Safety Design Guidelines (SDG) on Safety Approach and Design Conditions for Generation-IV Sodium-cooled Fast Reactor System

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GIF SDC Task Force

7th Joint IAEA-GIF Technical Meeting/Workshop on Safety of LMFRs, 27-29 March 2018, IAEA HQ, Vienna
Contents

- Update of SDC Report
- SDG Development and Interaction with External Entities
Safety Design Guidelines Development

- Safety Goals
  - Fundamental safety principles and common safety goals for all Gen-IV systems
- Safety Design Criteria
  - A set of criteria reflecting GIF safety approach to achieve harmonized safety requirements of SFR system
- Safety Design Guidelines
  - A set of guidelines on how to implement the design criteria and address SFR-specific safety topics
- Country-specific codes and standards
  - Domestic regulations for design of reactor core, cooling system, and other structures, systems, and components

- SDC (Phase I report issued 2013, to be updated)
- SDG on Safety Approach and Design Conditions
- SDG on Key Structures, Systems and Components
SDC Update

» Original SDC report (2013) has been open to public on GIF web page

   https://www.gen-4.org/gif/jcms/c_93020/safety-design-criteria

» The revised SDC report (Rev.1) submitted to EG members of GIF in October 2017.

   ◆ The SDC TF received the comments from China’s NNSA, USNRC, IAEA and IRSN. SDC TF has produced the revision of SDC as well as the resolution documents that include the response to the comment.

   ◆ The revised SDC also reflects the revision of IAEA SSR 2/1.
### SDG Development Schedule

<table>
<thead>
<tr>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016-2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG on Safety Approach</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Table of Contents</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Identification of discussion points</td>
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<tr>
<td>Reactivity issue</td>
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<tr>
<td>Prevention &amp; Mitigation of severe accidents</td>
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<tr>
<td>Loss of heat removal issue</td>
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<tr>
<td>Accident conditions to be practically eliminated</td>
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<tr>
<td>Report</td>
<td>PG Review</td>
<td>External Review</td>
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### SDGs on Key Structures, Systems and Components

<table>
<thead>
<tr>
<th></th>
<th>Table of Contents</th>
<th>Identification of discussion points</th>
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</thead>
</table>
| Functional Requirements on SSC | Set of design conditions (e.g. postulated events, design parameters & constraints…)

#### Guidelines for Reactor Core
- Discussion points (e.g. fuel performance in DBA, DEC, Passive or inherent reactivity features)

#### Guidelines for Reactor Coolant System
- Discussion points (e.g. sodium chemical reactions, passive or alternative cooling features)

#### Guidelines for Containment Vessel
- Discussion points (e.g. severe accident conditions and measures, Accident management)

<table>
<thead>
<tr>
<th></th>
<th>Drafting SSC SDG Report</th>
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<tbody>
<tr>
<td></td>
<td>PG Review Report</td>
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SDG Development

- GIF SDC-TF (Phase II)
  » Started 2013
    - 1st Meeting 2013.9
    - 11th Meeting 2017.5
    - 12th Meeting 2017.10
    - 13th Meeting 2018.4

» Members
  - China, EU, France, Japan, ROK, Russia, USA
  - IAEA (observer)
SDG on Safety Approach and Design Conditions

- Safety Approach SDG report (2016) has been open to public on GIF web page
  https://www.gen-4.org/gif/jcms/c_93020/safety-design-criteria

- Focus on Prevention and Mitigation of Severe Accidents, and Use of Inherent/Passive Safety Features

- Delivered the SDG report on Safety Approach and Design Conditions to GSAR and IAEA for External Review on April, 2016

GSAR : OECD/NEA Joint CNRA/CSNI Ad-hoc Group on the Safety of Advanced Reactors
Interaction with IAEA

- **Progress of IAEA’s review** was presented at 6th GIF-IAEA Joint Workshop on SFR Safety on November 2016
- **FR 17 at Yekaterinburg, Russia** on 26-29 June 2017
  - Papers submitted
  - Presentation
    - Y. Okano, R. Nakai, P. Gauthe, I. Ashurko, J. Yoo, S. C. Chetal
- **7th Joint IAEA-GIF Workshop on LMFR Safety is planned**
  - 27-29 March 2018
Scope of SDG on Safety Approach

• This report is intended to provide recommendations and guidance on how to comply with the GIF SFR Safety Design Criteria. It presents examples for the measures stated in criteria as the best practices to help the designers achieve high levels of safety.

• Initially, the guidelines will focus on specific safety concerns, such as reactivity characteristics of SFRs and heat removal issues.

• To address the potential consequences of such accidents, this report focuses on providing examples of design approaches for “prevention and mitigation of severe accidents” and for “loss-of-decay heat removal capability as a situation that needs to be practically eliminated”.
# Table of contents

1. INTRODUCTION
   1.1. Background and Objectives
   1.2. Scope of the Safety Design Guidelines

2. MAIN CHARACTERISTICS OF GEN-IV SFR SYSTEMS

3. GENERAL APPROACH
   3.1. Design Basis and Residual Risk
   3.2. General Approach to Normal Operation, AOOs, and DBAs
   3.3. General Approach to Design Extension Conditions
   3.4. Design Considerations for Design Extension Conditions
   3.5. Practical Elimination of Accident Situations

4. GUIDELINES FOR APPLICATION OF SAFETY DESIGN CRITERIA
   4.1. Reactivity Issues
   4.2. Decay Heat Removal Issues
   4.3. Postulated Initiating Events and Design Limits
   4.4. Testability
   4.5. Demonstration

5. CLARIFICATION AND QUANTIFICATION OF TECHNICAL POINTS CONCERNING SAFETY DESIGN CRITERIA
   5.1. Consideration concerning SFR Reactivity Characteristics
**SFR Design Tracks under GIF**

<table>
<thead>
<tr>
<th>System structure</th>
<th>Loop-type, Pool-type, Small modular</th>
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</thead>
<tbody>
<tr>
<td>Electric output</td>
<td>50 - 2,000MWe</td>
</tr>
<tr>
<td>Coolant system</td>
<td>Primary and secondary [intermediate] coolant system utilizing sodium coolant</td>
</tr>
<tr>
<td>BOP system</td>
<td>Water/Steam cycle (alternative concept: Supercritical CO₂ cycle)</td>
</tr>
<tr>
<td>Fuel</td>
<td>MOX, Metal, others</td>
</tr>
</tbody>
</table>

![Systems Diagrams]

JSFR [Large Loop]  
ESFR [Large Pool]  
KALIMER [Pool]  
SMFR [Small Modular]
Safety Advantages of SFRs

- Low pressure primary and intermediate coolant system
  - Guard vessel and guard pipes to “maintain” coolant inventory
  - No LOCA concern, no ECCS, no risk for control-rod ejection
- Liquid-metal coolant with excellent natural circulation characteristics and a wide margin (~400 degC) to boiling
- Inherent safety with “net” negative reactivity feedback during accidents that lead to elevated core/coolant temperatures
- Dedicated systems for decay heat removal to an ultimate heat sink
  - Large difference between core outlet and inlet temperatures to facilitate reliance on passive systems
- Low pressure (~0.5 bar) design pressure for containment (mostly against heat from sodium fires)
- Much simpler operation and accident management (long grace period for corrective action)
Challenges with SFRs

- **High temperature** (>500 degC core outlet temperature) and high core power density
- **Liquid sodium coolant** that reacts with air, water and concrete
  - These reactions have to be prevented and/or mitigated to avoid their effect on SSCs important to safety
- **Fast reactor cores** are not in their most reactive configuration
  - Relocation of core materials may lead to a hypothetical core disruptive accident (HCDA)
- **For large cores**, sodium void worth can be positive
- **Opaque sodium coolant** could pose in-service inspection and maintenance challenges
Points of General Approach

• Design Basis and Residual Risk
• General Design Approach
  – AOOs and DBAs
  – DECs
• Practical Elimination of Accident Situations
**Design Basis and Residual Risk**

- **Postulated initiating events in the plant states provide the design basis for the safety design of nuclear power plants.**
- **Residual risk is not included in the plant states.**
- **Practically eliminated situations are considered to be part of the residual risk.**

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**Diagram:**

- **Prevention of core damage**
- **Mitigation of core damage**
- **Design Basis Situations**
  - Design Basis Accidents
    - Examples of DBA: LOF, Sodium leaks...
  - Prevention Situations
    - DBA initiators with additional failures including safety systems
    - Initiators more severe than DBA initiators
  - Mitigation Situations
    - Severe accidents from postulated scenarios
- **Residual Risk**
  - Situations covered by Practical Elimination demonstration
TABLE 1. PLANT STATES CONSIDERED IN THE DESIGN

<table>
<thead>
<tr>
<th>Operational states</th>
<th>Accident conditions</th>
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<tbody>
<tr>
<td>Normal operation (NO)</td>
<td>Design basis accidents (DBA)</td>
</tr>
<tr>
<td>Anticipated operational occurrences (AOO)</td>
<td>Design extension conditions (DEC)</td>
</tr>
<tr>
<td></td>
<td>without significant fuel degradation</td>
</tr>
<tr>
<td></td>
<td>with core melt</td>
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</table>

TABLE 2. INDICATIVE EXPECTED FREQUENCIES OF OCCURRENCE OF DIFFERENT PLANT STATES

<table>
<thead>
<tr>
<th>Plant state</th>
<th>Indicative expected frequency of occurrence</th>
</tr>
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<tbody>
<tr>
<td>Normal operation</td>
<td>-</td>
</tr>
<tr>
<td>Anticipated operational occurrences</td>
<td>&gt; $10^{-2}$ events per year</td>
</tr>
<tr>
<td>Design basis accidents</td>
<td>$10^{-2} - 10^{-6}$ events per year</td>
</tr>
<tr>
<td>Design extension conditions without significant fuel degradation</td>
<td>$10^{-4} - 10^{-6}$ events per year</td>
</tr>
<tr>
<td>Design extension conditions with core melt</td>
<td>&lt; $10^{-6}$ events per year</td>
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General Design Approach

• Safety is primarily based on the use of multiple redundant engineered safety features to lower the probability of accidents and to limit the consequences of anticipated operational occurrences and design basis accidents.

• These safety features include independent and diverse scram systems, multiple coolant pumps and heat transport loops, decay heat removal systems, and multiple barriers against release of radioactive materials.

• In addition to these features, passive/inherent features for cooling and shutdown / power reduction may also play a significant role in the safety performance of Gen-IV SFRs by improving the diversity of safety systems.
Design Approach to Normal Operation, AOOs and DBAs

• Strong emphasis should be given to the prevention, detection and control of accident sequences.
• AOOs and DBAs are managed by using safety systems to shut down the reactor and to remove decay heat.
• Potential initiating events are identified and grouped into AOOs and DBAs, primarily on the basis of their frequency of occurrence.
  – For AOO, fuel cladding tube, reactor coolant and cover gas boundary should be kept their barrier function.
  – For DBA, core should be coolable. Reactor coolant and cover gas boundary should be kept their barrier function.
## Typical AOOs and DBAs for SFR

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Mechanism</th>
<th>Typical initiating events</th>
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</thead>
<tbody>
<tr>
<td>Imbalance of core power and cooling</td>
<td>Core power increase</td>
<td>- Erroneous withdrawal of control rod (normal speed)</td>
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<tr>
<td></td>
<td></td>
<td>- Control rod drop</td>
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<tr>
<td></td>
<td>Primary coolant flow decrease</td>
<td>- Loss of external power</td>
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<tr>
<td></td>
<td></td>
<td>- Primary pump trip</td>
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<tr>
<td></td>
<td>Abnormality in heat sink</td>
<td>- Secondary pump trip</td>
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<tr>
<td></td>
<td></td>
<td>- Feedwater pump trip</td>
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<tr>
<td></td>
<td></td>
<td>- Loss of load</td>
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<tr>
<td></td>
<td></td>
<td>- Small leak of steam generator heat exchanger tube</td>
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<tr>
<td></td>
<td></td>
<td>- One secondary pump seizure</td>
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<tr>
<td></td>
<td></td>
<td>- Secondary coolant pipe breach</td>
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<tr>
<td></td>
<td></td>
<td>- Main feedwater/steam generator pipe rupture</td>
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<tr>
<td></td>
<td></td>
<td>- Heat exchanger pipe rupture on steam generator</td>
</tr>
</tbody>
</table>

- AOO
- DBA
Design Approach to DECs

- Preventive design measures provide lines of defence to avoid conditions leading to significant core damage.

- Mitigative design features are provided for mitigation of consequences of postulated accidents where significant core damage occurs, with the objective of maintaining the containment function to limit radioactive release.

- All initiating events for DECs should be considered as long as they are physically realisable and credible, based on SFR design characteristics, as well as deterministic and probabilistic safety assessments (PSA).
Exploiting SFR Characteristics to Enhance Safety

• **Passive/Inherent safety for DEC**
  
  – On reactivity
    
    » *Inherent reactivity feedback* to reduce the power as core temperatures rise or
    
    » *Passive mechanism* are applicable for shutdown systems, such as SASS, HSR, and GEM
  
  – On decay heat removal
    
    » *Natural circulation* of single phase sodium coolant
    
    » can be placed in different locations for enhancing diversity
Exploiting SFR Characteristics to Enhance Safety

• In-Vessel Retention
  - Safety design strategy aimed at ensuring long-term retention of core materials inside the RV for any accident situation, including those resulting in degradation or loss of core integrity, by providing coolability of the core materials under sub-critical conditions
  - Typically accomplished by providing the means to keep the core submerged under the sodium coolant and the decay heat removal paths available
DECs

Anticipated Transient Without Scram (ATWS)

• “Prevention of core damage”
  – Means for maintaining an acceptable balance between reactor power and heat removal capabilities should be provided to avoid core damage, given an assumed failure of the active reactor shutdown function in AOOs. These capabilities should include inherent and/or passive means.

• “Mitigation of core damage”
  – Provisions for prevention of a large energy release that could threaten the integrity of the containment and provisions for long-term cooling of a degraded core to avoid reactor coolant boundary failure, should be made available for achieving IVR against unprotected transients with core damage.
DECs

Loss of Safety Systems for Decay Heat Removal

• “Prevention of core damage”
  – Extension of the DHRS (normally designed for DBAs) capability should be considered, and other alternative cooling provisions should be made available to prevent core damage and reactor coolant boundary failures due to overheating, given the assumed causes of DHRS failures as DECs.

Reactor Coolant Level Reduction

• “Prevention of core damage”
  – Reactor Vessels (RVs) and Guard Vessels (GVs) should be designed, manufactured, installed, maintained and inspected to have the highest level of reliability in order to prevent double leakage from RVs and GVs. If double leakage from RVs and GVs cannot be practically eliminated, the situation has to be considered for implementing design provisions.

Since mitigative feature under total loss of cooling situation is not effective, enhancement of cooling function is strongly recommended so that total loss of cooling situation can be practically eliminated.
Practical Elimination of Accident Situations:

IAEA’s terminology

‘practically eliminated’ was used in requirements for the design of nuclear power plants to convey the notion that the possibility of the potential occurrence of certain hypothetical event sequences in scenarios could be considered to be excluded...

Application to Design

◆ Situations, which may lead to early or large radioactive release and which cannot be mitigated under acceptable conditions, are identified to be practically eliminated by implementation of design provisions.

◆ The approach is intended to demonstrate that the identified situation is physically impossible by design, or that implemented provisions eliminates the situation to a residual risk with a high degree of confidence.

◆ Practical elimination can be considered as part of a general approach and as an enhancement of the Defence-in-Depth principle. The design should restrain practical elimination to a very limited list of situations.
Practical Elimination of Accident Situations:

Example of situations

- Severe accidents with mechanical energy release higher than the containment capability
  - Power excursions for intact core situations
    » Large gas bubble through the core
    » Large-scale core compaction
    » Collapse of the core support structures

- Situations leading to the failure of the containment with risk of fuel damage
  - Complete loss of decay heat removal function that leads to core damage and failure of primary coolant boundary
  - Core uncovering due to sodium inventory loss

- Fuel degradation in fuel storage or during when the containment may not be functional due to maintenance
  - Core damage during maintenance
  - Spent fuel melting in the storage
Design considerations for practical elimination of complete loss of heat removal function (1/2)

• For DBA, decay heat removal system should be provided to deal with postulated initiating events typically caused by single failure of an SSC.
• For DEC, design measures should be provided against initiating events more severe than DBAs or originate from multiple failure of SSCs.
• Proven technology based on the design, construction and operation experience of SFRs should be applied for the basic design of decay heat removal systems.
• Extension of capabilities to deal with DECs, e.g. additional decay heat removal systems, increased capacities of heat removal, operation with natural as well as forced circulation, should be considered. Application of mobile power sources and manual operations in case of loss of power are examples of extensions of such capabilities.
• Ensuring diversity in systems is essential to improve the overall reliability. Duplication of systems does not bring the same reliability benefits. It is required to maintain heat removal functions, even under postulated severe external hazards, such as earthquakes, flooding, tsunami and missiles leading to a common cause failure.
Design considerations for practical elimination of complete loss of heat removal function (2/2)

- An SFR should proactively utilise its **natural circulation capability** to an ultimate heat sink (atmosphere), since this can significantly contribute to improving the reliability of the heat removal capability, even under long-term loss of power supplies. Natural circulation can be used as a measure for DBAs, as well as for DECs.

- Robust demonstrations of practical elimination should consider **independence of safety systems for DBAs and decay heat removal capabilities for DECs**. If necessary, additional independent decay heat removal systems should be installed as an ultimate measure.

- **It is necessary to clarify all credible factors leading to loss of decay heat removal function** and to confirm that measures can be implemented to overcome all of them.

- Each system, related to decay heat removal, should be able to demonstrate that it can perform its function as expected.
Consideration concerning SFR Reactivity Characteristics (1/2)

Normal Operation, AOO, DBA, DEC w/o Core Damage

» Shall require inherent reactor power stability
» Reactor Shutdown System shall prevent sodium boiling and maintain core coolable geometry

Design Extension Condition with Core Damage

» Shall prevent excessive insertion of reactivity by coolant boiling, cladding and fuel relocation after core damage
Consideration concerning SFR Reactivity Characteristics (2/2)

- **For Normal operation, AOO and DBA**
  - Power reactivity coefficient $< 0$ (Negative)
  - Reactor shutdown capability with inherent feedback
    - > Postulated reactivity insertion

- **For Design Extension Condition**
  - Before core damage: same as the requirement for DBA,
    - Achieved by passive measures or inherent features
  - After core damage:
    - Total reactor core reactivity $< 1\$ (below prompt criticality)

- Sodium void worth can be positive as far as the above conditions are satisfied.
Summary

• Safety Approach and Design Conditions SDG
  – Summarize general safety design approach and specific design consideration for reactivity issue and decay heat removal issue for Gen-IV SFR
  – Design approach for DEC and PE is mainly addressed, since it could be important factors of design.
    » Passive/Inherent reactivity control and decay heat removal
    » In-Vessel Retention
    » Practical Elimination, e.g. complete loss of decay heat removal function, core uncovering
  – Clarification and quantification are made for reactivity
Thank you for your attention!!