Design and Assessment Approach on Advanced SFR Safety with Emphasis on CDA Issue

Ryodai NAKAI
Japan Atomic Energy Agency

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Contents

1. *Introduction*
2. *Key Characteristic of SFR*
3. *Historical Perspective of Safety Approach to CDA issue*
4. *Safety Goal/Principles*
5. *Safety Design and Assessment Approaches*
6. *Conclusions*

Introduction

- *Long history since 1950 with more than 20 SFRs and approximately 400 rys operating experience*
- *SFR technology is mature well to a level that SFR is licensable and deployable*
- *One of promising concepts meeting to multi mission requirements for future reactor*
  - *Fast neutron – produce fuel, burn Pu and MA*
- *Need further investigation for commercialization*
  - *Economical competitiveness – rational safety*
- *Number of reactors be increased considerably in future*
  - *Enhanced safety*

Key Characteristics

Advantage

- *Good heat-transport characteristics of sodium*
  - *Natural circulation decay heat removal*
- *Relatively large thermal inertia and large margin to coolant boiling*
  - *Long grace time*
- *Low pressure system*
  - *Passively maintain reactor coolant – No LOCA*

Key Characteristics

Challenges

- *Sodium chemical reactivity*
  - *Sodium fire, sodium-water reaction*
- *Sodium void reactivity tends to be positive with larger core*
- *Re-criticality Issue*
  - *Reactor core is not highest reactivity configuration*
  - *Coherent molten fuel movement in CDA sequence might lead to high energy release*

Historical Perspective of Safety Approach to CDA

Safety Approach taken in SFRs 1970s-80s

- *Super Phenix(France), SNR-300(Germany), CRBRP(USA), and Monju(Japan)*
- *Defence-in-Depth principles with appropriate consideration of SFR characteristics*
- *Conventional safety approach to CDA issue*
  - *Minimize the occurrence probability of CDA*
  - *Assess the mechanical energy release due to re-criticality events assuming hypothetical CDA*
  - *Confirm the integrity of reactor vessel and component against mechanical energy and/or loading due to burning of sodium*

Historical Perspective of Safety Approach to CDA

Safety Approach taken in SFRs 1990s

- *EFR(France), BN800(Russia), ALMR(USA), DFBR(Japan)*
- *Technology advancement in 90s has successfully incorporated many innovative ideas and concepts*
- *Passive features for shutdown and cooling to significantly enhance safety level*
  - *Third shutdown level*
  - *Negative reactivity feedback by fuel expansion, radial core expansion, axial expansion of control rod driveline*
  - *Self-actuated shutdown system (Curie point type), Hydraulically suspended rods, Gas expansion module*
  - *Despite of preventive measures, CDA was considered to some extent*

Historical Perspective of Safety Approach to CDA

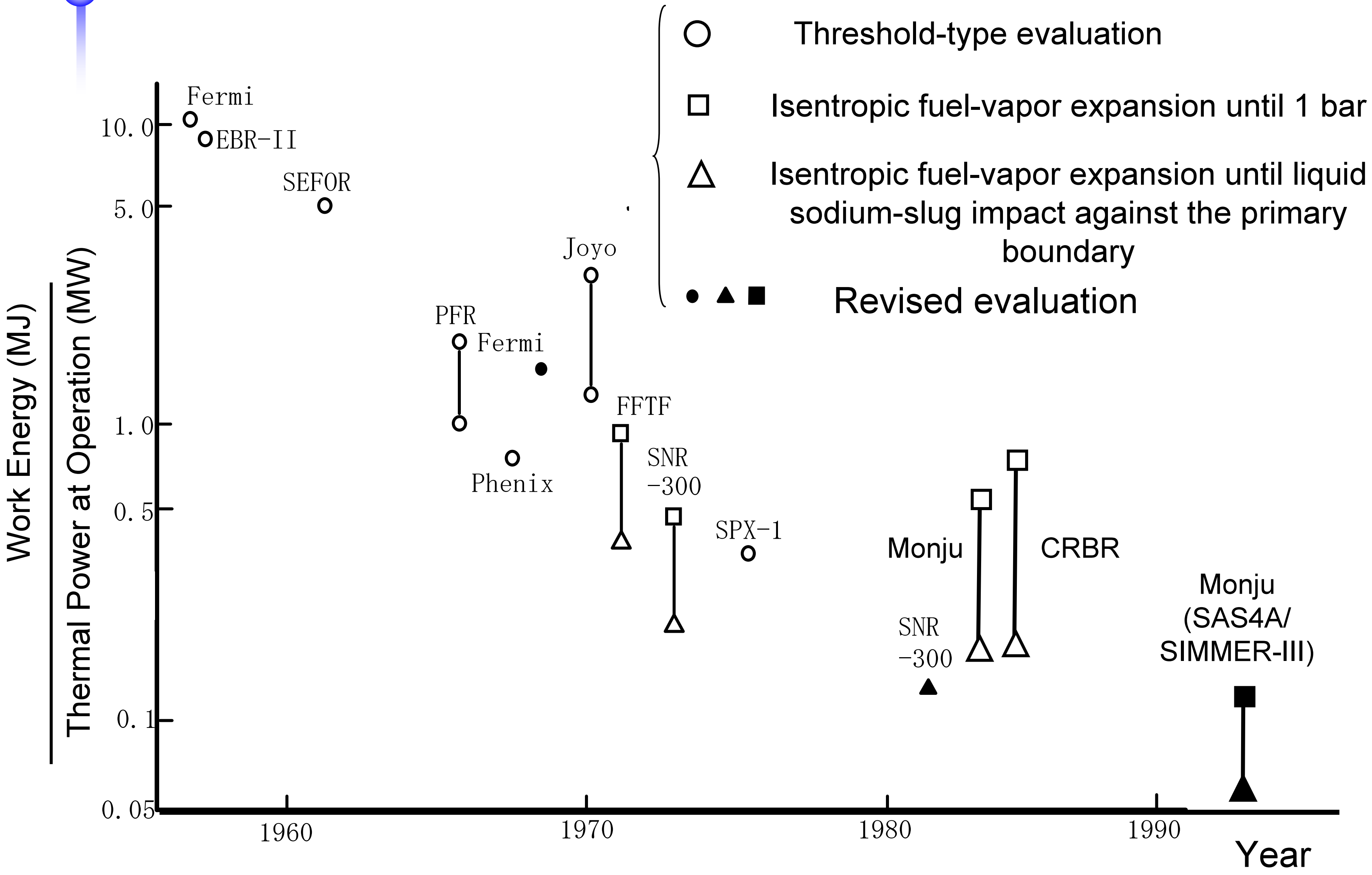
Assessment of CDA

- *The **re-criticality issue** in Core Disruptive Accident (CDA) has been one of the **major safety issues** of Sodium-cooled Fast Reactor (SFR) from the beginning of its development history.*

- ***Assessment method** of the mechanical energy release*
  - *Phenomenological approach: Bethe-Tait model in 1956*
  - *Mechanistic approach: SAS and SIMMER code series*

  - *Mechanistic approach has been improved with evolution of safety knowledge and has reduced the mechanical energy release*

Historical Transition of Evaluated CDA Work Energy Release



Safety Goals/ Principles

- ***Safety Requirements for existing reactors***
  - ***e.g. IAEA NS-R-1***
  - ***Take into account of developments of safety requirement – consideration of severe accidents in the design***

- ***Risk-informed Approach for new reactor design***
  - ***e.g. NUREG-1860, IAEA TECDOC-1570***

- ***International Forum for next-generation systems***
  - ***Generation-IV International Forum***
  - ***INPRO***

Safety Goals for Gen – IV Nuclear Systems

- ***Gen - IV nuclear energy systems operations will excel in safety and reliability.***

- ***Gen - IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.***

- ***Gen - IV nuclear energy systems will eliminate the need for offsite emergency response.***

Safety Basic Principles in INPRO

- ***Shall incorporate enhanced defence-in-depth(DiD), LOP in DiD shall be more independent***
- ***Shall excel in safety and reliability by incorporating inherently safe characteristics and passive systems.***
- ***Shall ensure that risk from radiation exposures are comparable to the risk from other industrial facilities.***
- ***Shall include RD & D work to bring the knowledge of plant characteristics and the capability of analytical methods used for design and safety assessment.***

Defence-in-depth Safety Approach

Level-1: ***Prevention of abnormal operation and failures,***

Level-2: ***Control of abnormal operation and detection of failures,***

Level-3: ***Control of accidents within the design basis,***

Level-4: ***Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents***

Level-5: ***Mitigation of radiological consequences of significant releases of radioactive materials.***

With taking into account safety goal/principles for next generation nuclear systems

Design Basis

- ***First 3 levels – Prevention, Control of Abnormal Operation and Detection, Control of Accident***
- ***Primary Emphasis on prevention of Accident***
- ***Basic Safety Function***
  - ***Reactor Shutdown, Decay Heat Removal, and Containment of Radioactive Materials***
- ***CDA shall be excluded from Design Basis Event***
- ***More independence between levels of DiD and high reliability for each LOP***
- ***Comprehensive identification of PIEs***
- ***Safety assessment in conservative manner***

Beyond Design Basis

- ***Eliminate the need for offsite emergency response -> Strengthen level-4 LOP – Control of severe accident***
- ***Prevent accident progression and Mitigate postulated severe accident within plant***
- ***ATWS : No operator action expected***
  - ***Sodium void reactivity***
  - ***Coherent movement of molten fuel core***
  - ***Degraded core fuel cooling***
- ***LOHRS : Relatively long time margin -> operator action***
  - ***Highly reliable natural circulation DHR***
  - ***Diverse heat removal measures***
- ***BDBE evaluation -> realistic or best estimate assumptions, method and analytical criteria***

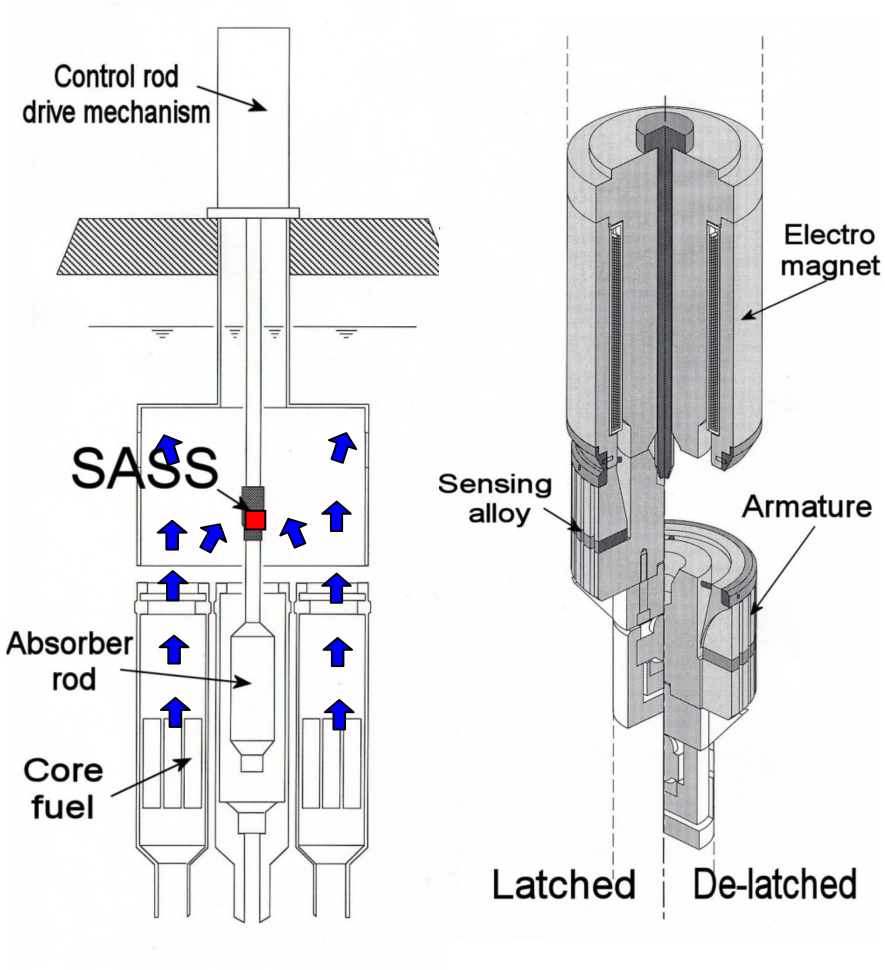
Passive Safety Features for Prevention of CDA

- ***Reactor Core with inherent negative reactivity feedback***
  - ***Axial Fuel Expansion, Radial Core Expansion, Control Rod Driveline Expansion, etc.***
  - ***ATWS Test - RAPSODIE(1983), EBR-II, FFTF(1986)***
  - ***System behavior will vary depending on system size, design features, and fuel type, thus functions and effectiveness should be demonstrated***

- ***Passive Reactor Shutdown System***
  - ***Self Actuated Shutdown System (SASS) with curie point magnet***
  - ***Hydraulically Suspended Rods (HSRs)***
  - ***Gas Expansion Module (GEM)***

Safety Provisions for Prevention of CDA

SASS (Self Actuated Shutdown System) as a third shutdown system



Core outlet coolant temperature rise

↓

Sensing alloy temperature reaching the Curie point

↓

Passive de-latch due to decreasing magnetic force

↓

Passive insertion of the rod by gravity

Safety Provisions for Mitigation of CDA

- *The re-criticality issue in Core Disruptive Accident (CDA) has been one of the major safety issues of Sodium-cooled Fast Reactor (SFR) from the beginning of its development history.*

- *Conventional safety approach:*
  - *to minimize the occurrence probability of CDA*
  - *to assess the mechanical energy release due to re-criticality events assuming conservative event progression*
  - *To confirm the containment integrity of the reactor vessel*

- *Re-criticality free core concept has been sought for, because:*
  - *Larger mechanical energy may be anticipated in a larger core*
  - *Re-criticality issue should be resolved prior to the commercialization of SFR*

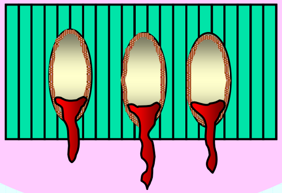
➡ *Restraint to core design and introduction of countermeasures*

Re-criticality-free core concept

Safety Provisions for Mitigation of CDA

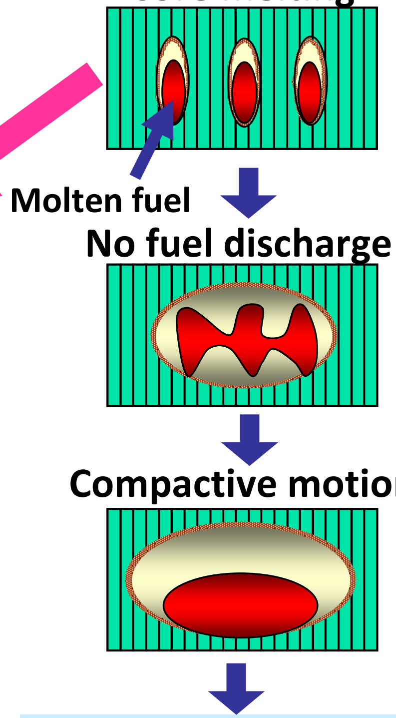
RFC approach

Early fuel discharge



Avoid large scale fuel compaction

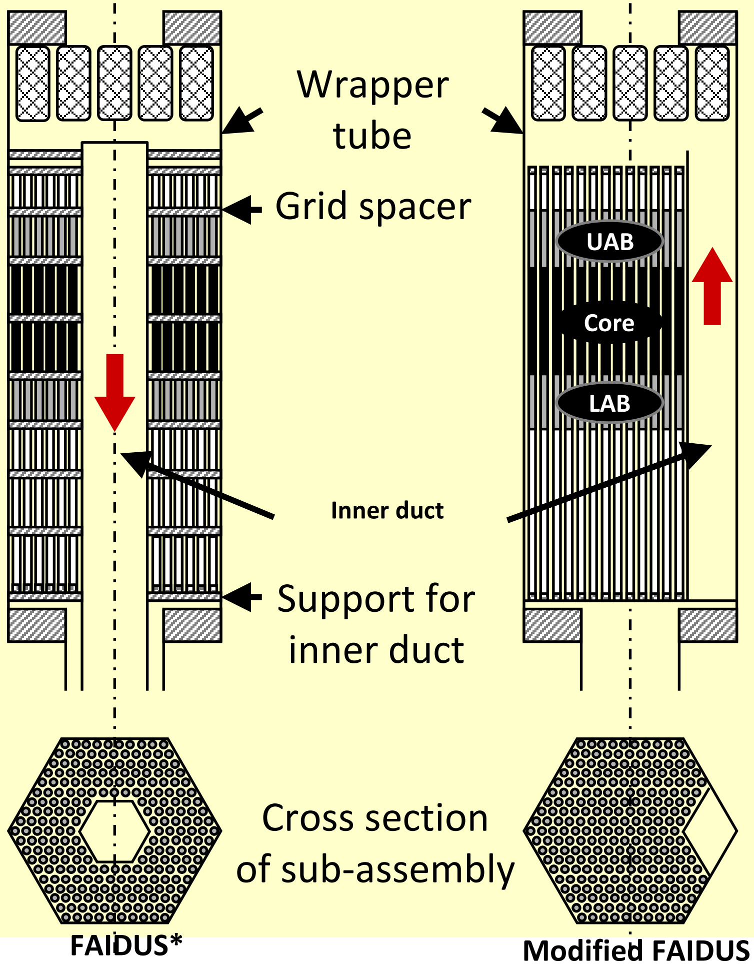
No large power excursion



Possibility of large power excursion
“re-criticality issue”

FAIDUS concept

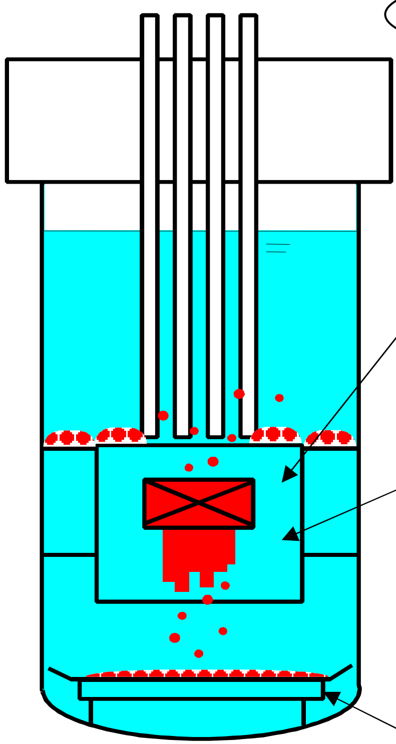
[Fuel Assembly with Inner Duct Structure]



Fuel Assembly Designs Enhancing Fuel Discharge

“Re-criticality free core” means that the fast reactor core which avoids severe energetics due to excursion in the course of core disruptive accident

Safety Provisions for Mitigation of CDA



Accident phases		Design Measures
(1) Initiating Phase	Prevent prompt criticality due to coolant boiling	***CABRI exp.+ SAS4A cal.*** · **Positive sodium void worth : less than 6$** · **Core height : around 1m and less** · **Average fuel specific heat : greater than 40kW/kg-fuel**
(2) Transition Phase	Prevent severe re-criticality due to large molten fuel compaction	***EAGLE exp.+SIMMER cal.*** · **Passive fuel discharge from the core region by FAIDUS**
(3) Material relocation and Decay Heat Removal Phase	Ensure stable long-term cooling for debris by natural circulation	***EAGLE exp.+ CFD code*** ▪ **Fuel relocation and quenching** ▪ **In-vessel core catcher**

Probabilistic Consideration

- ***Deterministic Safety Approach is complemented by Probabilistic Safety Approach which verify design features that assure very high level of public health and safety***

- ***Risk-informed Approach in design stage is desired for well-balanced safety design***
  - ***Assurance of reliability of LOP***

- ***Although reliability data on SFRs are not sufficient, PSA should be extremely beneficial for systematically comprehending the risk characteristics of a plant***

Conclusions

- ***Concept of DiD shall be applied to the safety design of advanced SFRs.***
- ***Safety level can be further improved especially enhancing prevention and mitigation features with more emphasis on passive safety features.***
- ***Through prevention, detection, and control of accident CDA shall be excluded from DBEs.***
- ***Toward a commercialization of SFR, not only prevention but also mitigation of typical severe core damage need to be enhanced taking into account the increase of number of plants and their scale.***
- ***In particular the safety approach with elimination of severe re-criticality is highly desirable and will contribute to establish public acceptance of the SFRs.***