Safety Approach based on Basic Safety Characteristics of SFR
- Harmonization of Safety Design Criteria -

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Contents

1. Introduction (1/2)

- Sodium-cooled Fast reactor technology
  - A key solution as effective energy resource for future.
- Safety of Nuclear Power Plant
  - Strongly recognized as a common worldwide issue, especially after the TEPCO's Fukushima Dai-ichi NPP [F1] Accidents
  - The highest and the most urgent priority is enhancing safety with taking account of the lessons learned from the F1 accident
- Differences in fundamental characteristics
  - Light water reactor (LWR) system uses pressurized water as a coolant under moderated neutron energy spectrum
  - Sodium-cooled fast reactor(SFR) uses atmospheric pressure sodium as a coolant under fast neutron energy spectrum

1. Introduction (2/2)

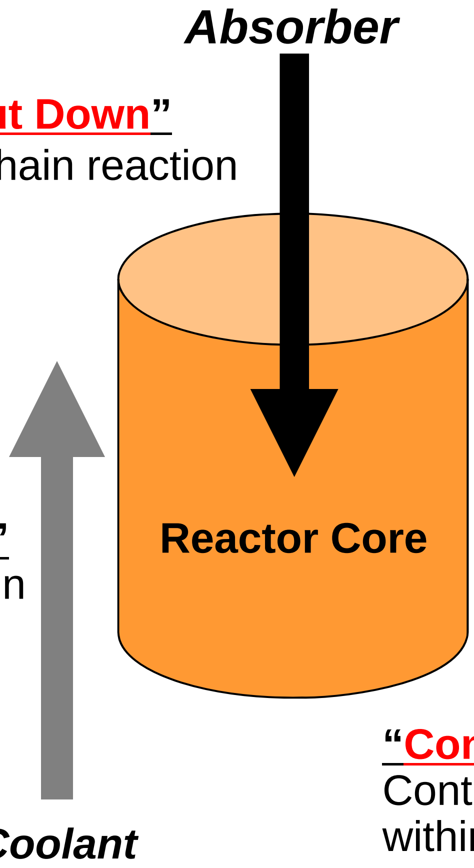
- Fundamental characteristic differences between LWR & SFR
  - Result in the differences in the accident initiator, scenario and consequences of the Severe Accident [SA]

- Measures to prevent and mitigate SA of the SFR will be based on:
  - Safety approach featuring SFR specific characteristics

- International harmonization related to SFR safety
  - It is reasonably believed that requirements and guidelines of the SFR safety will be harmonized in order to solve the common safety issues related to the basic safety characteristics of the SFR system.
  - It is also expected that international framework including safety-related research & development will contribute to enhance the safety level globally and commonly.

2. Basic safety characteristics of SFR

Three fundamental safety functions of SFR are the same as those of LWR



"Reactor Shut Down"
Stop the fission chain reaction

"Decay Heat Removal"
Remove the decay heat in the core

"Containment"
Contain the radioactive materials within the containment vessel

"Reactor Shut Down"→ RSS
Reducing the heat generation to the decay heat level by shutting down the reactor

⇩

"Decay Heat Removal"→ DHRS
Contain radioactive materials in the fuel pellet and/or in the fuel pin, as far as coolable conditions being kept

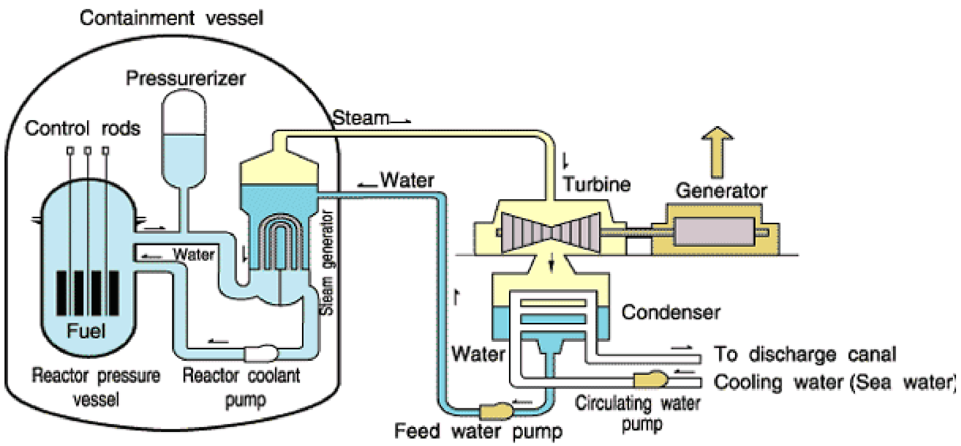
⇩

"Containment"→ CV
Final barrier of radioactive materials to the environment

2. Basic safety characteristics of SFR

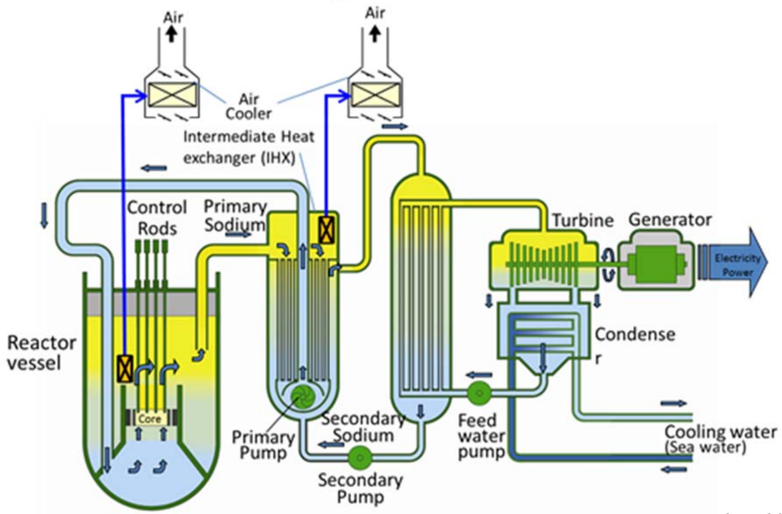
Item	LWR	SFR
Reactor core reactivity	Maximum configuration	Not in Maximum
Coolant pressure	High	Low
Sub-cool margin	Low (or zero)	Approx. 350deg-C
Natural circulation heat removal	Low capability	High capability
Ultimate heat sink (in accident)	Sea (/river /lake…)	Air
Coolant chemical reactivity	Low	High

LWR (PWR)



Ref. from www.fepc.or.jp

SFR*



* JSFR, as an example of loop-type

2. Basic safety characteristics of SFR

SFR - CDA has been concerned because relocation of core materials may lead a re-criticality and generate the energetics.

SFR - Guard vessel & guard pipes are used to maintain coolant level in case of primary coolant leakage; No ECCS is required.

Item	LWR	SFR
Reactor core reactivity	Maximum configuration	Not in Maximu
Coolant pressure	High	Low
Sub-cool margin	Low	Approx. 300deg-C
Natural circulation capability	Low	High
Ultimate heat sink (in accident)	Sea (/river /lake…)	Air
Coolant chemical reactivity	Low	High

SFR - Sodium reacts with air, water and concrete. These reactions have to be prevented and/or mitigated in sodium leak events in order not to affect the fundamental safety functions.

SFR - Decay heat can be removed by natural circulation due to the large coolant temperature difference between reactor core outlet and inlet.

2. Basic safety characteristics of SFR

Characteristics of SFR reactor core

LWR	SFR
High pressure system (7~16MPa)	Low pressure system (~0.3MPa)
• Design measures against control rod ejection (reactivity insertion accident)	• No control rod ejection
Thermal neutron	Fast neutron
Even if reactor shutdown is failed, • Coolant boiling or fuel relocation not lead positive feedback, and results in reactor power decrease. May need boric water for ensuring sub-criticality	If reactor shutdown is failed, • Coolant boiling and/or cladding melt lead positive feedback, and can result in reactor power increase. • Molten fuel compaction may lead large positive feedback; it may result in energetics by re-criticality.

		LWR	SFR
Power coefficient (Normal operation)	\$ / (dP/P)	Negative	Negative
Power coefficient (Coolant boiling/Cladding melt)	\$ / (dP/P)	Negative	±0~Positive*

**Increases with larger power core in general*

Safety Approach

Reliability of reactor shutdown system is a key to enhance prevention capability from core damage

2. Basic safety characteristics of SFR

Characteristics of SFR coolant

LWR	SFR
High pressure system (7~16MPa)	Low pressure system (~0.3MPa)
• High potential pipe break & Flashing after leak • Need measures against LOCA caused by pipe break (coolant injection by ECCS) • Water feed & breed under SA	• Low potential pipe break & No flashing potential • No need of ECCS • Need measures to keep coolant level above the core even under leak accidents or SA

		LWR (PWR)	SFR
System pressure	MPa	16	~0.3
Thermal conductivity	W/m/℃	0.6	67
Boiling point	℃	340	1000
Temperature at core outlet/inlet	℃	325/290	550/395* (~700 at max.)

Large sub-cooling margin till boiling

**Need provision on large temperature difference (i.e. thermal stress, thermal striping and stratification)*

Safety Approach

- Maintain coolant level in reactor vessel is a key for reactor core cooling.
- Passive structure enables to keep coolant level (instead of the ECCS of the LWR)

2. Basic safety characteristics of SFR

Characteristics of SFR containment

LWR	SFR
High pressure water (7~16MPa)	Low pressure sodium (~0.3MPa)
Loss of Coolant Accident [LOCA] • High pressure water/steam dispersion • Need pressure-resistant vessel; plus water spray for CV cooling & depressurization Severe Accident [SA] • Hydrogen by zircaloy-water reaction	Sodium leak accident • Release of sodium fire heat • Containment boundary is pressurized little Severe Accident • Potential of significant energy release by recriticality in the course of Core Disruptive Accidents [CDA]

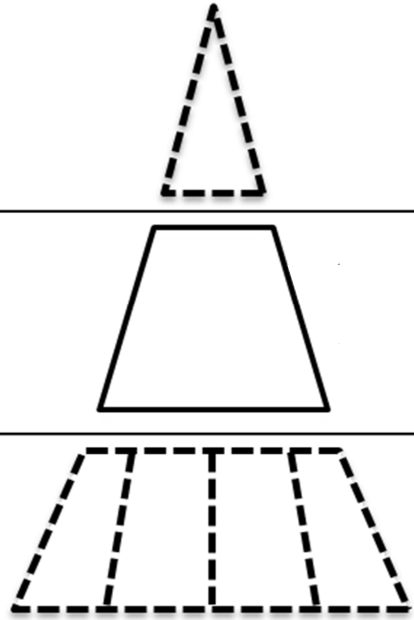
LWRs

LOCA	High pressure water/steam	By pressure boundary failure, Containment boundary is pressurized
SA	Hydrogen production & Potential of explosion	Potential of impact on the Containment

SFRs

Sodium Leak	Potential sodium chemical reaction	By coolant boundary failure, Containment boundary is pressurized little
CDA	Potential of significant energy release by recriticality	Potential of impact on the Containment

3. International Harmonization on SFR Safety

Hierarchy of Safety Standards		Safety-related developments under Generation-IV International Forum [GIF]
Safety Fundamentals		**Safety Goals**
Safety Requirements (LWR)		**Safety Design Criteria SFR**
Safety Guides or Code and Standards		

- Safety Goals for the Generation-IV reactor systems were already set-up under GIF.
- Safety Design Criteria [SDC], ranks as safety requirements, should be developed next in order to resolve internationally the common issues related to basic safety characteristics of the SFR and to achieve concurrently the GIF safety goals.
- The GIF SDC Task Force started to develop the SFR SDC.
  The IAEA contribution is currently via e.g. GIF-IAEA/INPRO workshop, and it is expected in future to be on SDC-based standardization as an IAEA's safety requirement.

3. International Harmonization on SFR Safety

Safety goals of the Generation-IV reactor systems

- Safety & Reliability-1:
  - Gen-IV nuclear energy systems operations will excel in safety and reliability.
- Safety & Reliability-2:
  - Gen-IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.
- Safety & Reliability-3:
  - Gen-IV nuclear energy systems will eliminate the need for offsite emergency response.

- After the F1 accidents, these goals are of increasing significance because the unexpected offsite emergency response has been realized actually in Japan.
- It should be noted that SR-3 "Elimination of the need for offsite emergency response" is not intended to deny the preparedness of emergency response activities but to promote innovations of safety measures to practically eliminate the situation.

3. International Harmonization on SFR Safety

Relation between GIF Safety Goals and IAEA Safety Level

GIF Safety Goals	IAEA*	
	Levels of Defence-In-Depth	Plant state
SR-1: Operational Safety and Reliability	Level-1: Prevention of abnormal operation and failures	Normal operation
	Level-2: Control of abnormal operation and detection of failures	Anticipated operational occurrence(AOO)
SR-2: Low likelihood and degree of CDA	Level-3: Control of accidents within the design basis	Design basis accidents (DBA)
SR-3: Elimination of need for offsite emergency response	Level-4: Control of severe plant conditions, including prevention of accident progression and mitigation of severe accidents	Design extension conditions(DEC) - including significant core degradation -
	Level-5: Mitigation of radiological consequences of significant releases of radioactive materials – corresponds to offsite emergency response ―	

* IAEA SSR 2/1(Revised NS-R-1)

3. International Harmonization on SFR Safety

Basic Scheme to outline the SDC

<u>High level safety fundamentals, and safety goals</u>
(e.g.GIF Roadmap (safety & reliability goals))

1) Particular issues for Sodium-cooled Fast Reactor

- Characteristic of Sodium-cooled Fast Reactor
  - Reactivity, Na coolant …
  - Sodium fire & Sodium-water reaction…
- Consideration on Severe Accident
  - Core Disruptive Accident in DiD Level 4
- High Temperature & Low pressure system
  - Creep property, Leak-Before-Break…
  - No LOCA and no need of ECCS…
- Fundamental Safety Approach
  - Passive system for shutdown & cooling

2) Reference of SDC Framework

<u>IAEA SSR 2/1</u>

- Management of safety in design
- Principal technical requirement
- General Plant design
- Design of specific plant system

3) Lesson learned from F1 accidents

- Common cause failure by external event
- Loss of off site power for longer period
  - Decay heat removal, Fuel pool cooling
- Containment function on spent fuel in the pool
- Preparing multiple AMs, e.t.c.

SFR SDC

3. International Harmonization on SFR Safety

SDC: Table of contents (ToC)

- ***Basic structure follows IAEA SSR2/1 & additional criteria as <u>SFR-SDC</u>***

<u>1. INTRODUCTION</u>

<u>2. SAFETY GOALS AND SAFETY APPROACH</u>

<u>3. MANAGEMENT OF SAFETY IN DESIGN</u>

4. PRINCIPAL TECHNICAL REQUIREMENTS

•Fundamental safety functions

•<u>Application of defence-in-depth</u>…

5. GENERAL PLANT DESIGN

•Design basis
(<u>Internal & External hazards</u>, DBA, <u>DEC</u>…)

•<u>Design for safe operation over the lifetime</u>

•Human factors

•Other design considerations

•Safety analysis

6. DESIGN OF SPECIFIC PLANT SYSTEMS

•<u>Overall Plant System</u>

•<u>Reactor Core & Associated Features</u>

•<u>Reactor Coolant Systems</u>

•<u>Containment Structure & System</u>

•<u>Instrumentation & Control Systems</u>

•<u>Emergency Power Supply</u>

•<u>Supporting and Auxiliary Systems</u>

•<u>Other Power Conversion Systems</u>

•<u>Treatment of Radioactive effluents & Waste</u>

•<u>Fuel Handling & Storage Systems</u>

Terminology

Based on the IAEA Safety Glossary (2007),

Plus the definitions of SFR specific terminology

3. International Harmonization on SFR Safety

Safety Goals & Approaches for next generation system

- Defence in Depth
- Further enhancement of DiD Level 4 for prevention and mitigation of the severe accident [SA]
- Built-in safety function, and not by add-on

Design Basis	Level1：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
Design Extension Condition (DEC)	Level 4: Control of severe conditions including prevention of accident progression and mitigation of the consequences of a severe accident • Built-in measures for Prevention & Mitigation of Severe Accident
Off-site response	Level 5: Mitigation of radiological consequences of significant external releases of radioactive materials

3. International Harmonization on SFR Safety

Particular Pro/Con Features of SFR

- Core Characteristics

  Positive void reactivity & Not the most reactive configuration

  → Prevention of severe energetics at CDA

- Sodium Coolant
  - High thermal conductivity of sodium

    → Capable of decay heat removal by natural circulation
  - Chemically active

    → Measures to sodium leak (fire & reaction with water)

    → The leak not to affect on the fundamental safety functions

- Operation under high temperature & high fluence conditions
  - Consideration of creep and radiation effect on materials

- Operation under low pressure condition
  - Leaks not lead to LOCA (No need of ECCS)
  - Need to maintain sodium level for reactor core cooling

3. International Harmonization on SFR Safety

Lessons learned from the F1 Accidents

Key points on learning listed in below are based on the Japanese Government Report

- Strengthen preventive measure against a severe accident
  - Measures against extreme external hazards (such as earthquake & tsunami)
  - Robust electric power supplies
  - Robust cooling functions (core, containment & spent fuel pools)
- Enhancement of measures against severe accidents
  - Measures to prevent hydrogen explosions
  - Instrumentation to identify status of reactor core and CV
- Reinforcement of safety infrastructure
  - Ensuring independency and diversity of safety systems

4. Conclusions

- Safety approach & associated safety measures should be based on the basic safety characteristics of the SFR
  - e.g. core reactivity feedbacks, low pressure coolant, high boiling point, air as an ultimate heat sink, sodium chemical activity...
- SFR is the system suitable to utilize passive safety mechanism such as natural circulation for decay heat removal. The superior safety features should be commonly utilized for all the SFRs in future with sharing the common safety design criteria [SDC].
- The SDC should be based on these common safety approach in order to realize enhanced safety level as a standard. Key point of the SDC as the next generation SFR is to take account of design for prevention and mitigation of severe accident.