The Safety Design Criteria Development and Summary of Its Update for the Generation-IV SFR Systems

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Abstract. The Generation-IV International Forum (GIF) Task Force completed development of Safety Design Criteria (SDC) for the Generation-IV SFR systems in May, 2013. SDC reflects the high-level GIF safety and reliability goals (excellence in operational safety and reliability and reduced likelihood and degree of core damage) and follows GIF basic safety approach (application of defense-in-depth and emphasis on inherent and passive safety features so that safety is built-in to the design, not added-on). It aims to establish reference criteria for safety design of structures, systems and components and achieve harmonization of safety approaches among GIF member states. Following its public release, SDC report was distributed to international organizations and national regulatory bodies for review and feedback. Based on comments received during the following two-year period, SDC report underwent a revision reflecting feedback received from IAEA, NRC (USA), IRSN (France), and NNSA (China). This paper provides an overview of SDC development effort, and summarizes its revisions based the comments/suggestions received from the international review.

Key Words: Generation-IV International Forum (GIF), Safety Design Criteria.

1. Introduction

The Generation-IV International Forum (GIF) Task Force was established in 2011 following the Policy Group recommendation to develop Safety Design Criteria (SDC) and Safety Design Guidelines (SDG) for Sodium-cooled Fast Reactors (SFRs). The main objective was to present reference criteria and guidance for the safety design of structures, systems and components to achieve the safety goals of the Generation-IV SFR system design tracks. While the national codes and standards are available for detailed designs of structures, systems and components, they are largely LWR based and there is a gap between the high-level safety fundamentals and these detailed codes and standards. As shown in FIG 1, the GIF Task Force mission was to address this gap by developing Safety Design Criteria and Guidelines for the Generation-IV SFR design tracks.

By the end of 2012, the Task Force completed the first version of the SDC report[1] that consisted of an introduction that describes the background, objectives and formulation principles of the effort, an overview of safety goals and approach expected for Generation-IV SFR system, and eighty-three criteria for the overall safety and specific structure, system and component design. SFR-specific safety features (e.g. passive decay heat removal) and related system configurations (e.g. intermediate coolant loops) are incorporated in the SDC criteria.

The SFR SDC is intended to be applicable to the design of key structures, systems and components, (such as the reactor core, the fuel, the coolant system and the containment) and used IAEA's LWR safety requirements (IAEA SSR2/1) as a reference document.[2] It is formulated as a consensus document by the international R&D community of designers and developers for a broad spectrum of SFR design tracks (small modular vs. large and pool vs. loop designs with various fuel types). The SDC maintains the basic structure of IAEA SSR 2/1 and its terms and definitions as well as original text is preserved as much as possible.

Following its completion and release, the SDC report has been distributed to international and regulatory organizations for review and comments. The feedback from IAEA and regulatory bodies in the U.S., China and the France has been reflected in the revised version of SDC report by the end of 2016.

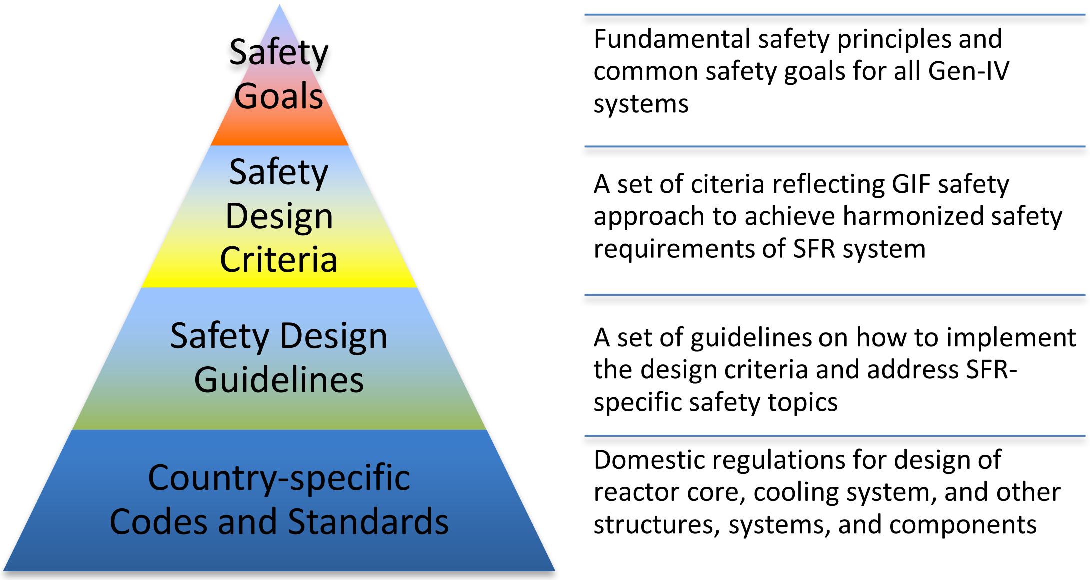

FIG. 1. Hierarchy of Safety Standards

2. GIF SFR Safety Design Criteria

The GIF safety and reliability goals were established by the Policy Group in 2002 in the “Generation-IV Nuclear Energy Systems under the GIF Roadmap.”[3] The goals state that the Gen-IV systems are expected to excel in safety and reliability for Defence-in-Depth Levels 1 and 2 (operational states), and to have a very low likelihood and degree of core damage for Defence-in-Depth Levels 3 and 4 (design basis accidents and design extension conditions). These goals are expected to be achieved by implementing a robust design to reduce the likelihood of abnormal occurrences and by employing design features to control the progression of an accident and to mitigate its consequences. Focus is given to safety design for accident prevention and a robust safety demonstration that uses a methodology (based on “deterministic and probabilistic” with associated confidence) to address uncertainties.

The SDC follows this Defence-in-Depth philosophy[4] as the fundamental safety approach to assure design measures for every plant state, i.e. normal operation, anticipated operational occurrence, design basis accident and design extension condition. The design for operational states (i.e. normal operation and anticipated operational occurrence) and design basis accidents is required to be conservative with due account of uncertainties of design conditions and transient phenomena. For design extension conditions, the design is required to prevent significant radioactive material releases to the environment based on best estimate analysis. To further ensure safety, the appropriate management of the fuel handling and storage as well as the radioactive waste management systems are also required.

2.1 Safety Approach for Events Considered in Different Plants States

The events considered for the safety design are internal events, resulting from human errors or plant component failures, and external events. For internal events, anticipated operational occurrences, design basis accidents and design extension conditions are defined and preventive and mitigation measures are required to be built into the design. As for external events, design conditions are required to be established in accordance with site conditions in order to protect safety functions, including additional margins to the design conditions as necessary. An exhaustive approach is expected regarding the design basis against external hazards, taking into account the type of hazards, the combinations of loadings, and the design margins to improve the robustness of the power plant safety, and to confirm that consequences of degraded plant situations induced by extreme hazards are acceptable.

The approaches for normal operation, anticipated operational occurrences, and design basis accidents include continuous feedback on 'operation/accident experience' and 'maintenance/repair experience' to achieve high system reliability, enhancement of safety margins from introduction of new technologies, and advances in inspection technology for early detection of the conditions that could lead to failures.

The approaches for design extension conditions include providing additional measures to prevent their occurrences and mitigate their consequences along with robust demonstration of these measures. Due consideration of the potential for common cause failures is also required. Application of passive design measures, by utilizing/enhancing favourable safety features specific to the Generation-IV SFR system, is also required for design extension conditions with feedback from past experience to improve their reliability. The selection of design basis accidents and design extension conditions is required to be based on the combined use of deterministic approach based on fundamental characteristics of the reactor system, supplemented by probabilistic analysis, based on prior operational, external event, and licensing experiences to support a risk-informed framework.

Provisions for a well-balanced design measures using an appropriate combination of active and inherent/passive safety systems to enhance safety against a number of wide-ranging events are prescribed. For design basis accidents, importance of characterizing the safety features of structures, systems and components with enhanced reliability based on proven technologies and adequate redundancy and diversity is emphasized. For design extension conditions, independence and additional diversity of the preventive design measures from those relied on during design basis accidents based primarily based on inherent and passive safety principles are also emphasized. Using inherent and/or passive safety features of the design are required to allow termination of accidents in DEC category, or mitigation of their consequences, even with postulated failure of the active safety systems.

A leak-tight containment structure is prescribed to prevent release of radioactivity to the environment. Non-radiological and chemical risks are also required to be considered in the design to limit their impact on safety function of SSCs and to protect the health of workers and the public. Severe accidents that could lead to a significant and sudden radioactivity release due to a possible cliff edge effect are required to be practically eliminated.

2.2 SFR-Specific Revisions to the General Design Criteria

SFR-specific revisions are included in the criteria for fuel elements and assemblies, reactor core structure and characteristics, reactor shutdown systems, primary coolant and cover gas systems, containment system, fuel handling and storage systems. New criteria for intermediate coolant system, decay heat removal system (including final heat sink), sodium heating systems, sodium purification system, sodium leak detection and sodium fire suppression system are also created.

Considerations are required for SFR fuel elements and fuel assemblies that are operated in a fast neutron spectrum under the conditions of high power density, high burn up, and high sodium temperature. The creep and radiation effects on core structural materials are also emphasized. Since the SFR reactor core is not in the most reactive configuration under normal operating conditions and it is possible to have a positive void reactivity at the centre area of the reactor core, provisions are specified for design of the reactor core to prevent excessive reactivity insertion.

Since sodium is chemically reactive, it is necessary to manage sodium fire on contact with air or concrete to prevent its potential impact on the safety functions of systems, structures, and components. An intermediate coolant system is required for a Gen-IV SFR system to control/manage the consequences of sodium-water reaction during steam generator tube failure accidents. Provisions are also requested to address opaqueness and high melting point of sodium coolant that pose challenges to in-service inspection, maintenance and repair. Since SFRs allow the use of near-atmospheric-pressure coolant systems, application of the Leak Before Break concept to enable continuous leakage-monitoring as an inspection method for the coolant boundary is recommended and expected.

As for the design for normal operation, anticipated operational occurrences, and design basis accidents, it is required that the reactor can be reliably shutdown as needed, continuous effective core cooling can be maintained by the decay heat removal systems, and the core remains covered in the case of a leak in the primary coolant boundary. Since SFRs operate at near-atmospheric pressure and with a large margin to sodium boiling, coolant leakage from primary coolant system does not lead to the type of LOCA (loss of coolant accident) with depressurization (i.e. concurrent losses of not only cooling function but also coolant inventory). Therefore, an ECCS (emergency core cooling systems) for coolant injection under high and low pressure conditions is not required for SFRs.

Two reliable and independent shutdown systems that comply with relevant national or international codes and standards based on proven engineering practices are required to assure safe shutdown in the event of abnormal occurrences. Reliability of the shutdown system is achieved by monitoring, testing, and maintaining of the system throughout the life time of plant. The shutdown systems are required to be designed with adequate shutdown margin in all operational states and design basis accidents.

2.3 Considerations for Design Extension Conditions

For design extension conditions, additional measures to prevent core damage and maintain containment function are required in addition to the measures that are relied on for design basis accidents. Typically, design extension conditions include an off-normal event followed by failure to shut down the reactor or inability to remove heat from the core.

The failure to shutdown is paired with the three typical SFR accident sequences: Loss of flow, loss of heat sink, and transient overpower. In these instances, the design is required to make use of inherent and/or passive reactivity control capabilities. Analysis of the plant response to design extension conditions are recommended to be done using best estimate analysis, supported by PRA to ensure comprehensive coverage of postulated events and to consider their frequency and consequences. If the core damage cannot be prevented, in-vessel retention and core debris coolability are also requested to reduce the potential impact on the containment function.

The inability to remove heat from the core can result in three other design extension condition events: loss of coolant flow (when forced-circulation flow in the reactor core become disrupted), loss of primary coolant level (when core becomes uncovered), and long-term loss of heat sink (with scram). In these instances, the design is required to provide a means to prevent core damage or loss of containment function by maintaining sodium coolant level for core cooling and ensuring decay heat removal even under the conditions. Similar approaches that address the loss of heat removal events may also apply to spent fuel storage systems.

Design extension conditions also include sodium chemical reactions (e.g. combustion and sodium-concrete reactions resulting from leakage, and sodium-water reaction resulting from steam generator tube failure) since they could affect the safety of the reactor core or loss of containment function. The capability of ensuring containment integrity is required so that it can withstand thermal and mechanical loads generated from sodium combustion, sodium concrete reaction, and potential debris-concrete interaction.

2.4 Structure of the GIF SFR Safety Design Criteria Report

Consistent with the structure of IAEA SSR-2/1, the SFR safety design criteria are categorized in several chapters. The responsibilities in the management of safety in plant design, management system for the plant design, as well as the safety of the plant design throughout the lifetime of the plant are addressed in Chapter 3 of the SDC report. The principal technical criteria that cover the fundamental safety functions (control of reactivity, heat removal, and confinement of radioactivity), radiation protection, application of defence in depth, interfaces of safety with security and safeguards, proven engineering practices, and provisions for waste management and decommissioning are addressed in Chapter 4.

A wide ranging criteria relevant to the general plant design issues such as identification of plant states, design limits, postulated initiating events, internal and external hazards, common cause failures, engineering design rules, operational limits and conditions for safe operation, design basis accidents, design extension conditions, principles for physical separation and independence of safety systems, design basis, safety classification and reliability of items important to safety, support service systems, calibration, testing, maintenance, repair, replacement, inspection and monitoring of items important to safety, qualification of items important to safety, ageing management, design for optimal operator performance, sharing of safety systems between multiple units of a nuclear power plant, communications and emergency management, interactions between the electrical power grid and the plant, safety analysis are covered in Chapter 5.

The remaining criteria related to design of specific plant systems including the reactor core (fuel elements and assemblies and other core structures, reactivity control and shutdown systems), reactor coolant system, decay heat removal system, containment system, instrumentation and control systems, main, supplementary, and emergency control rooms, emergency power supply, fuel handling and storage systems, as well as other supporting and auxiliary systems are covered in Chapter 6. A glossary covering SFR-specific terminology and a number of important terms as defined in the IAEA safety standards/glossary[5] are also incorporated into the report.

3. Revisions to SFR SDC based on External Feedback

After the approval by the GIF Policy Group in May 2013, the SDC report was circulated to international organizations (i.e. IAEA, MDEP, OECD/NEA/CNRA) and regulatory bodies of the SFR developing states under GIF (i.e. China, EC, France, Japan, Korea, Russia, United States) for external feedback. The comments received from the IAEA, the USNRC, the China

NNSA, and the France IRSN varied from general comments (e.g. safety approach for the Gen-IV reactor systems, differences with Gen-III systems, and relation between safety and security) to detailed specific recommendations for individual criterion related to technical characteristics of SFRs (e.g. sodium-fire/water reactions and their consequences, accident initiators and parameters crucial to transient, design basis accidents and design extension conditions). The Task Force conducted a thorough analysis of the feedback received from these external reviews and summarized its resolutions in a separate TF report along with the revised version of SDC report by the end of 2016.

3.1 Revisions based on U.S. NRC Comments

USNRC Office of New Reactors provided a review of SDC report noting that their review did not constitute an endorsement of the GIF SFR SDC or indicate any commitment for future use. In their review, USNRC staff broadly compared GIF SFR SDC with applicable requirements and processes in the U.S. Code of Federal Regulations: 10 CFR 50 (Domestic Licensing of Production and Utilization Facilities) including its Appendix A (General Design Criteria for NPPs), 10 CFR 52 (Licenses, Certifications, and Approvals for NPPs), and NUREG-0800 (Standard Review Plan for Review of SARS for NPPs).

USNRC commented that the GIF SFR SDC report is comprehensive and their review did not identify any “insurmountable safety or regulatory issues.” An “appropriate” mark was given for six specific criteria and no comments were made for 33 criteria (it was indicated that absence of comments did not imply agreement or approval). Generally, no comments were made on the criteria specific to SFR technology, introductory chapters, or appendices of the report. Since the GIF SFR SDC is largely based on IAEA SSR-2/1 (Safety of NPPs: Design), the USNRC review largely reflected the similarities (generally in scope) and differences (in terminology and level of detail) between the USNRC and IAEA requirements for LWRs.

GIF Task Force deliberated the USNRC comments and recommendations throughout 2014-15 and adopted changes to 21 of 83 criteria and added a new definition for confinement function in the glossary in response to a recommendation. In instances USNRC comments highlight the differences between U.S. regulations and the IAEA requirements not specific to SFR technology, to stay consistent with IAEA SSR 2/1 on which GIF SFR SDC is based, original wording is retained. As for sodium chemistry, non-radioactive sodium risk is categorized as “industrial safety” as long as it does not affect the safety functions. The resolutions by the GIF Task Force were presented at the fifth GIF-IAEA SFR Safety Workshop, held June 23-24, 2015 in Vienna with presence of the USNRC and GIF Task Force representatives.

A common theme of the USNRC recommendations was to expand the scope of GIF SFR SDC to address security considerations and protection against design-basis threats such as cyber-attacks and sabotage, as well as the risk of material theft and diversion. Since the plant security and physical protection is beyond the TF scope, recommendations to include provisions to maintain adequate security postures against design basis threats are adopted only for a select set of criteria in which plant security considerations also have an impact on safety.

3.2 Revisions based on IAEA Comments

IAEA department of nuclear energy sent a letter to the GIF Chair, dated April 28, 2014, on the review results of the SDC Phase I Report. IAEA had ten comments: three are general comments and the other seven were on specific criteria. Three general comments are on “consistency of terminology with the IAEA SSR 2/1”, “comprehensiveness to cover different types of SFR system”, and “robust safety based on deterministic approach”. The seven specific comments are on “passive/inherent reactor shutdown to prevent core damage”, "importance of primary coolant inertia on the safety of SFR", "propagations of sodium-water chemical reaction", "prevention of sodium fire spread", and some suggestions on terminology and expressions. These review results were also presented from the IAEA at the GIF-IAEA SFR Safety Workshop, held June 10-11, 2014 at the IAEA, and related discussions were made along with engineering solutions to address specific SFR design criteria.

GIF Task Force deliberated the IAEA comments and recommendations for about a year, and submitted its resolutions for consideration of GIF Policy and Expert Groups in December 2014. The Task Force resolutions were presented at the fifth GIF-IAEA SFR Safety Workshop, held June 23-24, 2015 in Vienna where the IAEA reviewers and GIF Task Force representatives were present.

In general, the GIF mostly agrees with the IAEA's comments and suggestions. However, some detailed technical points (e.g. coolant inertia requirement for loss of flow accident) are being incorporated in the safety design guidelines reports that are currently under development by the GIF Task Force.[6] As the summary, GIF Task Force adopted changes to one part in Section 2, two out of 83 criteria and one definition in the glossary in response to IAEA comments and recommendations, and the rationales and explanations are provided for other points.

3.3 Revisions based on NNSA Comments

The China NNSA sent a letter to the GIF Chair dated October 10, 2013 and a supplemental letter dated January 16, 2014 on the review results of the SDC Phase I Report. The NNSA had six general comments on the SDC Report: sodium void reactivity, temperature limit of fuel cladding, sodium chemical toxicity, measures against sodium-fire and sodium-water reaction accident, consideration on external hazards, and structural variety of containment. GIF Task Force deliberated the NNSA comments in their meetings for around half-year, and submitted the responses for consideration of GIF Policy and Expert Groups.

As for the comment on "sodium void reactivity," the SDC gives due consideration on general reactivity characteristics for a fast reactor core. More important issue is to specify total core reactivity limits corresponding to plant conditions, and those detailed explanations have been incorporated in Chapter 5 of the recently completed "Safety Approach" guidelines report.[6]

Despite NNSA's call for specific design limits, the SFR SDC is intended to provide general technical requirements and do not include quantitative limits for specific design measures (e.g. temperature limit of fuel cladding). The SDC requires fuel element integrity to be maintained under the operational states in general. Technical key point is to prevent creep rupture although "temperature limit" value cannot be fixed because it varies by material choices and design ranges for fuel and cladding materials, fuel discharge burn-up, and accident sequence. The detailed but general specification will be incorporated in the safety design guideline report for structures, systems and components.[6]

As for sodium chemical toxicity, non-radioactive chemical risk is categorized as "industrial safety" as long as it does not affect the safety functions, "industrial" codes and standards are to be applied. The SDC does not include criterion on industrial safety since it falls outside the scope of IAEA SSR 2/1. As for sodium fire and sodium-water reaction, the SDC requires due considerations on coolant system and containment system, and more specific measures will be summarized in the SFR safety design guidelines reports being developed by the Task Force.[6] Consideration of external hazards and containment configuration in designs will also be incorporated in the SFR safety design guidelines reports.

3.4 Revisions based on IRSN Comments

The French IRSN provided the review results of the SDC Phase I Report on June 2015, and the related presentation and discussion were made at the fifth GIF-IAEA SFR Safety Workshop at the IAEA on June 23-24, 2015. There were overall and technical specific comments provided. As an overall point of view, IRSN pointed out that implementation of only the SDC does not guarantee the achievement of a high level of safety as the Gen-IV, and several important comments specific to safety issues related to sodium, high temperature structure, design measures for DBA/DEC were provided. GIF Task Force deliberated the IRSN comments and recommendations around one-year period and its resolutions are going to be submitted for consideration of GIF Policy and Expert Groups in 2017.

IRSN suggested adding a section dealing with SFR design differences, e.g. electrical power range, coolant system configuration (i.e. pool and loop) and fuel materials (e.g. MOX, metal), and a section to identify safety goals. As for the 27 specific comments, most of them are constructive comments and suggestions for improving the explanations and for items to be explained in detail as the level of the SDG. Important comments are on multiple failure event and relationship to DBA/DEC, identification of situation to be practically eliminated, fuel handling of minor actinide bearing fuel, drawbacks of high temperature system on structure, Leak-Before-Break approach on SFR system, fuel handling and storage for fuel assembly used in sodium, sodium chemical toxicity, best estimate plus uncertainties analyses for DBA, design measure to mitigate sodium-water reaction accident, reactor trip parameters, and role of sodium heating system.

GIF Task Force mostly agreed with IRSN's comments and suggestions. However, some detailed technical points, such that reactor trip parameters and mitigation device to reduce initial pressure peak just after the sodium-water reaction, are considered too detailed and outside the scope. The Task Force resolutions were presented at the sixth GIF-IAEA SFR Safety Workshop, held November 14-15, 2016 in Vienna where the representatives from IRSN and GIF Task Force representatives were present.

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References

[1] GIF, SDC Phase 1 Report: "Safety Design Criteria for Generation IV Sodium-cooled Fast Reactor System", GIF SDC-TF/2013/01, May 1 (2013)

[2] IAEA, 'Safety of Nuclear Power Plants: Design', SSR-2/1 (2012)

[3] USDOE & GIF "A Technology Roadmap for Generation-IV Nuclear Energy Systems", GIF-002-00 (2002)

[4] IAEA, "Defence in Depth in Nuclear Safety", INSAG-10, A report by the International Nuclear Safety Advisory Group, IAEA, Vienna (1996)

[5] IAEA, "IAEA Safety Glossary, Terminology Used in Nuclear Safety and Radiation Protection, 2007 Edition" (2007)

[6] R. Nakai, "The Safety Design Guideline Development for Generation-IV SFR Systems," Paper number 15, International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development (FR17), Yekaterinburg, Russian Federation, June 26-29 (2017).