Design features and safety assessment of a sodium-cooled fast reactor in Japan for mitigation of severe accidents

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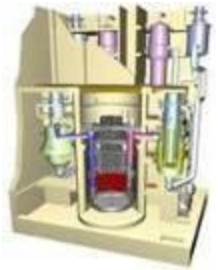
SeFARD

Safety approach for severe accidents in Japan

Next-generation reactor

Demonstration reactor
Commercialization reactor
(Under design)



- ✓ Passive mechanisms
- ✓ In–vessel retention using recriticality–free core concept

Design in 2000~present

Innovative technologies

DFBR
Utility-led
Demonstration reactor
(only design)

- ✓ Passive reactor shutdown mechanism
- ✓ Accommodate the consequence of severe energetics, which was evaluated using mechanistic analysis codes

Design in 1990's

Power : 1,600MWt/660MWe, Temperature: 550ºC

Mechanistic safety analysis

Monju
Prototype reactor

- ✓ Accommodate the consequence of severe energetics, which was evaluated using mechanistic analysis codes

First Criticality in 1994, restart 2010, decommissioning 2016~

Power : 714MWt/280MWe, Temperature: 529ºC

Joyo

Experimental reactor

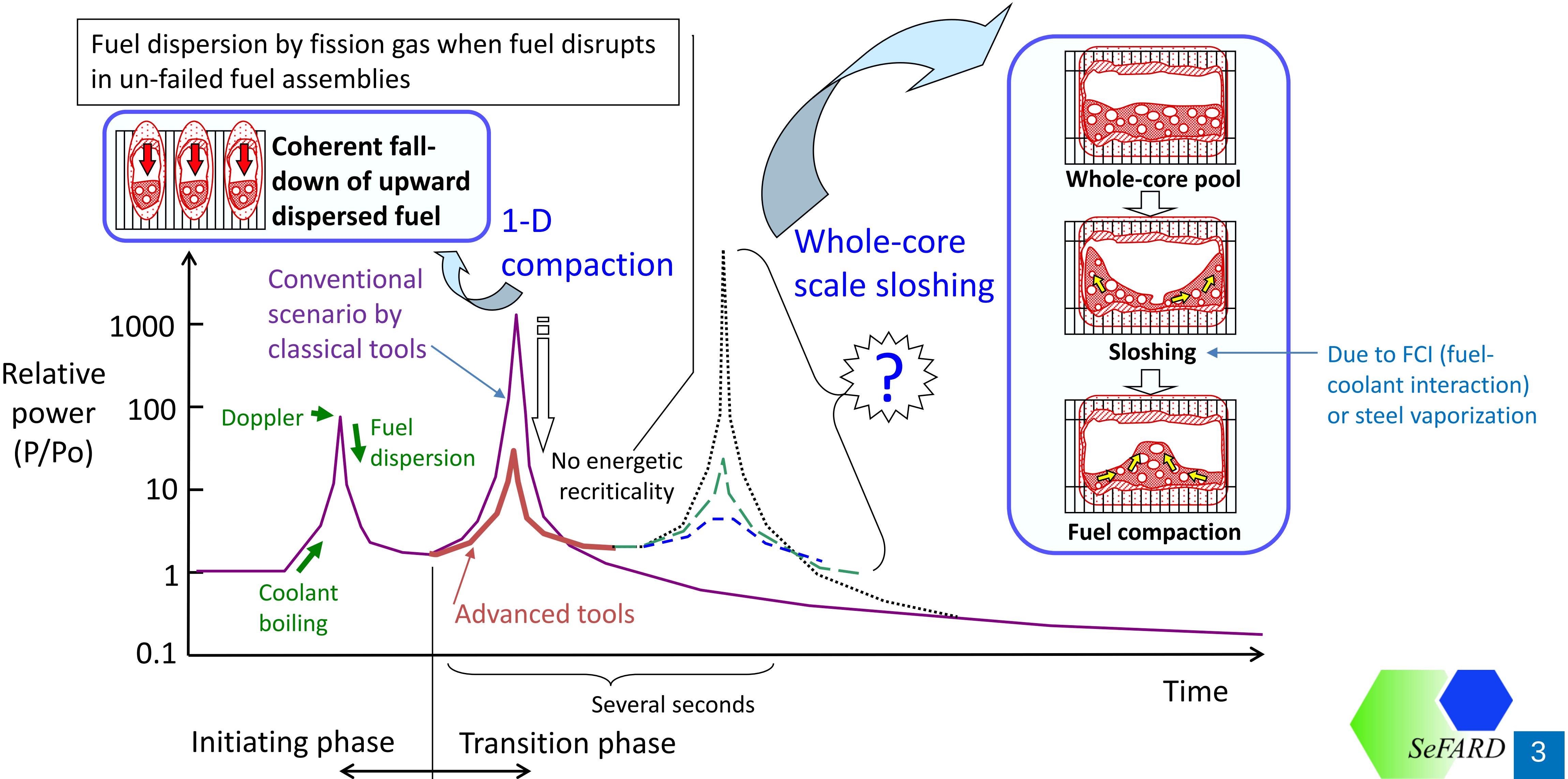
- ✓ Accommodate the consequence of severe energetics, which was evaluated using the Bethe–Tait model

First Criticality in 1977

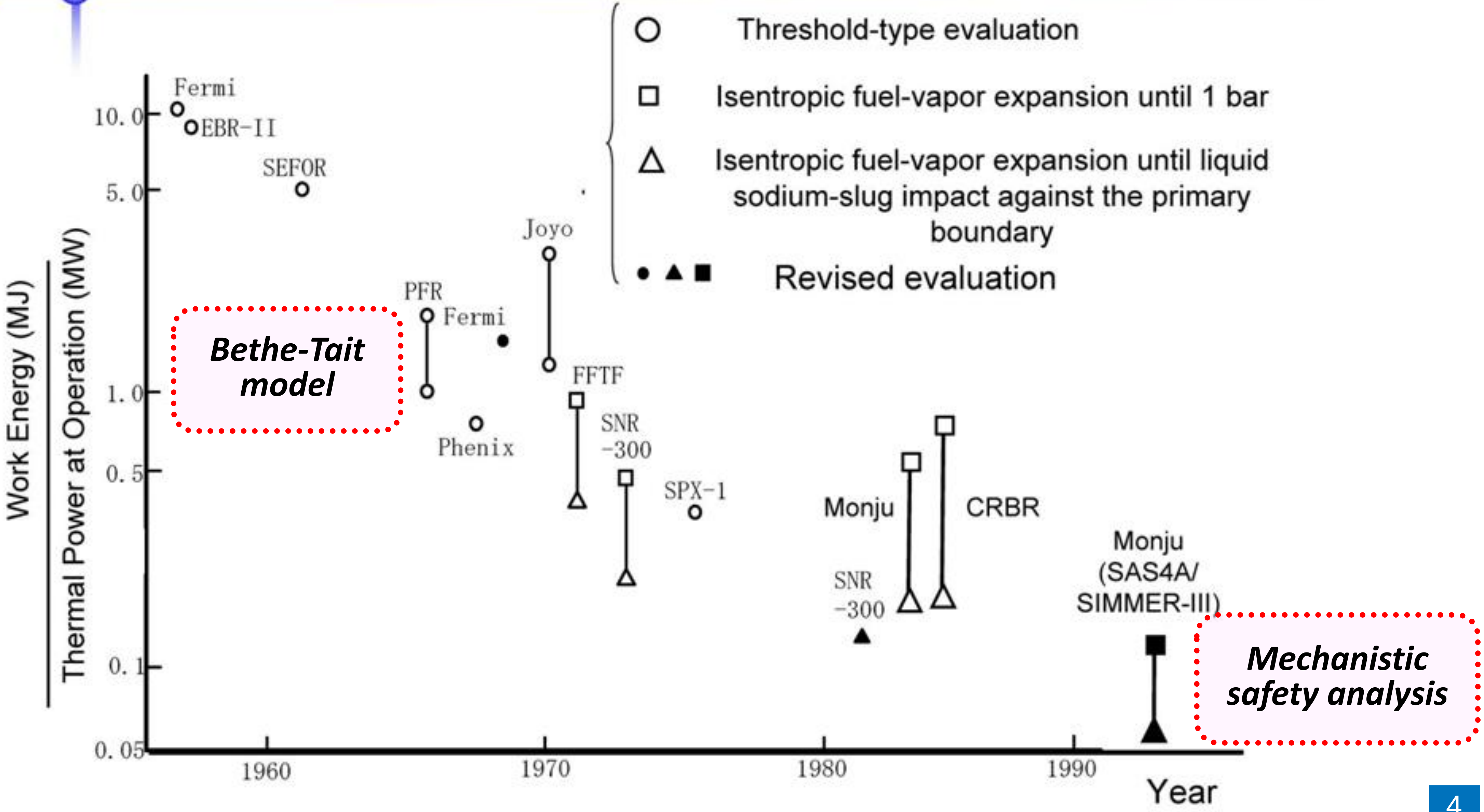
Power : 50MWt → 100MWt → 140MWt → 100MWt (Mk-IV core)
Temperature: 435ºC → 500ºC → 500ºC

Recriticality issue in SFR severe accidents (CDAs)

Typical scenarios appeared in unprotected loss-of-flow (ULOF) events in oxide-fuel SFRs (e.g., Monju)



Historical Transition of Evaluated CDA Work Energy Release

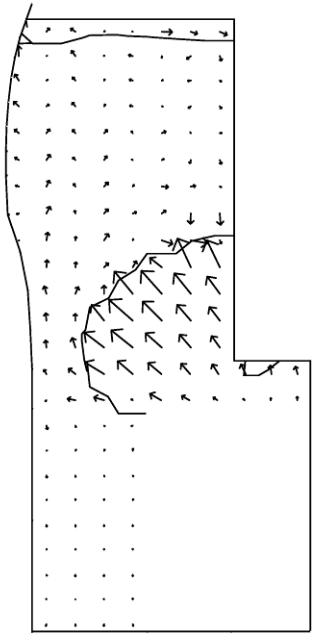


Bethe-Tait model

Mechanistic safety analysis

Structural response assessment for DFBR (670kWe)

- About 150 MJ was evaluated as a mechanical energy generated by core expansion
- Safety assessment methodologies were developed based on 1/10 and 1/20 tests which simulated core expansion and reactor vessel structure response

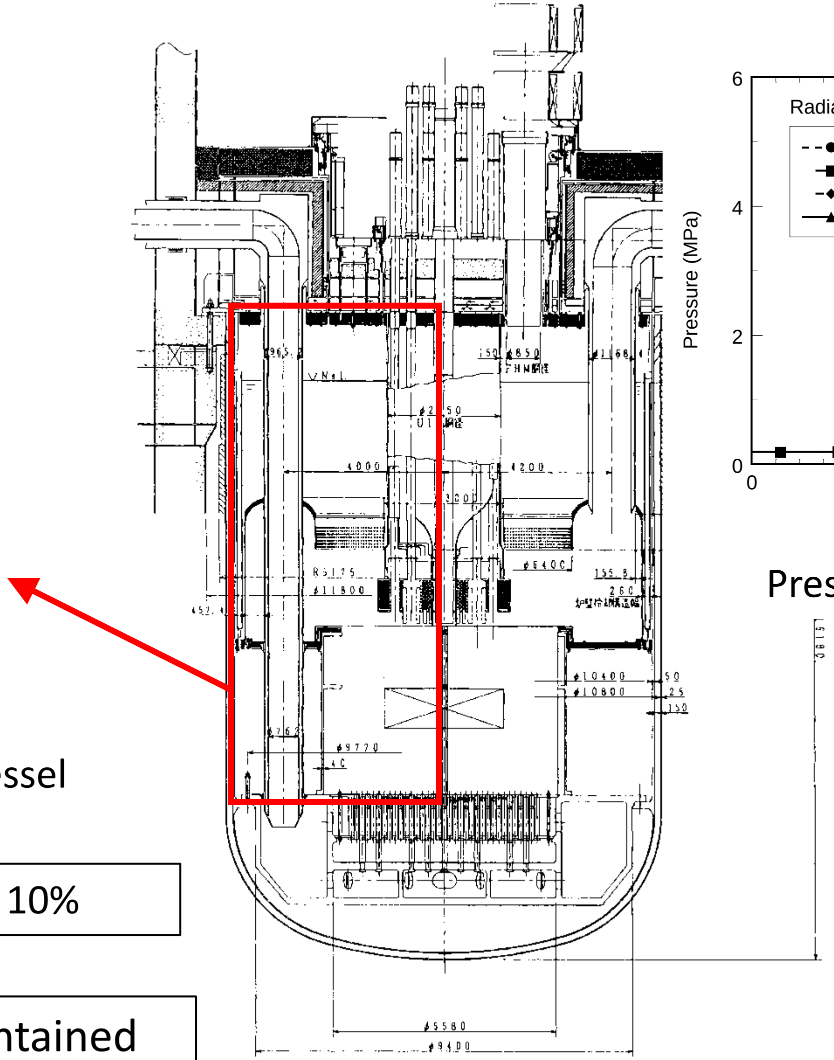


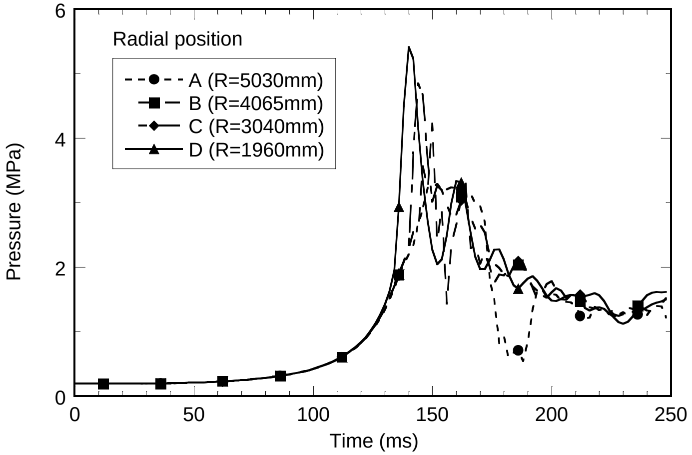
Core expansion and reactor vessel deformation

The maximum strain was about 10%

⇩

The boundary function can be maintained





Pressure transient in cover gas region

Why do we need to eliminate recriticality issue?

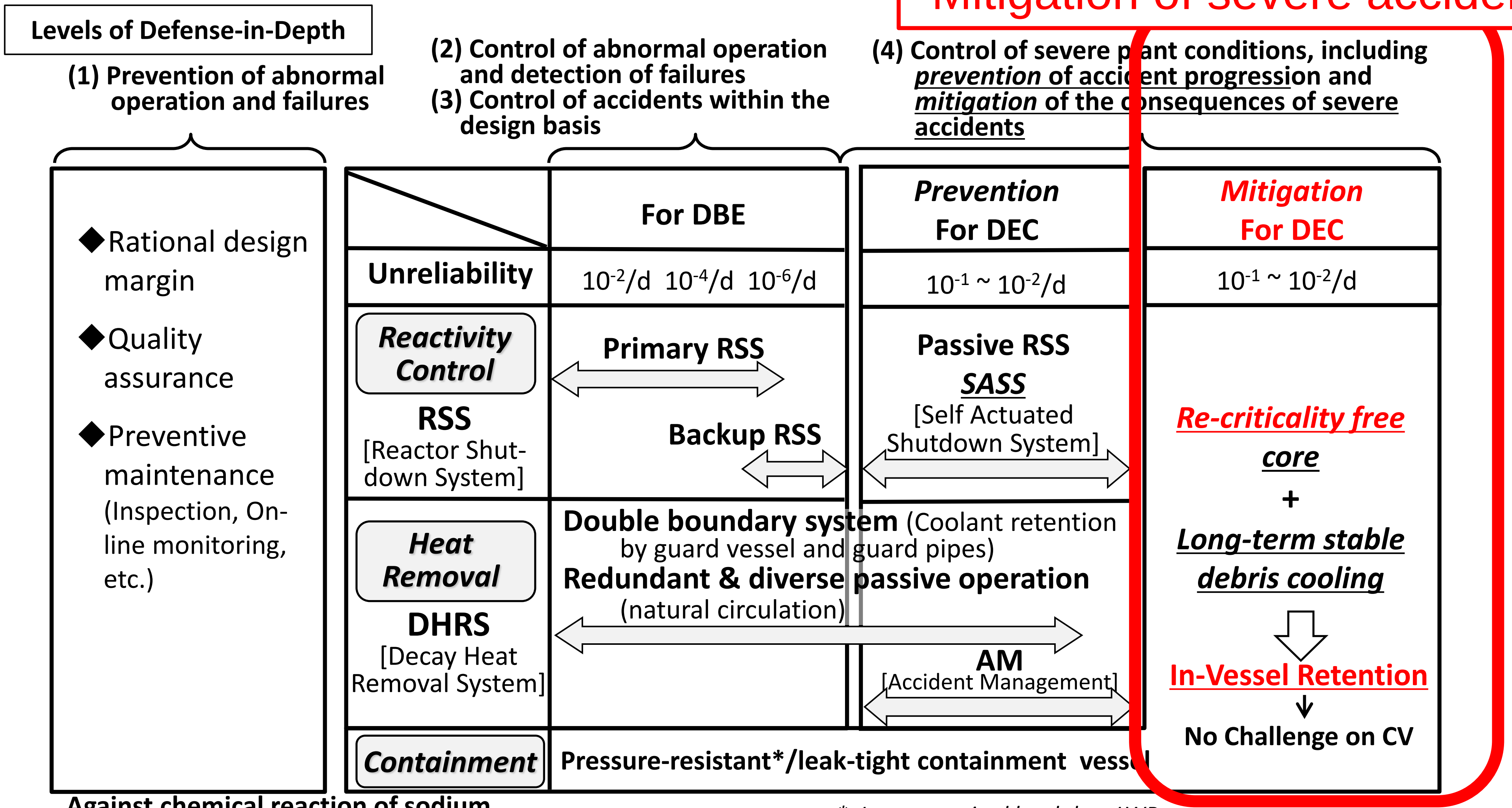
- Like LWRs, large-sized SFRs are desirable for future main power plants in Japan
- Severe accident assessments involving energetic recriticality are necessary
- Molten fuel pool can be extended to a whole core scale as a result of connection of molten pool between fuel assemblies due to assembly wall failure by molten fuel
  - ✓ This is because the possibility of molten fuel/steel blockage is extremely high after their dispersion and relocation in the SFR fuel assembly
- Since core fuel inventory increases in large-sized SFRs, the consequence and uncertainty of mechanical energy released in energetic recriticality with fuel compaction could increase
  - ✓ Difficult to accommodate the mechanical energy in the reactor vessel in large-sized SFRs
- Design features to avoid the formation of molten core pool?
  - ✓ Competition of molten pool formation and molten fuel discharge should be taken into account
  - ✓ Fuel discharge through a control rod guide tube (CRGT) might be slow because of double wall failure, i.e., fuel assembly and CRGT
  - ✓ Fuel discharge mechanism prior to the wall failure of fuel assembly

⇩

- Recriticality-free core concept

Safety Design Concept for future SFR in Japan

Mitigation of severe accidents



Levels of Defense-in-Depth

(1) Prevention of abnormal operation and failures

(2) Control of abnormal operation and detection of failures
(3) Control of accidents within the design basis

(4) Control of severe plant conditions, including *prevention* of accident progression and *mitigation* of the consequences of severe accidents

- Rational design margin
- Quality assurance
- Preventive maintenance (Inspection, On-line monitoring, etc.)

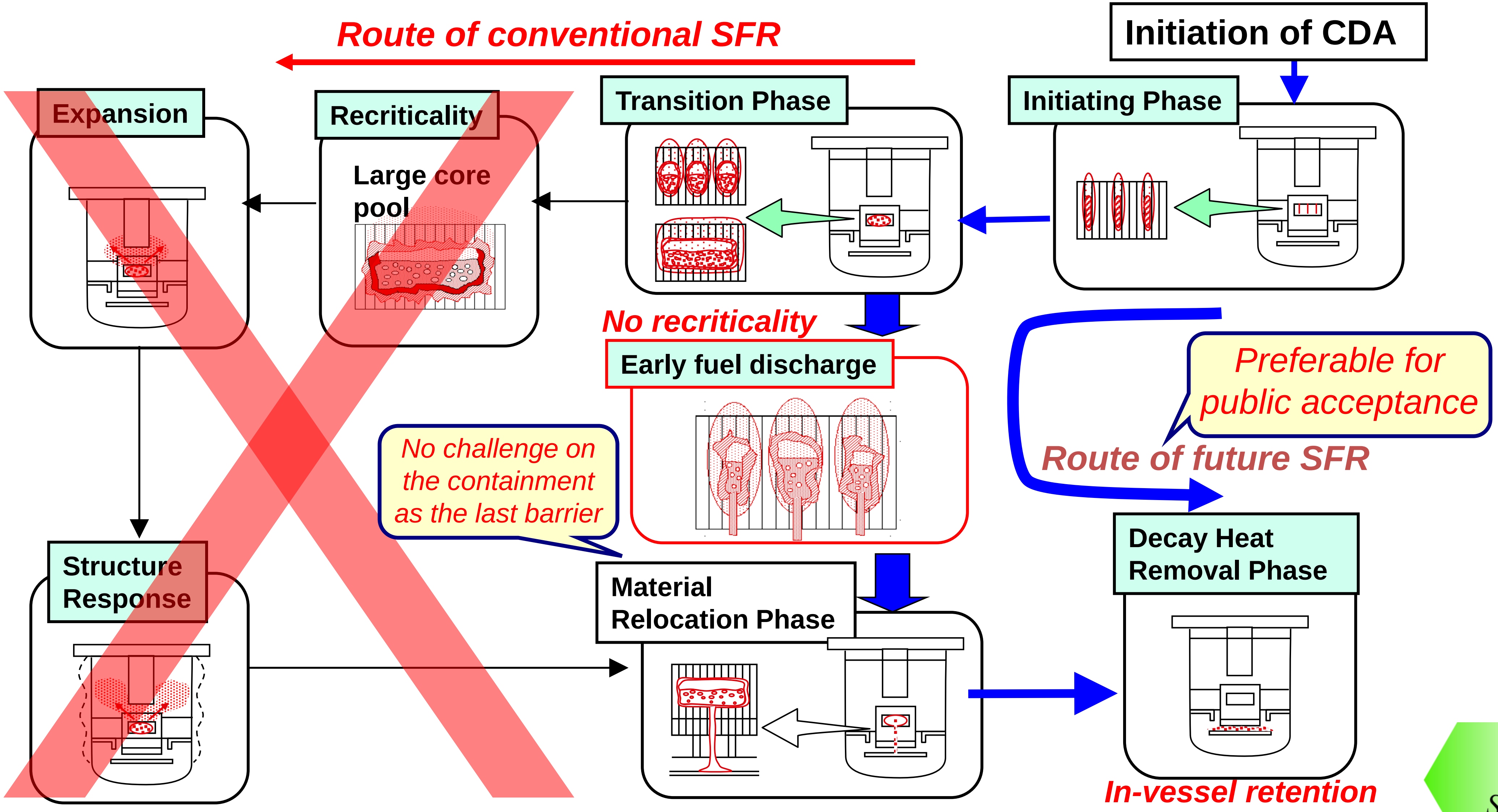
	For DBE	*Prevention* For DEC	*Mitigation* For DEC
Unreliability	10^{-2}/d 10^{-4}/d 10^{-6}/d	10^{-1} ~ 10^{-2}/d	10^{-1} ~ 10^{-2}/d
Reactivity Control **RSS** [Reactor Shut-down System]	**Primary RSS** **Backup RSS**	**Passive RSS** ***SASS*** [Self Actuated Shutdown System]	***Re-criticality free core*** **+** ***Long-term stable debris cooling*** ⇩ **In-Vessel Retention** ↓ **No Challenge on CV**
Heat Removal **DHRS** [Decay Heat Removal System]	**Double boundary system** (Coolant retention by guard vessel and guard pipes) **Redundant & diverse passive operation** (natural circulation)	**AM** [Accident Management]	
Containment	**Pressure-resistant*/leak-tight containment vessel**		

Against chemical reaction of sodium
- **Sodium leak -> leak-tight guard vessel & pipes (double boundary)**
- **SG tube leak -> double-wall tube, early detection & rapid depression of steam-water side**

**: Lower required level than LWRs*

Ref. H. Yamano, et al., ICAPP'11, 11219.

Event progression of ULOF/CDA



Initiation of CDA

Initiating Phase

Transition Phase

Route of conventional SFR

Recriticality

Large core pool

Expansion

Structure Response

No recriticality

Early fuel discharge

No challenge on the containment as the last barrier

Material Relocation Phase

Preferable for public acceptance

Route of future SFR

Decay Heat Removal Phase

In-vessel retention

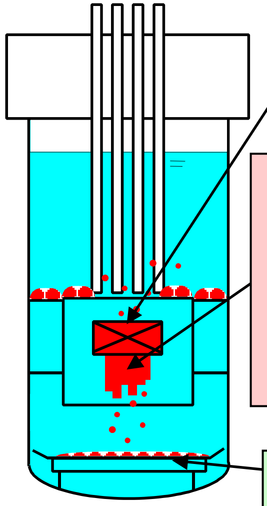
Ref. H. Yamano, et al., ICAPP'11, 11219.

Design features for mitigation of severe accidents

Prevention

Events	Mechanisms	Design features
(0) ULOF start	- Passive shutdown - Passive decay heat removal (DHR)	- **Self-actuated shutdown system** - **Natural circulation DHR system**

Mitigation



Core disruption phases	Mechanisms	Design features
(1) Initiating phase	•limitation of Sodium void •Limitation of core height	•Core and fuel design
(2) Early fuel discharge phase (instead of transition phase)	•Enhancement of Early fuel discharge	•Fuel assembly with inner duct
(3) Material relocation and cooling phases	•Fragmentation due to quenching •Long-term cooling by sodium	•Structure design for relocation •In-vessel core catcher •Sodium plenum space for relocation and cooling •DHRS design against CDA

In-vessel retention concept

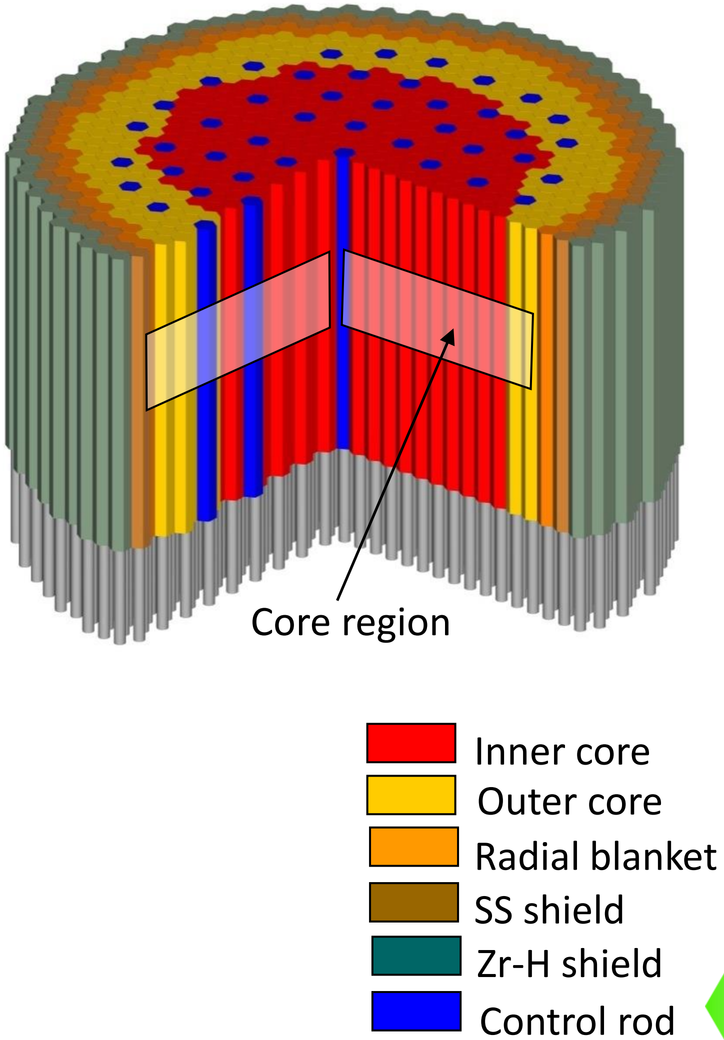
Recriticality-free core concept (covers: •Core and fuel design; •Fuel assembly with inner duct)

SeFARD

Design features for initiating phase

Core design to avoid power excursion driven by void reactivity

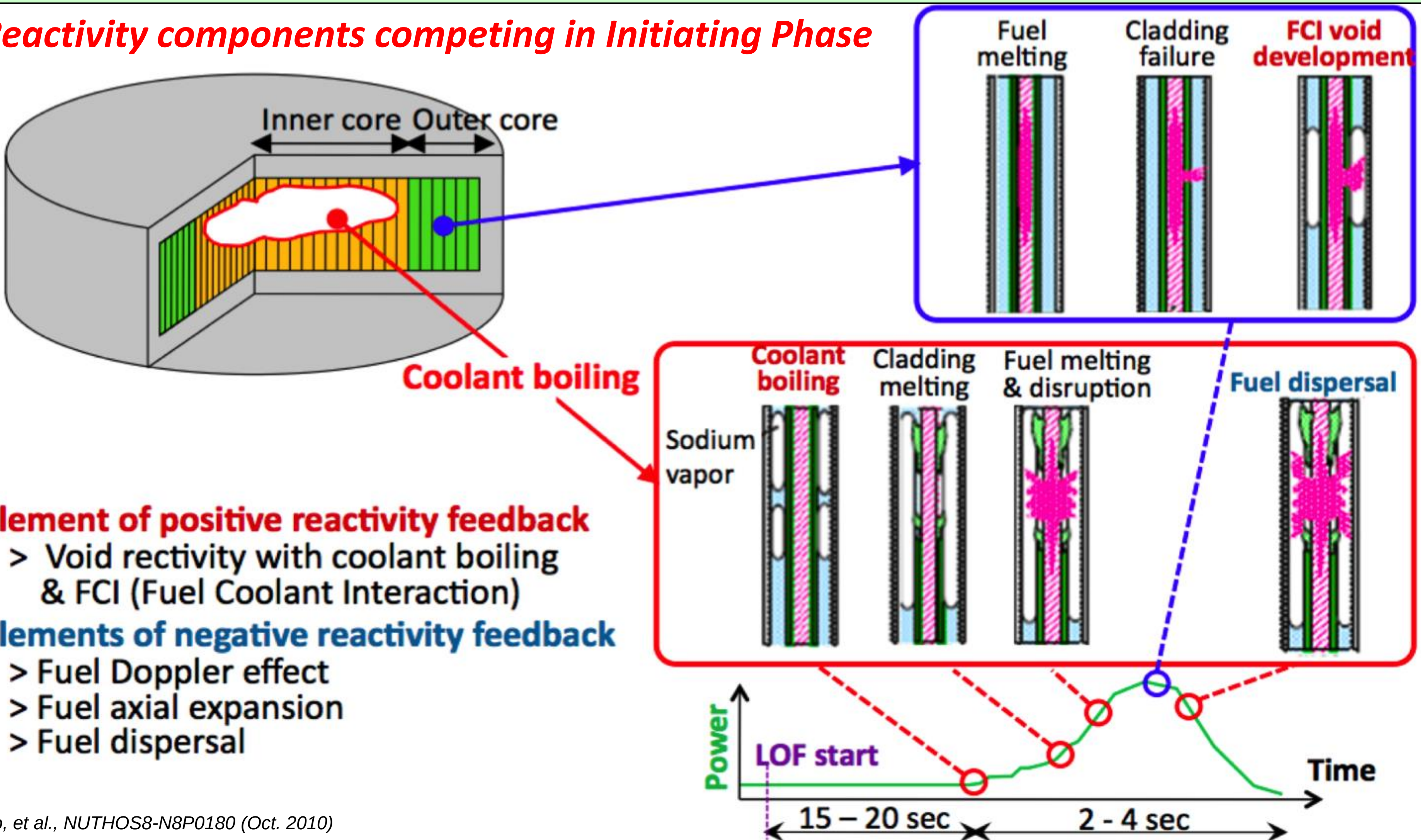
- ➢Sodium void reactivity
  - ✓ Less than around 6$ including uncertainty
- ➢Core Height
  - ✓ Less than around 1m
- ➢Specific Power
  - ✓ High enough for milder power sequence in transient
- ➢Fuel smear density
  - ✓ High failure threshold with annular pellet



Safety assessment for initiating phase (SAS4A calculation)

- Possibility of energetics is dependent on competition between positive/negative reactivity components.
- The energetics can be eliminated provided that appropriate design parameters are selected, e.g. **sodium void worth limitation**.

Reactivity components competing in Initiating Phase



Element of positive reactivity feedback

> Void rectivity with coolant boiling & FCI (Fuel Coolant Interaction)

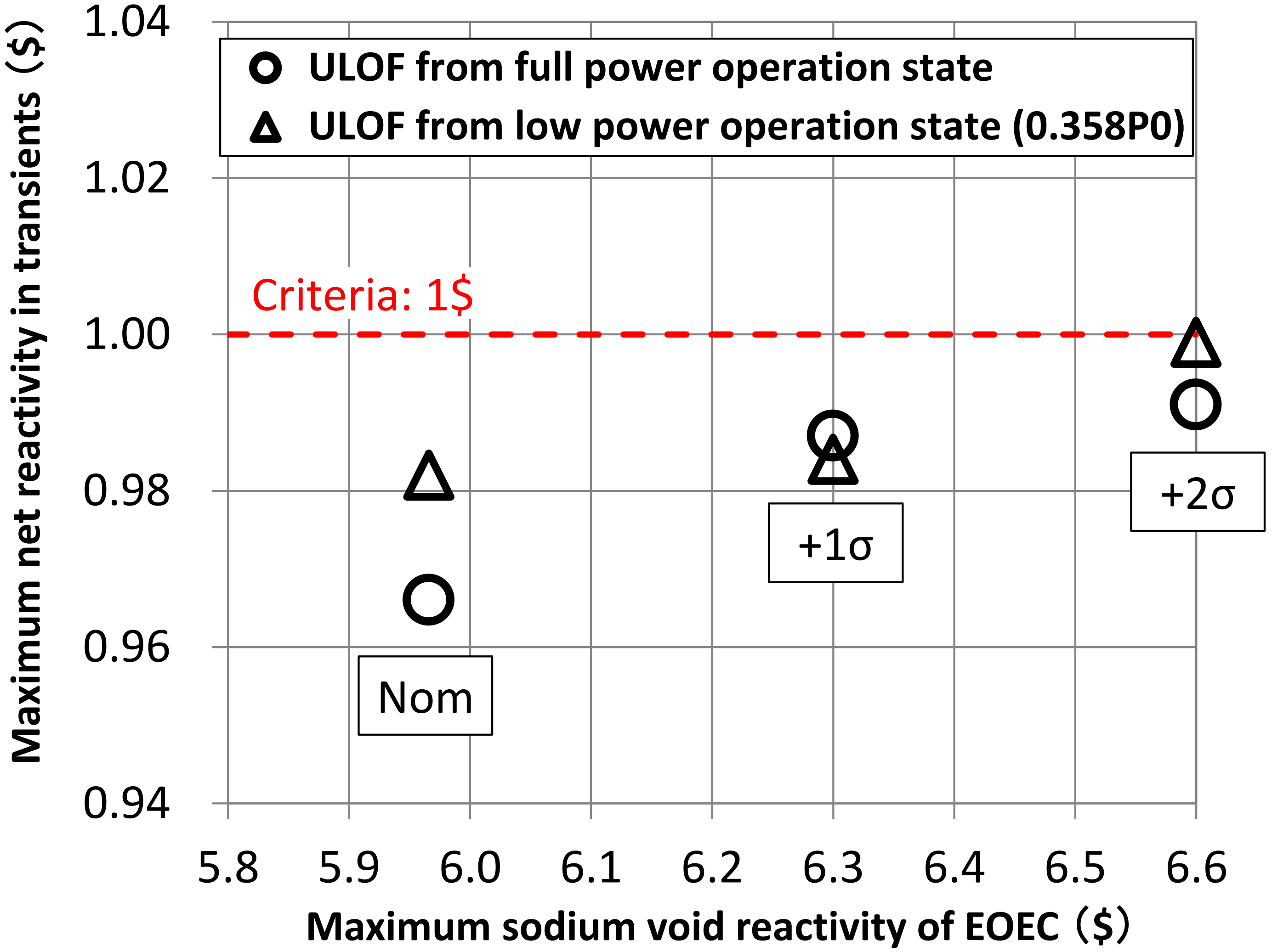
Elements of negative reactivity feedback

> Fuel Doppler effect
> Fuel axial expansion
> Fuel dispersal

Ref. I. Sato, et al., NUTHOS8-N8P0180 (Oct. 2010)

SAS4A calculation in ULOF initiating phase

ULOF
Flow reduction with 9 seconds of half time in full power cases

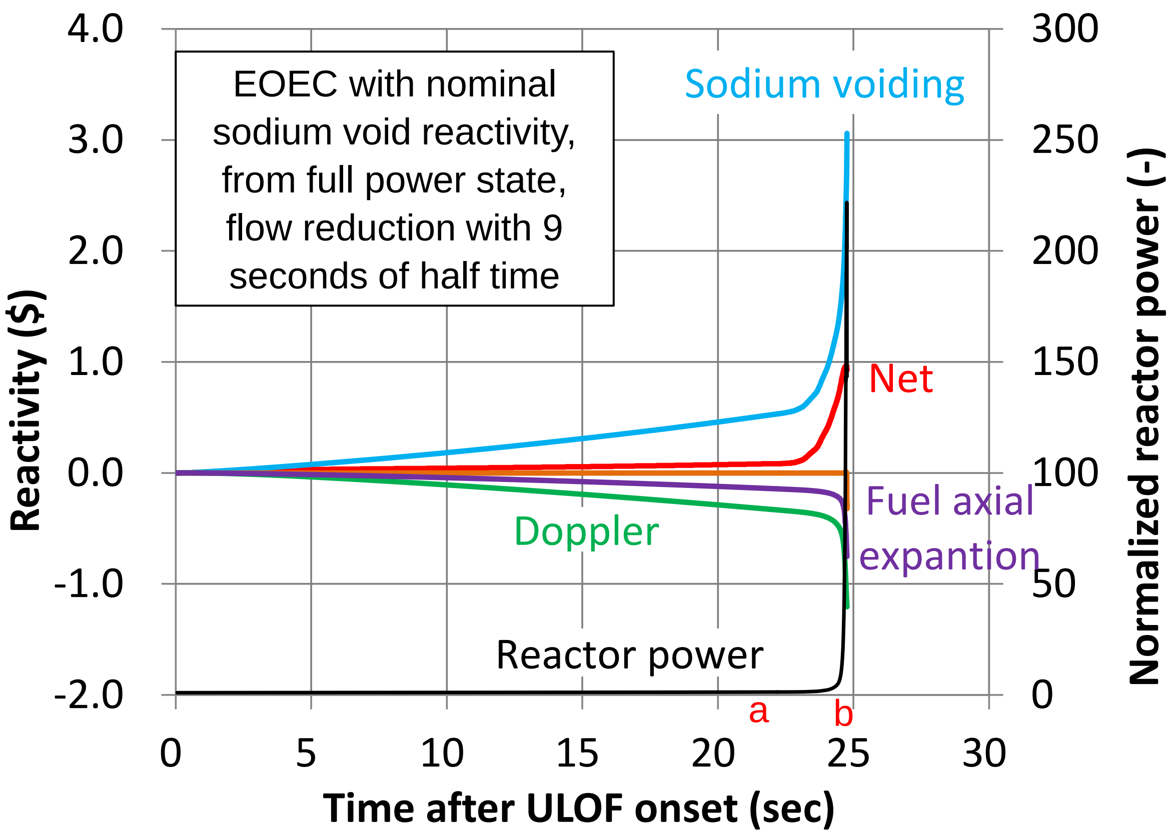


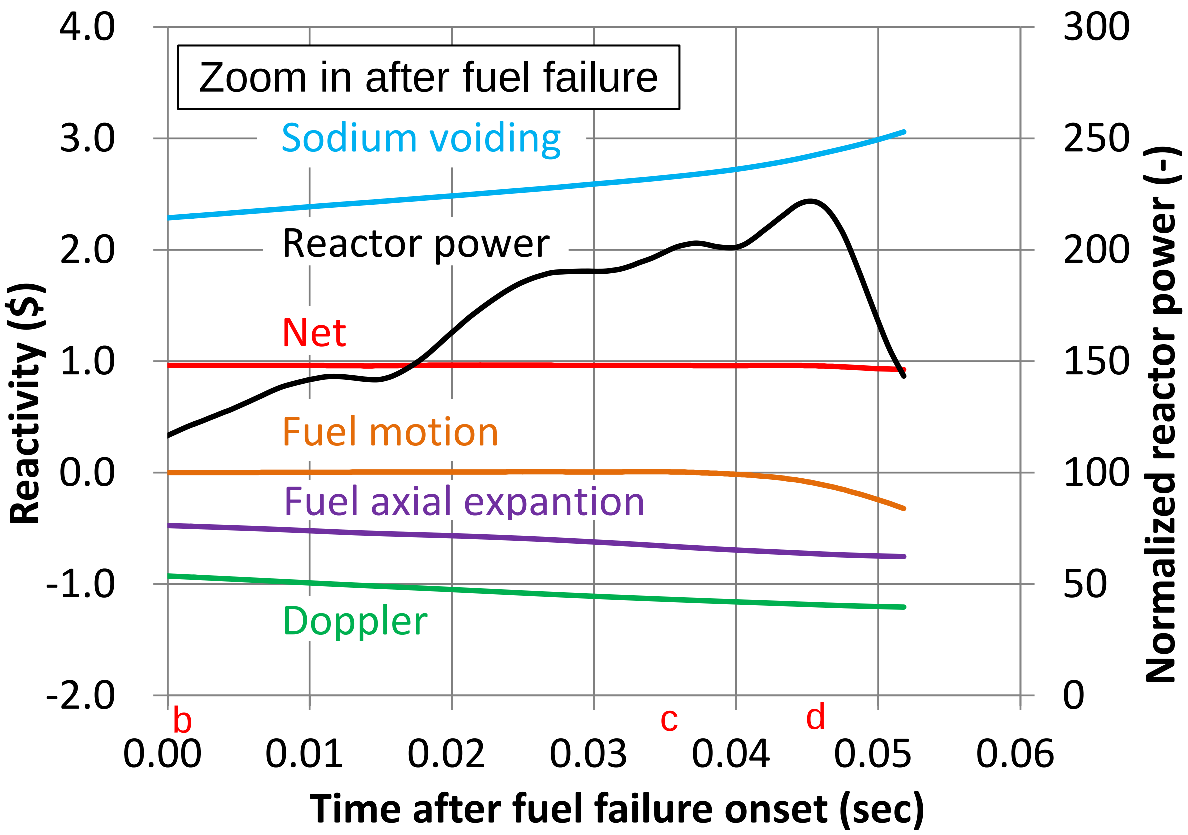
Prompt criticality is prevented thanks to the current design measures such as the limitation of the maximum void reactivity.

Ref. R. Kubota, et al., ICAPP2017

Event progression in ULOF initiating phase

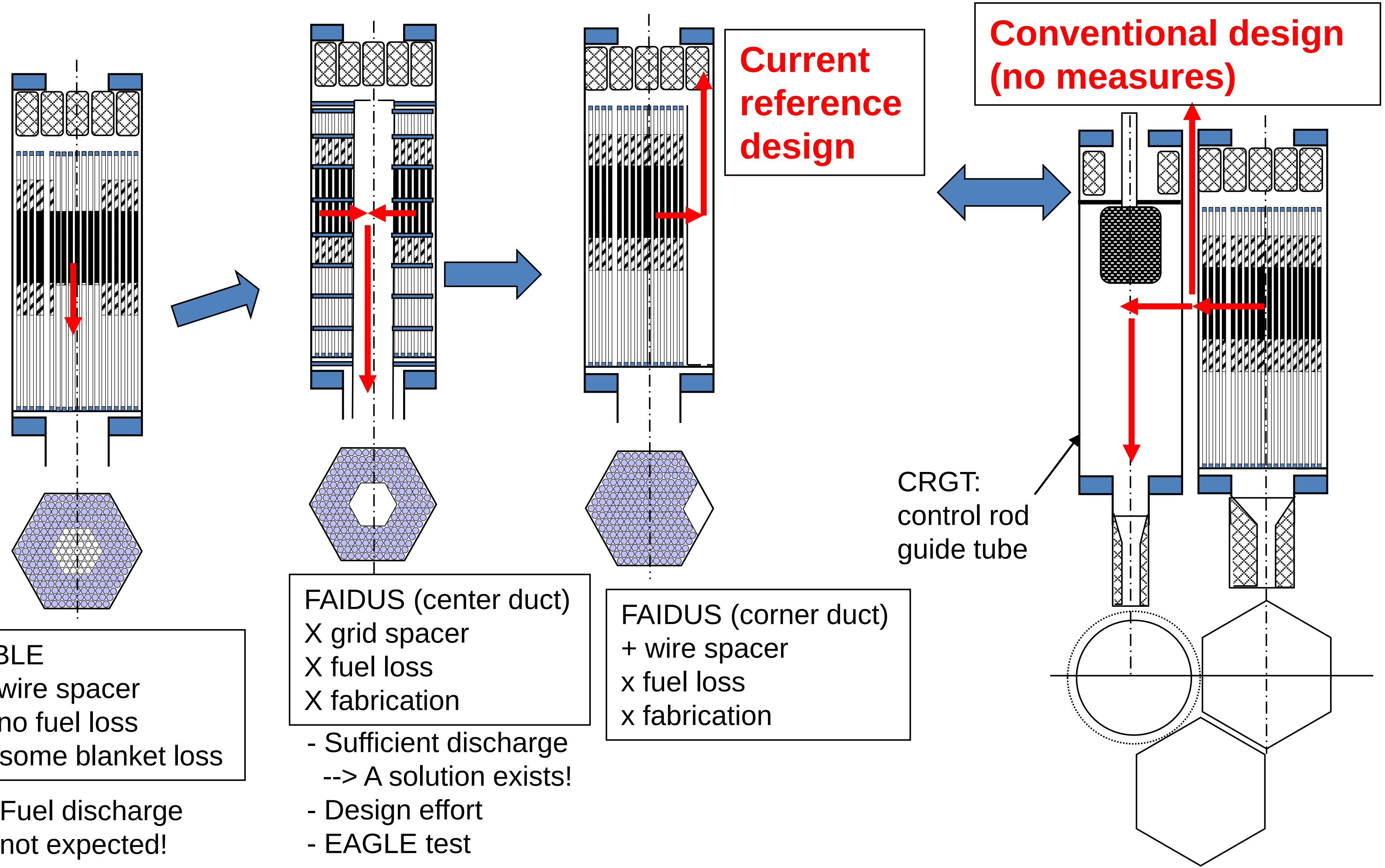
a. Coolant boiling onset at 21.7 sec after ULOF onset and increase in positive reactivity due to coolant boiling development
b. Fuel pin failure onset in coolant boiling SAS-channel from 24.7 sec
c. FCI due to fuel failure in non-coolant boiling SAS-channels
d. Prevention of prompt criticality thanks to dominant negative reactivity effect coming from fuel motion within FAs





Ref. R. Kubota, et al., ICAPP2017

Design features for early fuel discharge phase
Proposed recriticality-free concept



ABLE
+ wire spacer
+ no fuel loss
X some blanket loss

Fuel discharge
not expected!

FAIDUS (center duct)
X grid spacer
X fuel loss
X fabrication

- Sufficient discharge
  --> A solution exists!
- Design effort
- EAGLE test

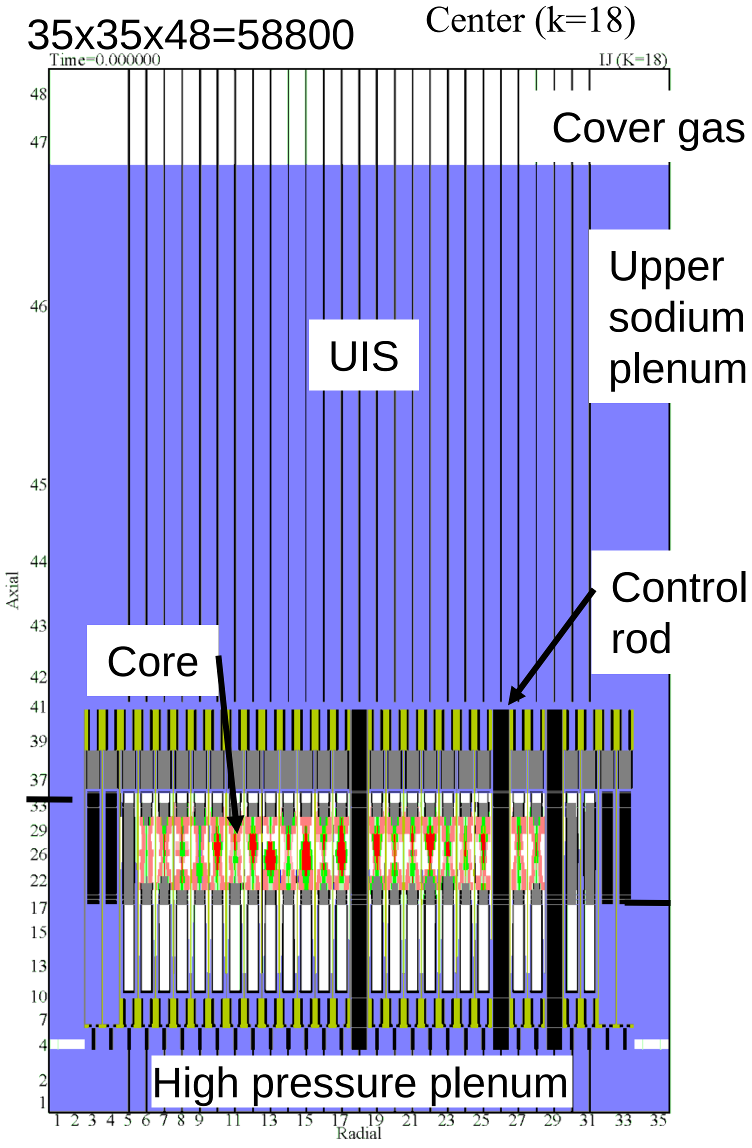
Current reference design

FAIDUS (corner duct)
+ wire spacer
x fuel loss
x fabrication

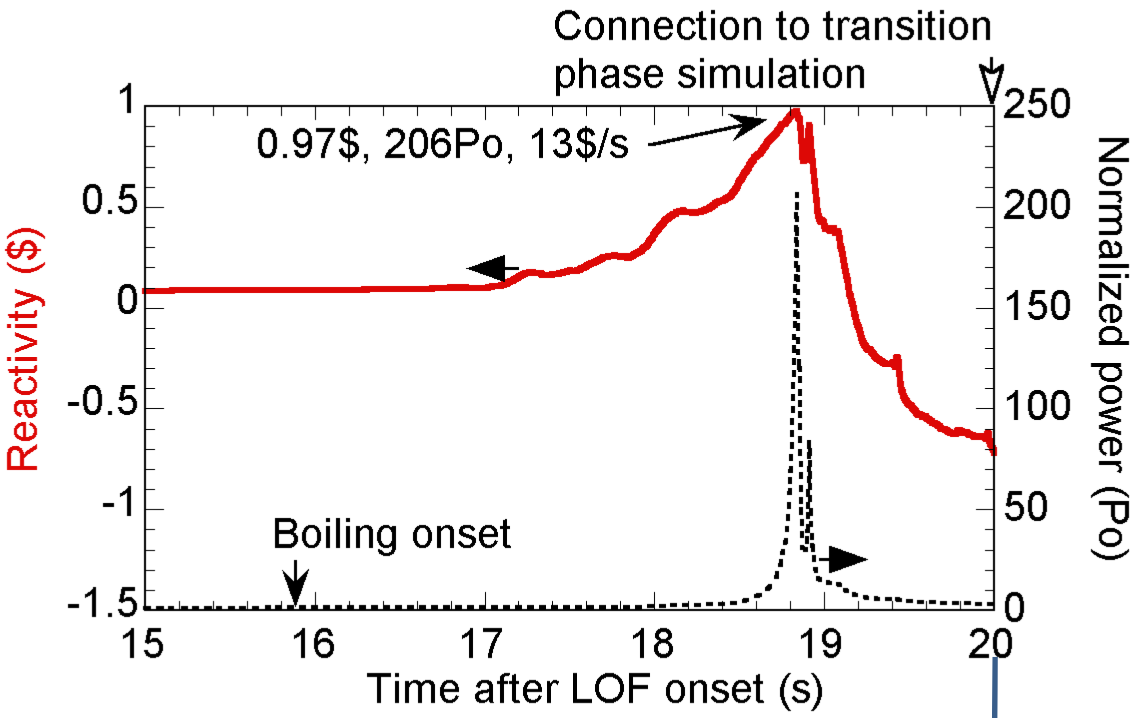
Conventional design (no measures)

CRGT:
control rod
guide tube

Typical SAS4A calculation results (initial conditions of SIMMER calc.)



Ref. H. Yamano, et al., PHYSOR'08 (Sep. 2008)



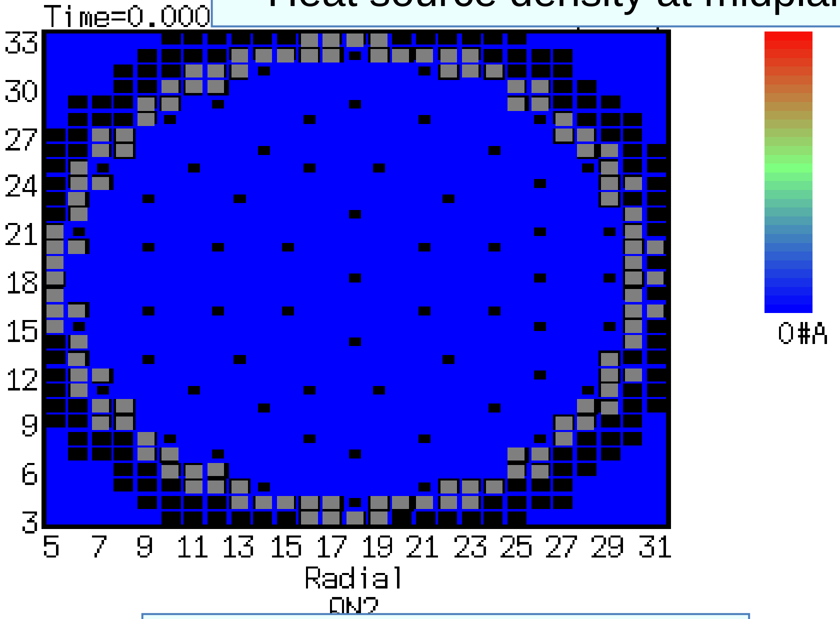
- Core-average fuel temperature: 2950K
- Most of fuel pins in the inner core were melted.
- About half of fuel pins in the outer core were failed.

- SAS4A results (mass, temperature, etc.)
  ➡ the SIMMER inputs.

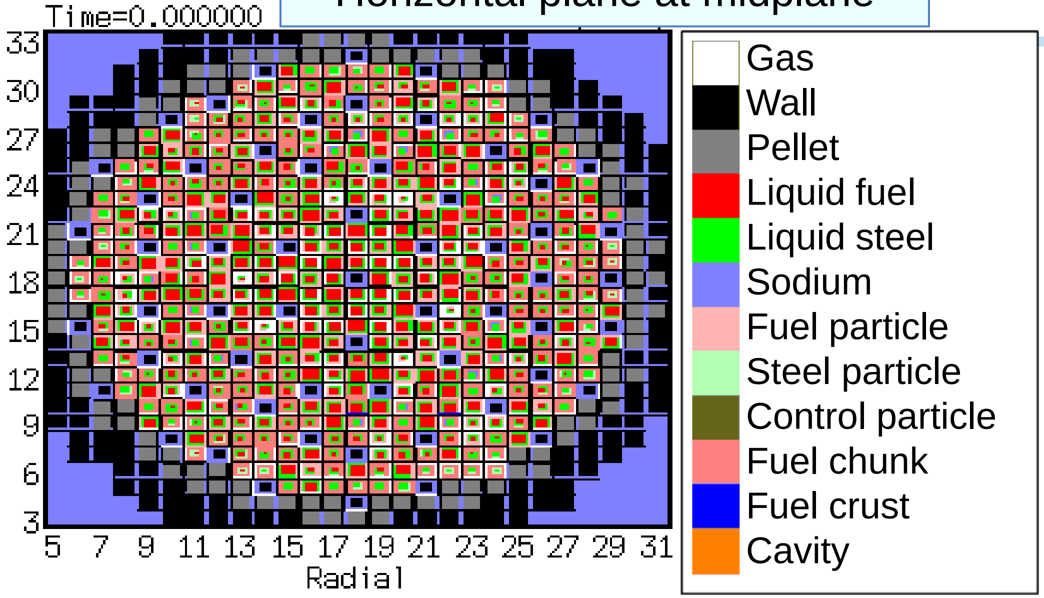
ABLE case

Yamano et al.,
PHYSOR'08

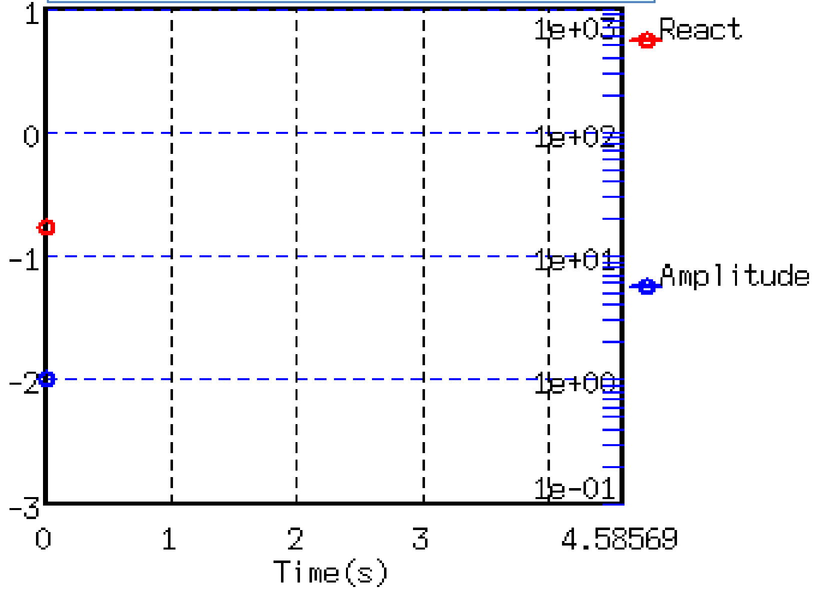
Heat source density at midplane



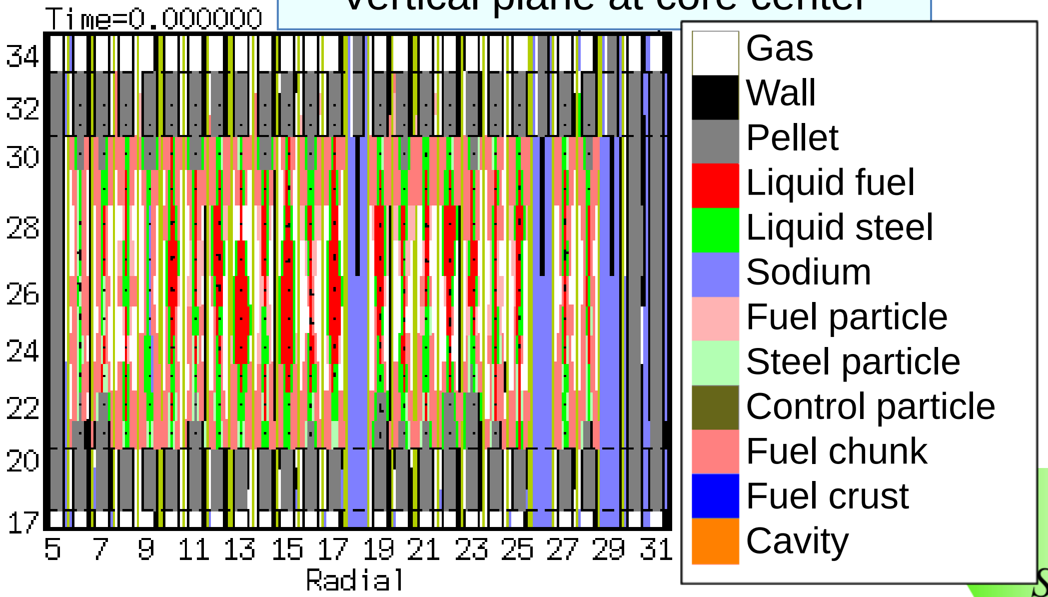
Horizontal plane at midplane



Reactivity and power

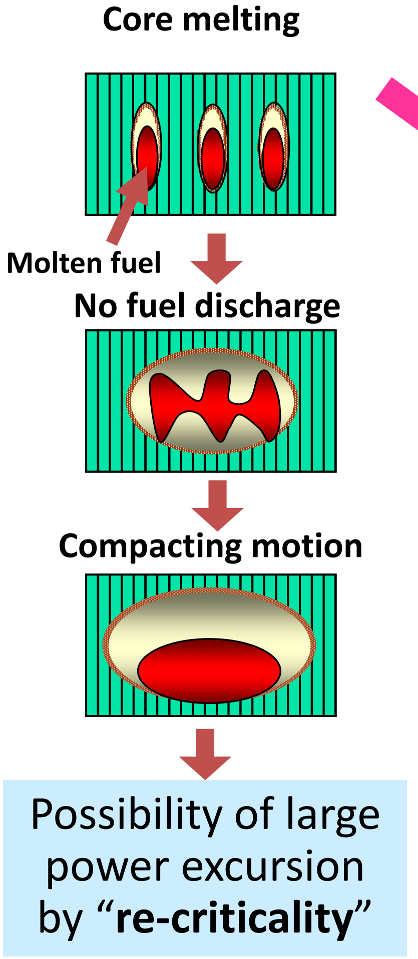


Vertical plane at core center



Design features for early fuel discharge phase

"Re-criticality free core"
features characteristic to avoid severe energetics due to excursion in CDA sequences



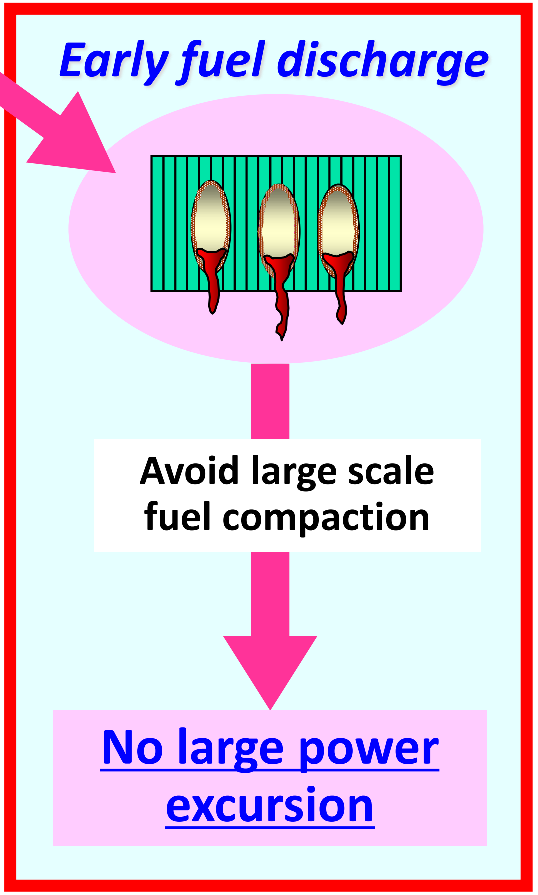
Core melting

Molten fuel

No fuel discharge

Compacting motion

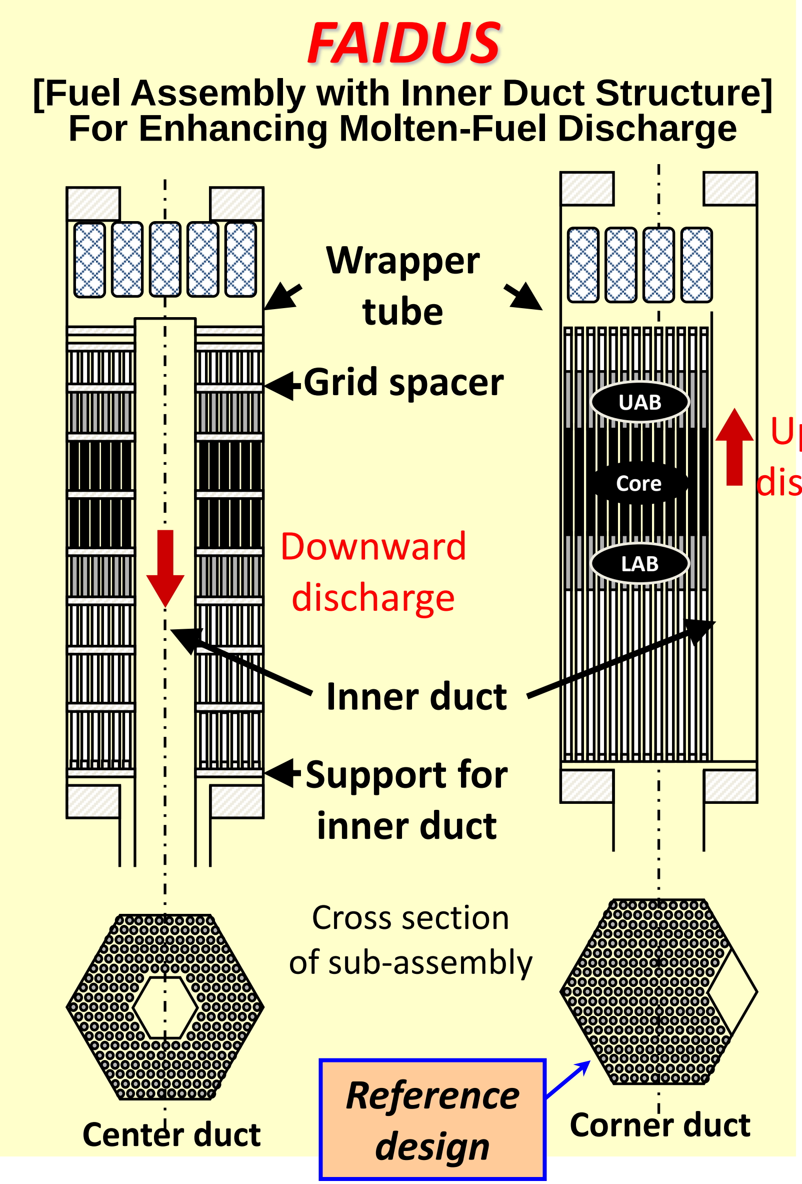
Possibility of large power excursion by **"re-criticality"**



Early fuel discharge

Avoid large scale fuel compaction

No large power excursion



FAIDUS

[Fuel Assembly with Inner Duct Structure] For Enhancing Molten-Fuel Discharge

Wrapper tube

Grid spacer

Downward discharge

Upward discharge

Inner duct

Support for inner duct

Cross section of sub-assembly

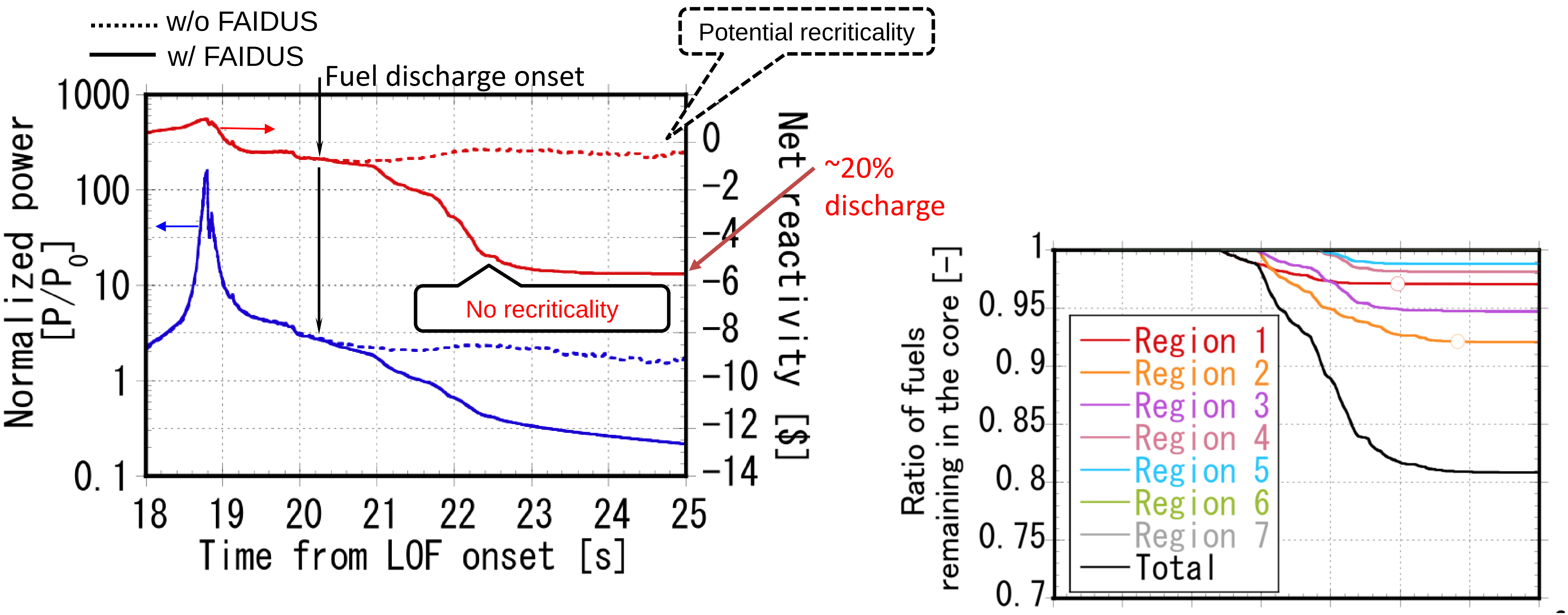
Center duct

Corner duct

Reference design

Safety assessment for initiating phase (SIMMER-III calculation)

Reactor analysis using SIMMER-III



- Molten fuel can be early discharged from the core before the failure of fuel-assembly can-wall.

Concluding remarks

- Specific design features are shown as well as the safety assessment results to demonstrate their effectiveness.
- For the initiating phase
  - ✓ One of key specific design features is to limit sodium void worth in the core design.
  - ✓ The SAS4A analysis code has been developed and validated with in-pile experimental data (i.e., CABRI), to simulate fuel pin disruption in a fuel assembly.
  - ✓ This code has been applied to reactor analyses, demonstrating no significant power burst.
- For the transition phase
  - ✓ To avoid significant power burst due to the recriticality event, a specific design feature is introduced for the fuel assembly design containing an inner duct, through which the molten fuel can be quickly discharged upward from the core region, resulting in no recriticality.
  - ✓ The effectiveness of this fuel discharge through the inner duct was demonstrated with the SIMMER-III/IV (two-/three-dimensional) analysis code.