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Comparative Analysis of the TI-RIPB and Conventional LWR Safety Analysis Reports

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1. Introduction

Globally, advanced reactors, including non-Light Water Reactors (non-LWRs), have been actively developed. Moreover, the necessity for new regulatory approaches that can effectively reflect the unique design characteristics of these advanced reactors is being recognized.

During the 2000s, the U.S. Department of Energy (DOE) pursued the Next Generation Nuclear Plant (NGNP) [1] project under the Energy Policy Act (EPAct) of 2005 [2], selecting the Very High Temperature Reactor (VHTR) as its prototype. Although the NGNP project ultimately did not reach completion, this experience demonstrated that the existing regulatory frameworks in 10 CFR Part 50 [3] and 10 CFR Part 52 [4] were insufficient to address the unique design characteristics of non-LWRs, thereby underscoring significant regulatory uncertainties.

To reduce such uncertainties and to enable the accelerated commercialization of advanced non-LWRs, the Licensing Modernization Project (LMP) [5] was initiated. The LMP developed a transparent, systematic, risk-informed, performance-based, and predictable methodology [6], culminating in the NEI 18-04 [7] and its subsequent endorsement by the NRC in Regulatory Guide (RG) 1.233 (2020) [8].

Building on the methodology established in NEI 18-04, the Technology-Inclusive Content of Application Project (TICAP) [9] was undertaken to develop detailed guidance for preparing the content of license applications for advanced non-LWR designs. TICAP primarily addressed the LMP-based safety analysis corresponding to Chapters 1-8 of the SAR. As a result of TICAP, NEI 21-07 [10] was developed and subsequently endorsed by the NRC in RG 1.253 [11].

In parallel, the Advanced Reactor Content of Application Project (ARCAP) [9], led by the NRC, concentrated on addressing Chapters 9-12 of the SAR, including site information, quality assurance, fire protection, emergency preparedness, and security plans. Together, TICAP and ARCAP supplement each other to ensure comprehensive coverage of the entire license application.

Domestically, research and development on non-LWRs have been conducted in the past [12] and is currently being pursued through public–private collaboration. [13] However, the licensing basis remains insufficient. Therefore, legal and institutional improvements are required. Above all, developing a SAR that reflects the distinctive characteristics of advanced reactors, which differ significantly from existing LWRs, is of critical technical importance. Accordingly, this paper aims to compare the structure and content of the SAR currently used for LWRs with those of the SAR proposed in RG 1.253, and focus on chapters 1-8 of the TI-RIPB SAR for comparison with the TICAP tabletop exercise reports.

2. TICAP Analysis

Following the success of the LMP and the resulting NEI 18-04, the TICAP was initiated to produce guidance for developing content for specific portions of the NRC license application SAR for non-LWR designs. TICAP generated a number of products culminating in an NRC-endorsable NEI document providing guidance on key elements of advanced reactor license applications. Table I below provides a list of TICAP products.

Table I: TICAP products

TICAP products
Fundamental Safety Functions Definition
Regulation Mapping to Fundamental Safety Functions
Safety Analysis Report (SAR) Options Assessment
LMP-Related Safety Case
Differences Between Licensing Paths
Tabletop exercises
Formulation of TI Content of Application
NEI Content of Application Guidance Document

2.1 TICAP tabletop exercises

TICAP tabletop exercises explored the application of a unique subset of the draft TICAP guidance to different non-LWR designs. These reports include example SAR content developed using the draft TICAP guidance. Furthermore, additional context about the specific design and safety case necessary to understand the example SAR content is also included. In addition, the reviews from the TICAP team are included for the example SAR content of each tabletop exercise report. In the Appendix of each report, context is provided which serve as example content that would be displayed in SAR developed using TICAP guidance.

2.1.1 TerraPower, Molten Chloride Reactor

This report describes the tabletop exercise conducted with TerraPower to explore the application of the draft TICAP guidance to the safety case for the Molten Chloride Reactor Experiment (MCRE) design. Example content for the parts of TI-RIPB SAR Chapters on Licensing Basis Events (LBEs), Safety Functions, Design Criteria, and SSC Classification, and Safety-Related SSC Criteria and Capabilities was developed.

Additionally, this report provides additional information which could be a part of TI-RIPB SAR. First, section 3.1 includes general plant and site description and explanations of systems with principal functions of MCRE. In section 3.2, there are explanations of tools, and models used to conduct tabletop exercise.

In section 3.3, the preliminary list of MCRE LBEs is provided. Furthermore, the results of preliminary safety classification of MCRE SSCs are provided in section 3.5, along with the Safety-Related (SR) SSC Criteria and capabilities, which are limited to specific MCRE SR SSCs. Also, the set of Principal Design Criteria (PDC) that was identified for MCRE using an RIPB process is displayed in Appendix B of this report.

Draft content for the SAR on LBEs is suggested in Appendix A. In Appendix B, draft content is suggested for Safety Functions, Design Criteria, and SSC Safety Classification. And draft content is suggested for Safety-Related SSC Criteria and Capabilities in Appendix C.

In summary, this tabletop exercise addressed content corresponding to the SAR chapters 1 and 2, while developing example content for the SAR which was specifically for chapters 3, 5, and 6, in comparison with the TI-RIPB SAR. [14]

2.1.2 WestingHouse, eVinci

This report describes the tabletop exercise conducted with Westinghouse Electric Company to explore the application of the draft TICAP guidance to the safety case for the eVinci micro-reactor design. A set of risk-informed, performance-based (RIPB) PDC, and feedback from the development of this content informed revisions to the TICAP guidance.

Design overview of the eVinci Micro-Reactor is provided in Section 2.2. The eVinci micro-reactor is a high-temperature Heat Pipe Reactor (HPR) and the section further describes its structural characteristics and safety systems such as Shutdown Rod System (SRS) and passive heat removal system.

Section 3 explores the development of PDC for the eVinci micro-reactor. The process begins with the identification of Fundamental Safety Functions (FSFs), which are defined as controlling heat generation, controlling heat removal, and retaining radionuclides. From these FSFs, the Required Safety Functions (RSFs) are derived through LBEs

Based on the three initiating events and possible mitigation systems (Reactor shutdown, Passive Heat Removal, and Canister Integrity), a total of 36 initial LBEs were identified. These LBEs were then evaluated through the Probabilistic Safety Assessment (PSA). The PSA defined three Probabilistic Safety Functions (PSFs) for the eVinci design, which align with the FSFs (control heat generation, control heat removal, and retain radionuclides.)

By comparing the PSA results and radiological consequences against the Frequency–Consequence (F-C) target, the LBEs were refined to include only those sequences that fall within the frequency ranges associated with Anticipated Operational Occurrences (AOOs), Design Basis Events (DBEs), and Beyond Design Basis Events (BDBEs). From this process, six representative LBEs were identified.

After the six representative LBEs were established, the RSF derivation process confirmed only one (reactivity control/shutdown reactor). However, in accordance with the NEI 18-04 and TICAP guidance, decay heat removal and containment of radioactive material were also included as RSFs. Based on these RSFs, the Required Functional Design Criteria (RFDC) were then developed, which in turn led to the establishment of the PDC.

In summary, applying the NEI 18-04 based approach resulted in a significantly smaller number of PDC compared to the RG 1.232 [15] based approach. During the process of deriving the PDC, the need to clearly define and distinguish the meaning and scope of safety functions and design criteria was identified. Furthermore, the eVinci tabletop exercise demonstrated that it is not necessary for every FSF to be mapped to an RSF, nor for at least one RSF to be derived from each FSF. [16]

2.1.3 X-energy, Xe-100

This report describes the tabletop exercise conducted with X-energy to explore the application of the draft TICAP guidance to the safety case for the Xe-100 reactor design. Example content for the parts of TI-RIPB SAR Chapter for Methodologies and Analyses, and Plant Programs were developed.

In section 3.1 general plant and site description and overview of the safety case was suggested. Next, the example SAR Chapter 2 content is provided in section 3.2 through Appendix A of this report.

In Section 3.3, the content is based on the Xe-100 Phase 0 PRA model. Internal initiating events are listed. Among them, Event tree with associated LBEs from Small Helium Depressurization (SD) are proposed. Then, LBEs that were identified in the Phase 0 PRA is listed with brief description of the event sequences, their estimated frequency and scaled dose at the Exclusion Area Boundary (EAB).

In summary, this report addresses information relate to portions of SAR chapter 1 and 3 while the example

SAR content was developed specifically for chapter 2 and 8, in comparison with the TI-RIPB SAR. [17]

2.1.3 Versatile Test Reactor

In this report, the TICAP guidance is applied to the current Versatile Test Reactor (VTR) design. The VTR project applied the LMP process described in NEI 18-04 in support of authorization for building the VTR supported by a RIPB approach. The VTR LMP application described in this report included all the major steps including documentation described in NEI 18-04, including PSA development, DBE selection, SSC Classification, Defense-in-Depth (DiD) Evaluation, and Performance of the Independent Decision-making Panel (IDP). Table II below shows comparison of terminology between DOE and NRC is also given in section 1.

Table II: DOE and NRC Terminology Comparison

VTR/DOE Term	LMP Term
Safety Basis Event 1. Anticipated 2. Unlikely 3. Extremely Unlikely	Licensing Basis Event 1. AOO 2. DBE 3. BDBE
SSC Classification	
1. Safety-Class 2. Safety Significant 3. Non-Safety	1. Safety-Related (SR) 2. Non-Safety-Related with Special Treatment (NSRST) 3. Non-Safety-Related with no Special Treatment (NST)

Section 2 provides VTR plant description and Appendix E gives description of VTR design. this information can be used in SAR Section 1.1

Section 3 presents a comprehensive review of the VTR PRA and LMP analysis including a description of key steps and outcomes. According to section 3.1, Internal events and preliminary internal/external hazards are the scope of VTR PRA. Sodium fire and seismic analysis are conducted as a result of the screening process in the preliminary hazard analysis. Using the VTR PRA results described in section 3.1, the generic LMP analyses have been performed in LBE analyses, LMP function/SSC importance analyses and LMP risk significance analyses.

In section 4, development of TICAP DID are suggested. Input form Appendix A is used. Section 4.2 provides method and results of DID for defining Safety-Significant SSCs. Section 4.3 provides method and results of evaluation of LBEs against layers of defense. However, section 4.3 states that Programmatic DID has not yet been fully developed and must be supplemented in the future through plant programs such as operations, quality assurance, and technical specifications.

Section 5 addresses the process of deriving safety functions in the VTR design and, based on them, establishing design criteria and system classification with Appendix B. RSFs were derived from the FSFs, with particular emphasis on the heat removal function as a key feature of the VTR. Each RSF was then translated into RFDC, which were subsequently established as PDC. Finally, SSC classification was performed, categorizing systems essential for carrying out RSFs as SR, systems important for risk significance or for strengthening DID as NSRST, and systems requiring no special treatment as NST.

Section 6 presents the Safety-Related Design Criteria (SRDC) and, in connection with the LBEs, defines the performance requirements that each SR SSC must fulfill, with particular emphasis on systems that perform the heat removal function, and Appendix C provides the draft SAR content based on this discussion.

Section 7 presents the criteria and capabilities for NSRST SSCs and, in connection with the LBEs, defines the performance requirements these SSCs must meet, with particular emphasis on systems that complement DID or are risk-significant, and specifies the use of Complementary Design Criteria (CDC) for these SSCs. Appendix D provides the draft SAR content based on this.

In summary, this report addresses technical results that relate to portions of SAR chapter 1, 2, and 3 while the example SAR content was developed specifically for chapter 4, 5, 6, and 7 in comparison with the TI-RIPB SAR. [18]

3. TI-RIPB SAR Analysis

3.1 NEI 21-07

As shown in Table 1, the TICAP aimed to produce an endorsable NEI document by consolidating the outcomes of its activities, including several tabletop exercises. This effort culminated in the development of NEI 21-07. This is a Technology-Inclusive guidance document for the development of SAR content for non-LWRs, based on the NEI 18-04 methodology. Table III below provides chapters of TI-RIPB SAR of NEI 21-07.

Table III: Chapters of TI-RIPB SAR based on NEI 21-07

Chapters of TI-RIPB SAR based on NEI 21-07
1. General Plant and Site Description and Overview of the Safety Case
2. Methodologies and Analyses
3. Licensing Basis Events
4. Integrated Evaluations
5. Safety Functions, Design Criteria, and SSC Safety Classification
6. Safety-Related SSC Criteria and Capabilities
7. NSRST SSC Criteria and Capabilities
8. Plant Programs

3.2 TICAP tabletop exercises vs TI-RIPB SAR

This section explains why the chapters of the TI-RIPB SAR were developed and how their content was defined. It also highlights the differences from the LWR SAR. Each TICAP tabletop exercise developed example SAR content based on the characteristics of the four reactors, whereas the TI-RIPB SAR covers all eight chapters, including those addressed in the TICAP tabletop exercises. When comparing the chapters addressed in the TI-RIPB SAR with the four TICAP tabletop exercise reports, the results can be summarized Table IV.

Table IV: TICAP tabletop exercises vs TI-RIPB SAR

TI-RIPB Chapter	MCRE (MSR)	eVinci (HPR)	Xe-100 (HTGR)	VTR (SFR)
1	○	○	○	○
2	○	X	○*	○
3	○*	○	○	○
4	X	X	○	○*
5	○*	○*	X	○*
6	○*	X	X	○*
7	X	X	X	○*
8	X	X	○*	X

'○' indicates that the report contains information relevant to that chapter.
'○*' indicates that report developed example SAR content specifically for that chapter.
'X' indicates that the chapter is outside the scope of this exercise.

3.3 LWRs vs TI-RIPB SAR

SAR is based on NUREG-0800 [19] which is a Standard Review Plan (SRP) for reviewing the SAR for LWRs. When compared with the TI-RIPB SAR, several differences can be observed. Details are suggested in Appendix A.

First, the interconnection between chapters. In the LWR SAR, each chapter is written and reviewed independently, based on the corresponding SRP chapter. In other words, the order of the chapters does not affect the review process. By contrast, in the TI-RIPB SAR, chapter 1 and 2 are independent, similar to those in the LWR SAR, but chapters 3-8 are structured sequentially in accordance with the NEI 18-04 methodology. This means that there are linkages between the chapters, where information developed in earlier chapters is utilized in the subsequent ones.

Second, there are some differences in the basis for demonstrating safety. SAR for LWRs is based on a conservative deterministic framework. Within this framework, the demonstration of safety is centered on the analysis of Design Basis Accidents (DBAs) and the application of the Single Failure Criterion. In contrast, the TI-RIPB SAR developed under NEI 18-04 and NEI 21-07 adopts an integrated approach that combines deterministic methods, PSA, and DiD.

Third, there are some differences in establishing PDC. PDC for LWRs are established by using the 55 General Design Criteria (GDC) specified in 10 CFR Part 50, Appendix A as the minimum legal requirements. And PDC for LWRs are based on the characteristics of each reactor type. In contrast, for non-LWRs, PDC for non-LWRs are established based on the ARDC or on technology-specific, non-LWRs design criteria such as MHTGR-DC and SFR-DC. In addition, RSFs derived from the analysis of LBEs, along with the corresponding RFDC, are incorporated into the PDC development process.

4. Conclusions

The SAR is technically significant as it formally demonstrates the safety and suitability of a nuclear reactor. This study further reviews the TICAP tabletop exercise reports and analyzes the example content of the TI-RIPB SAR that was developed in practice.

Through the analysis of the TICAP tabletop exercise reports, this study identified the research efforts and products aimed at addressing the licensing challenges of non-LWRs within the LWR-based regulatory framework.

Furthermore, based on a former study on the content and chapter of SAR for NEI 21-07, a comparative analysis was conducted between RG 1.253, which formally endorses NEI 21-07, and the LWR SAR. As a result, two principal differences are identified, structural differences and content differences.

The structural differences lie in the progression of the chapters. Compared with the SAR of LWRs, Chapters 3 through 8 of the TI-RIPB SAR must be followed in sequence. As for the content differences, fundamental distinctions were identified in that the basis for accident analysis is grounded in the NEI 18-04 methodology and in the approaches used to establish the PDC. A detailed explanation is provided in Appendix A.

These findings are expected to serve as a reference for future institutional improvements in the licensing of non-LWRs, as well as for the development of a domestic licensing process.

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Appendix A

Structural and content differences between conventional LWR and TI-RIPB SAR

As mentioned in Section 3.3, three differences between LWR and TI-RIPB SAR are derived from this study. Table A.I below presents comprehensive comparison of content between LWR and TI-RIPB SAR.

Table A.I: Comparison between LWR and TI-RIPB SAR

Main Topic	LWR SAR (Based on NUREG-0800)	TI-RIPB SAR (Based on RG 1.253)
Progression of the chapters	- The LWR SAR is composed of 19 chapters, each of which is written in accordance with the corresponding review guidance in the SRP and reviewed independently - Each chapter is prepared and reviewed separately, and the results of one chapter are not formally carried over as inputs to subsequent chapters	- TI-RIPB SAR of RG 1.253* is composed of 12 chapters - Chapters are sequentially and organically connected, with the results of earlier chapters serving as the basis and inputs for later ones (In particular, structure of chapters 3-8 follows the sequential and logical process of the NEI 18-04 methodology)
Approach for safety demonstration	- The LWR SAR is based on a conservative deterministic methodology, in which the demonstration of safety is centered on the analysis of DBAs and the application of the Single Failure Criterion	- TI-RIPB SAR of RG 1.253 adopts an integrated approach that combines deterministic methods, PSA, and DiD, - It demonstrates safety based on the methodologies of NEI 18-04
Approach for establishing PDC	- 10 CFR Part 50 Appendix A specified 55 GDC as the minimum legal requirements for LWRs - PDC are established by applying the GDC to the reactor and tailoring them to the specific reactor design	- Derive RSFs through the analysis of LBEs, and RFDC is then established - RFDC is used to supplement and adjust the ARDC1) and technology-specific design criteria2), leading to the final establishment of the PDC

1) RG 1.232 describes the Nuclear Regulatory Commission's (NRC's) proposed guidance on how the GDC may be adapted for non-Light Water Reactors (non-LWRs) designs. Furthermore, this RG describes the NRC's proposed guidance for modifying and supplementing the GDC to develop PDC that address two specific non-LWRs design concepts: Sodium cooled Fast Reactors (SFRs), and Modular High Temperature Gas-cooled Reactors (MHTGRs). DOE proposed a set of ARDC, which could serve the same purpose for non-LWRs as the GDC serve for LWRs. The ARDC are intended to be technology inclusive to align with the six technologies (i.e., SFRs, Lead Fast Reactors (LFRs), Gas-Cooled fast Reactors (GCRs), MHTGRs, Fluoride High temperature Reactors (FHRs), and Molten-Salt Reactors (MSRs)). [15]

2) In addition to the technology-inclusive ARDC, DOE proposed two sets of technology-specific, non-LWRs design criteria. These criteria are intended to apply to SFRs and MHTGRs and are referred to as the SFR-DC and MHTGR-DC, respectively. [15]

* Chapters of TI-RIPB SAR based on RG 1.253

1. General Plant and Site Description, and Overview of the Safety Analysis
2. Methodologies, Analyses, and Site Evaluations
3. Licensing-Basis Events
4. Integrated Evaluations
5. Safety Functions, Design Criteria, and SSC Safety Classifications
6. Safety-Related (SR) SSC Criteria and Capabilities
7. Non-Safety-Related with Special Treatment (NSRST) SSC Criteria and Capabilities
8. Plant Programs
9. Control of Routine Plant Radioactive Effluents, Plant Contamination, and Solid Waste
10. Control of Occupational Dose
11. Organization and Human-System Considerations
12. Post-Construction Inspections, Testing, and Analysis Programs