SFR Safety Principles & Safety Approaches for future SFR

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Introduction

- Long history of developments & operations, since ca. 1950
  - More than 20 SFRs in worldwide
  - ca. 400 reactor-years operation experience
- SFR reactor & related fuel cycle technology
  - Mature well for utilization & deployment in worldwide
- Promising concept meets to
  - Multi-mission requirements as a future reactor
  - U/Pu utilization & MA transmutation by fast neutron features
- Further investigations needed in near future
  - For commercialization - Economical competitiveness to LWRs & other power resources
  - For global utilization - Rational & enhanced safety features,
    fit in with considerable & rapid increasing in energy demands in worldwide

Key Characteristics

- Advantages
  - Sodium Heat-transport Characteristics
    - High Core Power Density
    - Efficient Natural Circulation Decay Heat Removal
  - Large Thermal Inertia & Margin until boiling
    - Long Grace-period during accident/transient
  - Low Pressure System
    - Inherent Retention Capability to maintain reactor coolant → No Loss-Of-Coolant-Accident (LOCA)
  - Non-Oxidation Condition
    - Non-oxidation affects on structural material alloys

Key Characteristics

- Challenges
  - Chemical activity
    - Sodium Fire, Sodium-Water Reaction
  - Neutronics reactivity
    - Void reactivity - positive in large-size core
  - Re-criticality matter
    - Core Reactivity: non-maximized core configuration
    - Molten fuel movement in Core Disruptive Accident (CDA) sequence

→ remain a possibility of large mechanical energy release situation in CDA

Historical Perspective on Approach to CDA

Re-criticality matter in CDA sequence = Major safety concerns,
from the beginning of development history of SFR

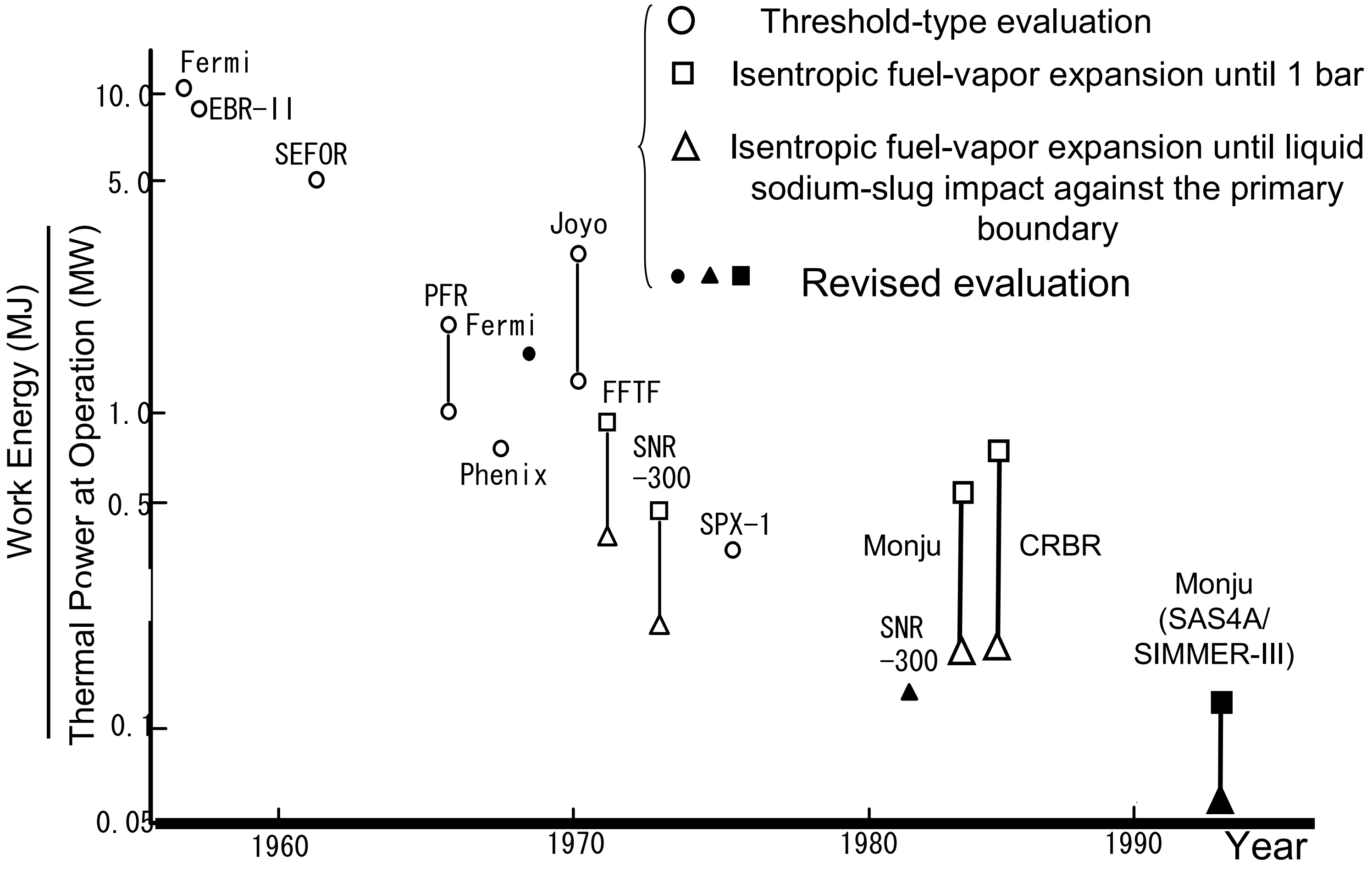
- Safety Approach for SFRs in early decades (~'70)
  - Phenomenological approach to CDA
    - Bethe-Tait model in 1956
- Safety Approach for SFRs in 1970s-80s
  - Defence-in-Depth [DiD] principles, with appropriate consideration of SFR characteristics
  - Super Phenix (France), SNR-300 (Germany), CRBRP (USA) and Monju (Japan)
  - Mechanistic approach to CDA
    - Minimize probability of CDA occurrence
    - Assess mechanical energy release by re-criticality, assuming hypothetical CDA condition
    - Confirm reactor vessel (RV) & containment integrities against mechanical energy/loading by sodium fire

CDA Assessment & Mech. Energy Release

– Phenomenological approach [Bethe-Tait model]

→ Mechanistic approach [SAS and SIMMER code series]

- Progresses in technical knowledge on phenomena in CDA
- Significant reduces in evaluated Mechanical Energy Release



Historical Perspective on Approach to CDA

- Safety Approach for SFR designs in 1990s
  - Innovative ideas & concepts against CDA

    e.g. Passive features for shutdown & cooling:
    - Confirmations on Inherent negative reactivity feedbacks
    - Developments on passive shutdown/reactivity-control system
    - Decay heat removal system by natural circulation

  → Successfully incorporated, based on technology progresses by/in 90s
  - Significantly improvements in safety features,
    although CDA still to be considered to some extent
  - EFR (France), BN800 (Russia), ALMR (USA), and DFBR (Japan)

Passive Safety Features

- Inherent negative reactivity feedbacks of fast reactor core

  e.g. Axial fuel expansion, Radial core exp., Control rod driveline exp., etc.
  - ATWS Tests: RAPSODIE(1983), EBR-II, FFTF(1986)
    → Behavior depends on system size, design features & fuel type
- Passive Shutdown/Reactivity Control System
  - Self-Actuated Shutdown System [SASS] using curie point magnet
  - Hydraulically Suspended Rod [HSRs]
  - Gas Expansion Module [GEM]
- Decay Heat Removal [DHR] by Natural Circulation
  - Simplified DHR system configuration,
    with sufficient elevation difference between heat source & heat sink,
    without active Pump or Blower.
  - Redundant & Multiple-Independent systems

Level of Defence-in-Depth [DiD]

Level of DiD*	**Objectives of defence-in-depth (DiD)***	**Event category**	
Level 1	Prevention of abnormal operation and failures	Normal operation	
Level 2	Control of abnormal operation and detection of failures	DBE**	Abnormal Transient
Level 3	Control of accidents within the design basis		Accident
Level 4	Control of severe plant conditions, including prevention of accident progression & mitigation of SA consequences	BDBE***	
Level 5	Mitigation of radiological consequences of severe accidents	Offsite emergency response	

- Two categories for DBE
  - Abnormal Transients: events leading abnormal conditions due to anticipated failure or malfunction of a single component or a single erroneous operation
  - Accidents: unlikely events that might lead to the release of radioactive materials outside the facility
- BDBE
  - Events more unlikely and more severe than DBE

** INSAG-10, IAEA (1996), ** Design Based Event, *** Beyond DBE*

Categorization of Safety Evaluation events

Comprehensive & Rational considerations for event identification

- DBE = Transient & Accident

  Postulated Initiating Event (PIE) = Malfunction in plant system, component, or control & to be identified comprehensively
  - Points for identification
    - Transient-Over-Power [TOP] events [e.g. CR withdrawal]
    - Loss-Of-Flow [LOF] events [e.g. Primary pump seizure]
    - External initiator events [e.g. Loss-of-Offsite Power]
    - System/Component malfunctions/failures [e.g. Primary sodium leakage]
- BDBE

  Hypothetical situations; then representatives to be identified from typical events based on probability with considering impact
  - Typical events:
    - ATWS* [UTOP, ULOF & ULOHS]
    - Local Faults
- Exclusion of rare events

  To be practically eliminated by reasonable perspective
    - Loss of heat removal system [LOHRS] (e.g. PLOHS, LORL)

      Highly reliable DHRS with natural circulation capability

      Grace period is quite long enough for accident managements
    - Double Boundary Break

      Double failure of highly reliable component; negligible occurrence frequency

      Prevention by In-Service Inspection & Continuous Monitoring

** Anticipated Transient Without SCRAM, ** Loss Of Reactor sodium Level*

For Design Basis Events [DBEs]

- Provisions to Operation/Transient/Accident (DiD Levels 1 to 3)
  - Prevention, Detection and Control of Accident Conditions
- Basic Safety Functions
  - Reactivity Control & Reactor Shutdown,
  - Decay Heat Removal,
  - Containment of Radioactive Materials
- Safety Assessment
  - Deterministic Safety Analysis for licensing
    - Sufficient margins to safety criteria of fuel, structure, system,…
    - Conservative Evaluation model & Criteria on
      - Neutronics Parameters (e.g. reactivity coefficients)
      - Thermal-Hydraulic correlations (e.g. flow splitting)
      - Structural Material correlations (e.g. creep strength)
      - Component mechanisms (e.g. detection decay, lag time for valve opening)
  - Probabilistic consideration in classifying DBE events

For Beyond Design Basis Events [BDBEs]

- Provisions for DiD Level 4
  - Prevent accident progression
  - Mitigate postulated Severe Accident [SA] within plant
  - Eliminate needs for offsite emergency response (strengthen level-4 LOP*)
- Safety Functions
  - Passive safety on Shutdown & Cooling for CDA Prevention
  - Design measures for CDA Mitigation
  - Accident Management
  - Containment of Radioactive Materials
- Safety Assessment
  - Deterministic Analysis
    - Best-estimate evaluation models with realistic assumptions & criteria
  - Complementary usage of PSA
    - Utilized for identifying representative initiator taking into account likelihood with event impact

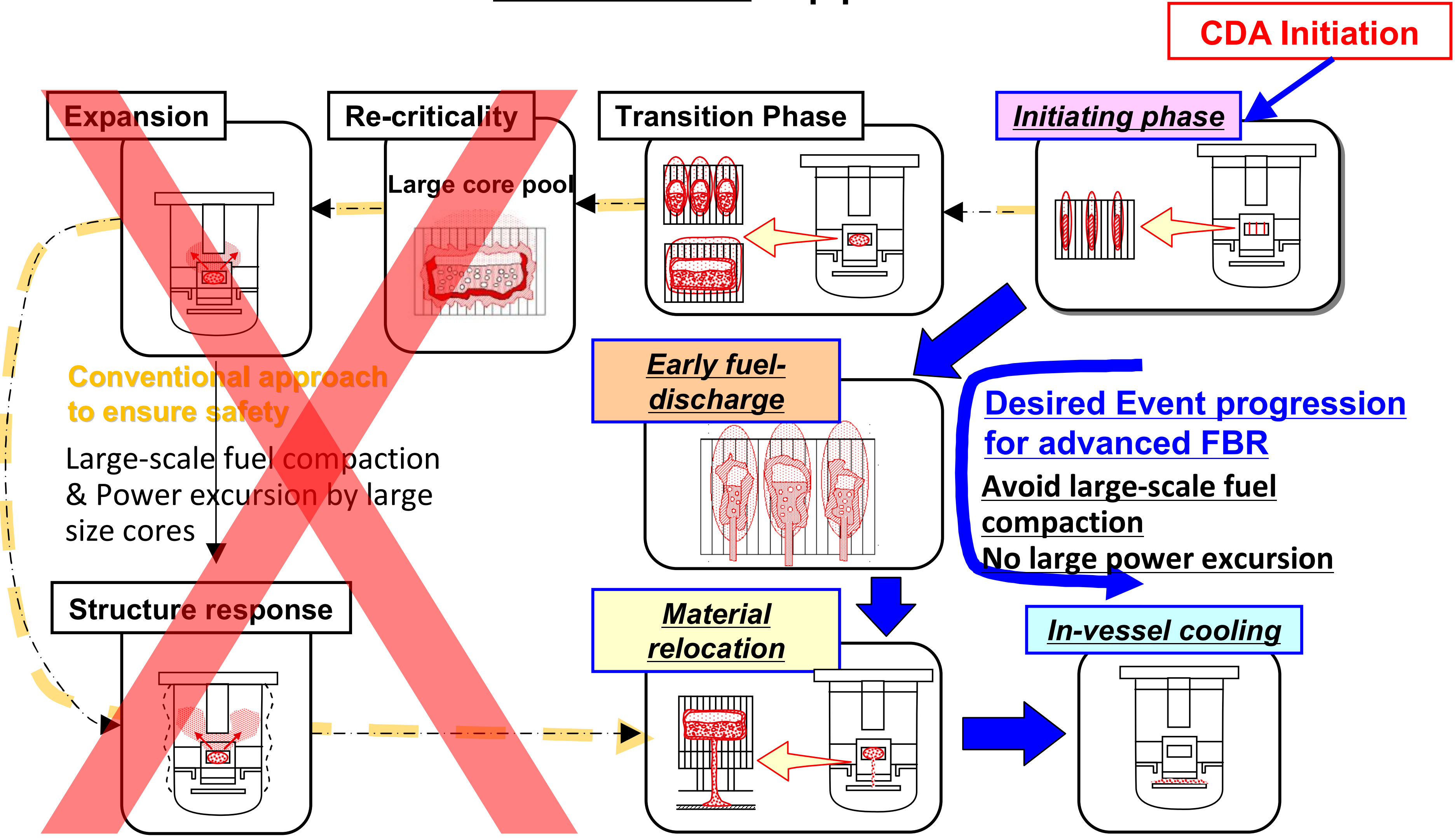
*Line-Of-Protection

SFR Design Measures against CDA

- CDA of advanced SFR for commercialization era
  - Larger output → Larger core → Larger mechanical energy
  - Countermeasures against CDA to be applied in SFR designs
  - In particular, Re-criticality Free Concept
- Safety design measures against CDA
  - Provision level
    - Prevention & Mitigation in CDA sequence
  - Concept level
    - Passive Safety Feature for Shutdown & Cooling
    - Avoiding Re-Criticality sequence & Achieving debris cooling
  - System level:
    - For Prevention
      - Passive Reactor Shutdown System
      - Natural Circulation Decay Heat Removal System
    - For Mitigation
      - Core safety parameters [e.g. sodium void worth]
      - Mechanism for early molten-fuel discharge
      - Stable cooling of debris

Safety Design Approach against CDA

- Conventional & Advanced Approaches



Conventional approach to ensure safety

Large-scale fuel compaction & Power excursion by large size cores

Desired Event progression for advanced FBR

Avoid large-scale fuel compaction

No large power excursion

Approaches against CDA

CDA Prevention

↑

Event Initiation	Approach for Prevention	Key points
(0) Just After Initiation	Passive Shutdown & Passive Cooling just after event initiation	· Passive-featured Reactor Shutdown System · Passive Cooling System for Decay Heat Removal

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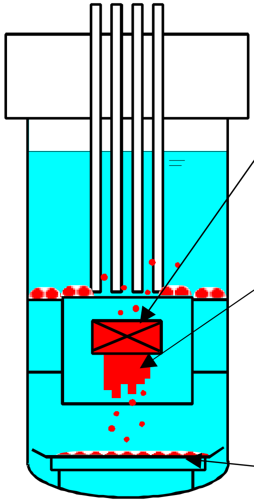
CDA Mitigation



CDA phases	Approach for Mitigation	Key points
(1) Initiating Phase	Prevent prompt criticality caused by coolant boiling	· Core & Fuel characteristics
(2) Early-Discharge Phase	Prevent severe re-criticality caused by large molten-fuel compaction	· Mechanism for early molten fuel discharge
(3) Material Relocation & Decay Heat Removal Phases	Ensure stable long-term cooling of debris, by natural circulation	· Molten-fuel relocation/quench · Core [Debris] catcher · Debris heat removal

Summary of Safety Principles & Provisions

DiD Level	**1**	**2**	**3**	**4**	
	Prevention of abnormal operation & failures	*Control of abnormal operation & detection of failures*	*Control of accidents within design basis*	*Control of severe plant conditions*	
Category	Operation	DBE		BDBE	
		Transient	Accident	Prevention of accident progression	Mitigation of severe accident consequences
Shutdown & Reactivity Control	**Key points** • Rational design margin • Quality assurance • Preventive maintenance	**Active RSS** [1] Redundancy & Independency		**Passive System** (e.g. SASS, HRS, GEM) Independent from Active RSS	**Core & Fuel characteristics** (e.g. Na void worth.) **Mechanism for early molten-fuel discharge**
Heat Removal (Cooling)		**Decay Heat Removal System [DHRS]**		**Passive DHRS** (e.g. PRACS, DRACS) **Accident Management**	**Stable cooling of debris**
Containment		**Containment Vessel** Pressure-resistant & Leak-tight for Radioactive Material containment			

Note: Containment to sodium leakage: Leak-tight boundary, Early detection & Rapid control

1) Reactor Shutdown System

Concluding Remarks

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