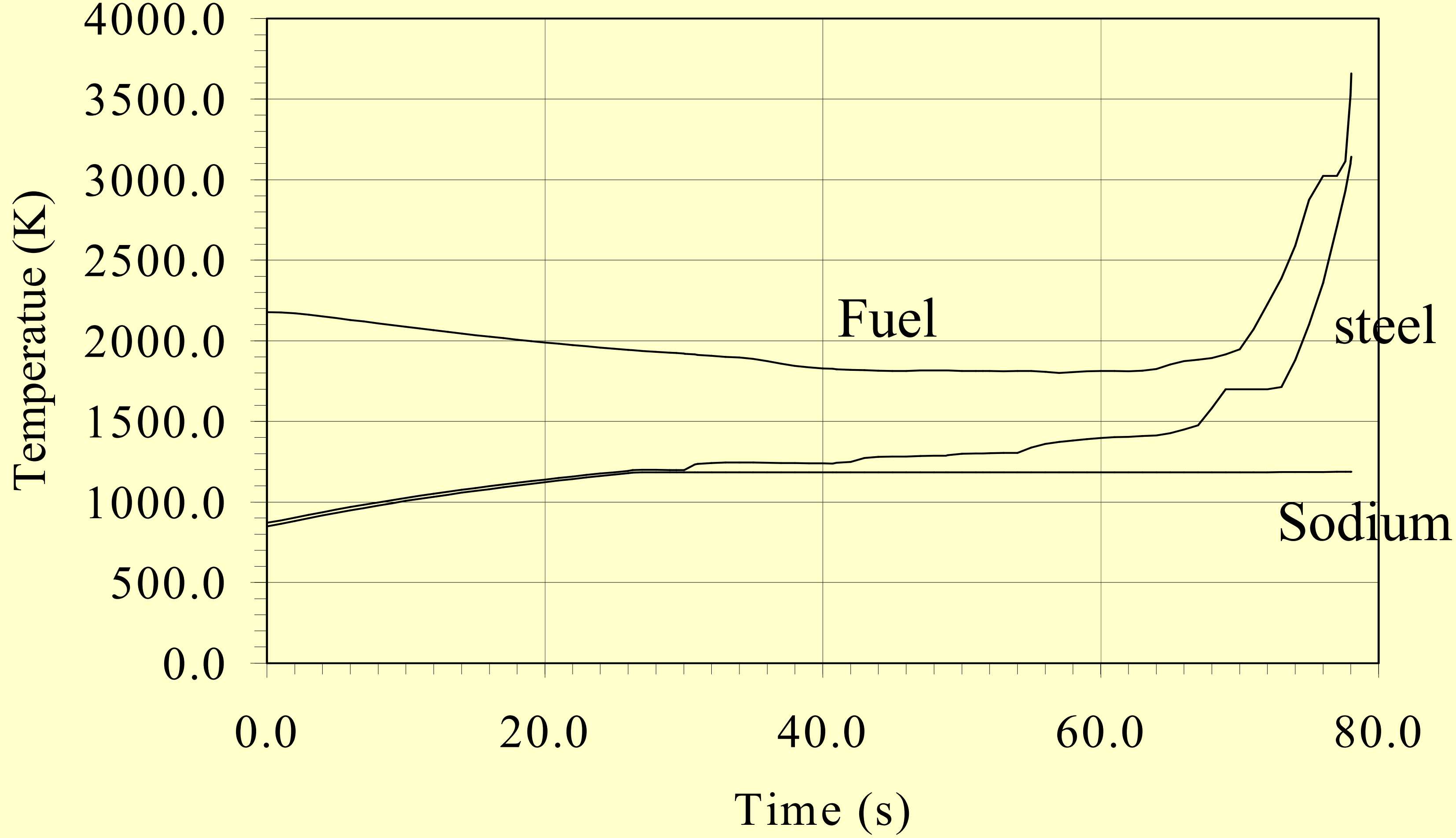
- **PREDIS (pre-disassembly phase) - Core and blanket represented as 10 radial channels and 14 axial zones - point kinetics model used. Doppler, core expansion, coolant expansion, control rod drive expansion, coolant voiding, fuel melting and slumping considered**
- **Transition phase where fuel melts, vaporizes and core configuration changes is not modeled**
- **VENUS code computes the short disassembly phase – melted core expands and becomes sub-critical**
- **Fuel vapour expansion and condensation**

ULOFA



14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Normalised Power
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Normalised Flow
flow
power
0.0
20.0
40.0
60.0
80.0
Time (s)

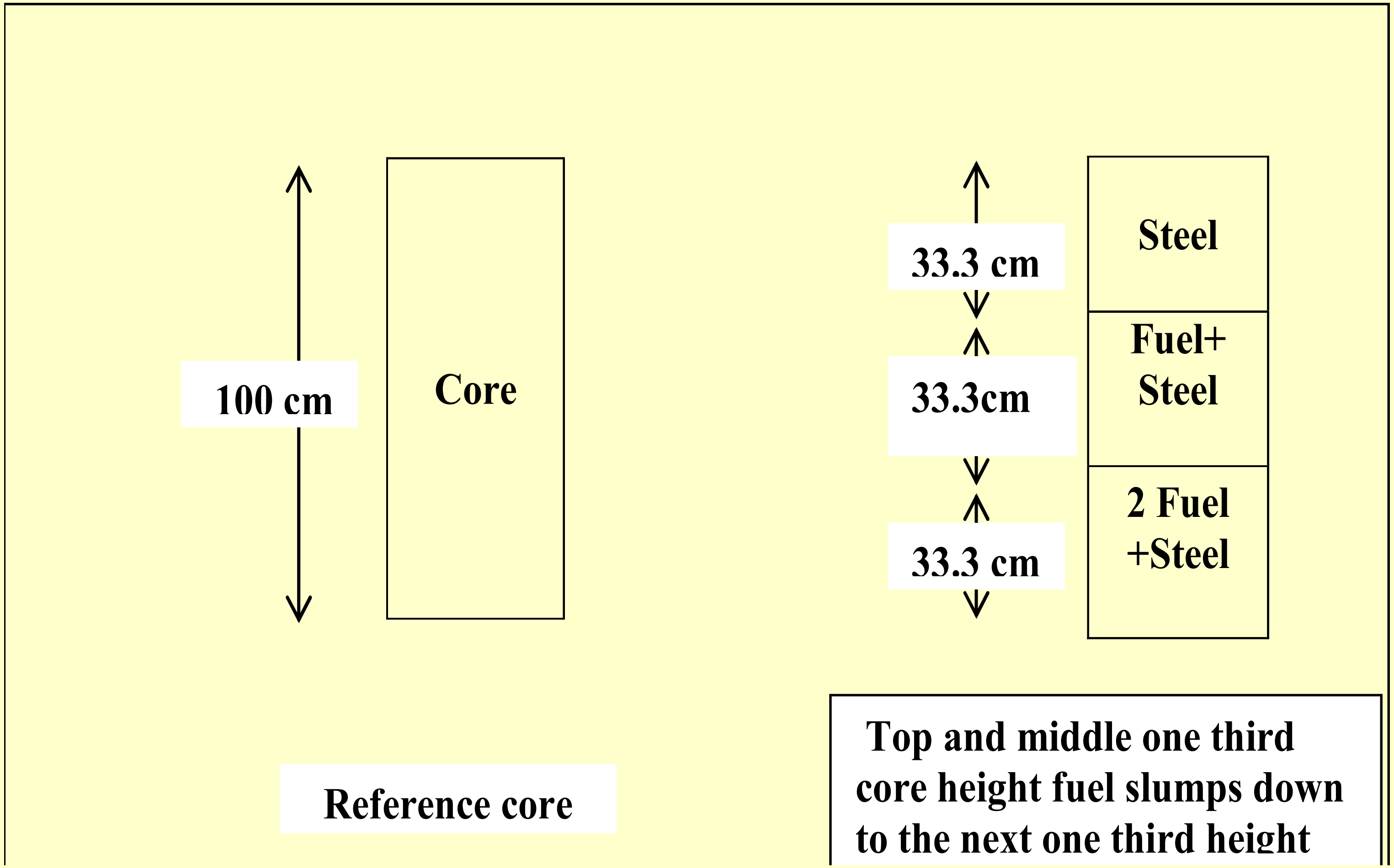
Temperatures



Transient Summary

- Core Na temperature increases
- Core expansion reactivity feed back is negative
- Reactor power and fuel temperature falls for initial 60 s
- Doppler reactivity feed back is positive
- Core voids during 25 s to 78 s and results in positive reactivity feed back
- Control drive expansion reactivity feed back neglected due to the short period of transient
- Power increases after 70 s
- Fuel melts at 77s and slumps after 78 s leading to core disruptive accident (CDA)
- In pin fuel motion not considered as only 1 s elapses between melting and slumping

Conservative Coherent Fuel Slumping Model
(To maximize the reactivity addition rate)



Results at 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

Core melts and vaporizes which is modeled by VENUS code (disassembly phase)- thermal energy release

This vapour expands and reactor becomes sub-critical releasing mechanical energy

Parametric Study of ULOFA Reactivity Addition Rate Required to Get 100 MJ Mechanical Energy

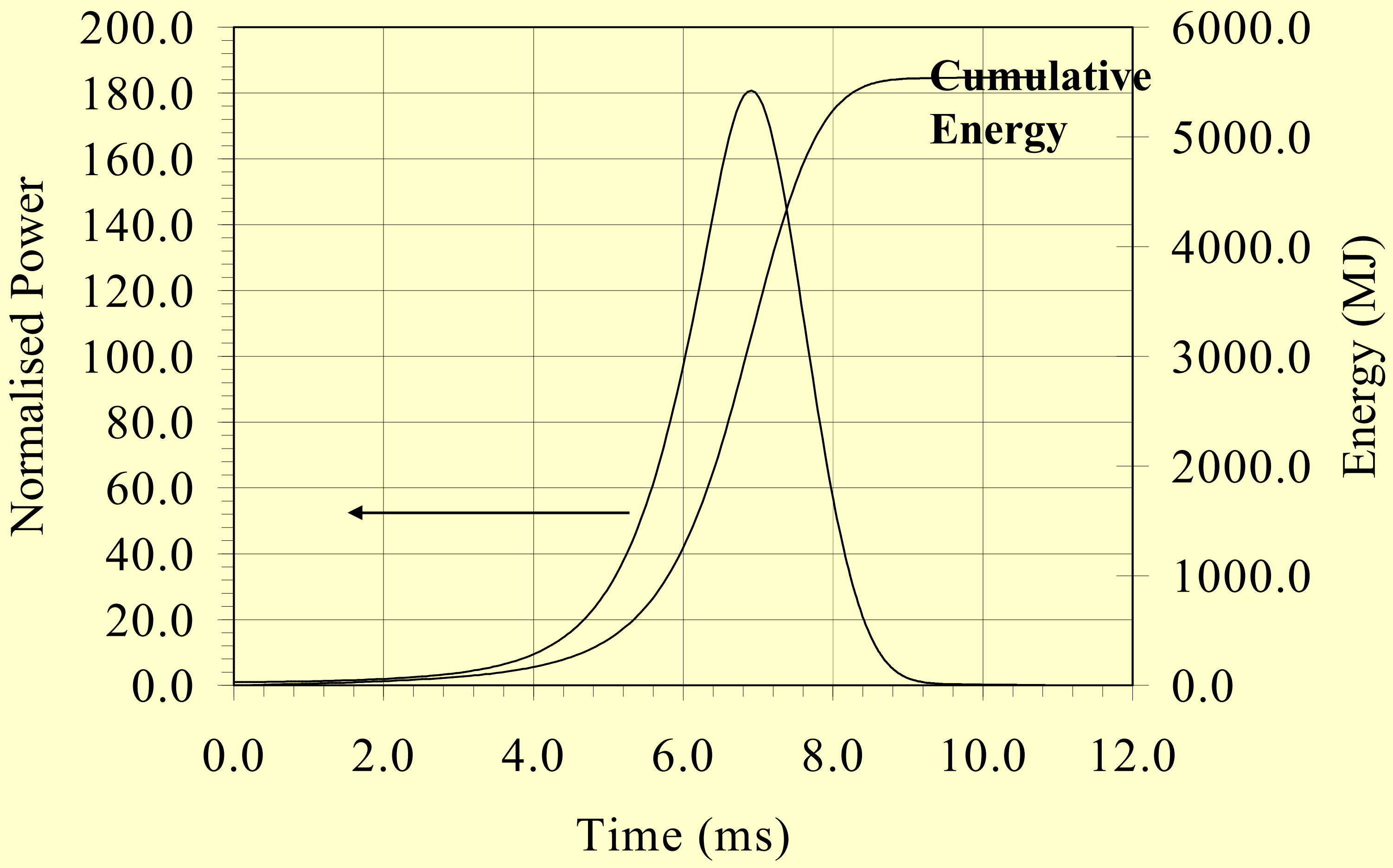
Reactivity Addition Rates ($/s)	Mechanical Energy Release (MJ)
10.5 (Nominal)	0.02
25	0.08
40	14.7
50	34
65.7	100
75	156
100	344

Pre-disassembly transient remains same

Reactivity addition rate increased in disassembly phase

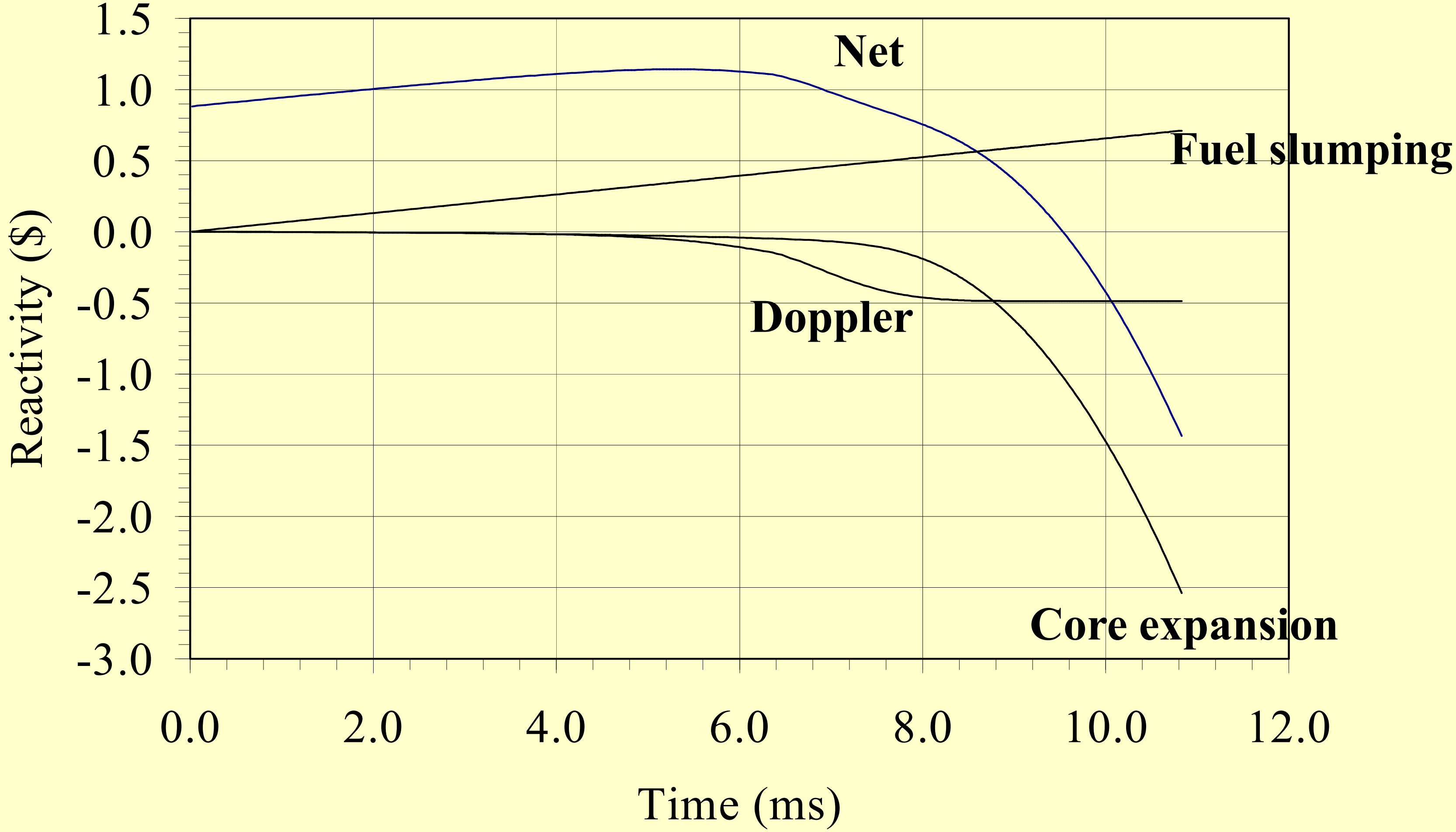
For 100 MJ energy, conservatism assumed in reactivity addition rate is large

Relative Power and Thermal Energy Release during Disassembly



Initial power (1.0) is the power at end of PREDIS which is 12 times nominal

Reactivity Changes during Disassembly



Nominal and 100 MJ case

Parameter	Nominal estimates	Case of 100 MJ
Reactivity addition rate ($/s)	10.5	65.7
Thermal energy release (MJ)	298.8	5546
Mechanical energy release for expansion up to 1 atm, (MJ)	< 1	100
Expanded volume of vapour at 1 atm pressure (m^3)	< 1	380.9
Mechanical energy release for expansion up to core cover gas volume (105 m^3 volume) (MJ)	-	57.7
Final Pressure in expanding up to 105 m^3 (MPa)	-	0.226
Peak Temperature (K) at the end of disassembly	3734	5218
Peak Pressure (MPa)	0.14	9.74
Fuel melt fraction (%)	46.4	53.9
Fuel vapour fraction (%)	0.11	39.8
Phase duration (ms)	42.2	10.8

Fuel coolant interaction (FCI) energy about 0.1 % of thermal energy based on experimental results – restricted geometry of FCI zone

UTOPA Event
Energetic CDA is Unlikely

- **Following cases of uncontrolled absorber rod (CSR) withdrawal were considered**

  BOL fresh core - conservative

  BOL fresh core - nominal

  BOEC core - conservative

- **In-pin fuel motion of melted fuel considered after**

  - CSR withdrawal is complete (250 s)

- **Simple model**
  7 % of melted fuel shifted to axial blanket region .
  15-25 % movement of melted fuel observed in experiments

In Pin Fuel Motion

- **HUT 52 A Experiments**
  -full length heated pins enhance in-pin fuel motion
- **Annular pellets increases in-pin fuel motion**
- **In FBR spectrum, fission gas driving force will be higher as there is no flux dip in the pellet**
- **TS experiments**

  - 22 % PuO_2 full length pins in TREAT reactor

  - 5 c/s TOP

  - Pre failure movement of 25 % of melted fuel even with solid fuel pellets
- **CABRI experiments also confirm central hole formation in TOP**

PFBR UTOP (Conservative and Nominal)

S.No	Parameter	Conservative	Nominal
1	Initial CSR position	50 cm in	40 cm in
2	CSR worth	479 pcm	317 pcm
3	Initiation of CSR drive expansion effect	After 500 s	After 100 s
4	CSR drive expansion coefficient	0.10 mm/C	0.15 mm/C
5	In-pin fuel motion	7 % of total fuel in melted region	In experiments more than 15 % of fuel in melted region

Iterations performed between PREDIS and DYANA-P (code modeling primary circuit) to get consistent reactor inlet temperatures and thermal balance

Summary of UTOP Analysis

- **BOL (conservative)**
  Fuel melts – With in-pin fuel motion, power stabilises at 111 % nominal
- **BOEC (conservative)**
  Fuel melts – With in-pin fuel motion, reactor power reduces to 44 % nominal

- **TOP event will not result in CDA with in-pin fuel motion reactivity feed back is present**

CONCLUSIONS

- ULOF - CDA scenario
  Predisassembly phase ~70 s - 80 s
  Disassembly phase ~ 10 ms
- Parametric study of disassembly phase is performed and very conservative reactivity addition rate is required to get 100 MJ mechanical energy during CDA in PFBR
- TOP event will not result in CDA in both fresh core or BOEC core, when in-pin fuel motion reactivity feed back is considered

THANK YOU