A Comparative Review of International Safety Case Development for High-Level Radioactive Waste Disposal

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1. Introduction

The safe management of high-level radioactive waste (HLW) is a crucial long-term challenge because of its radiological hazards, which persist over geological timescales. Deep geological disposal, relying on a multi-barrier system comprising engineered barrier systems and a stable host rock environment, is internationally recognized as the reference option for the long-term management of HLW [1]. The safety of a deep geological repository is demonstrated through a "Safety Case", an integrative framework that is progressively updated as site-specific data, repository design, and system understanding mature [2,3]. While the fundamental principles of safety demonstration remain consistent across nations, individual programs exhibit distinct organizational structures, procedural emphases, and methodological frameworks depending on their specific geological settings, disposal concepts, regulatory requirements, and program maturity.

Although several review studies have documented individual national safety case frameworks, a systematic comparison of the transition from early-stage, research-driven frameworks to legally binding regulatory demonstration models particularly tailored to countries in the early phase of site selection, remains limited [4]. Korea presents a unique case: while it established a preliminary, research-oriented safety case concept via KAERI in 2016, recent legislative and regulatory milestones (e.g., the enactment of the Special Act on the Management of High-Level Radioactive Waste in 2026 and updated NSSC regulatory guidelines) demand a fundamental evolution of its national safety case architecture [5,6].

The novelty of this study lies in its systematic synthesis of structural, procedural, and institutional elements across contrasting disposal programs (U.S., Switzerland, and Japan) to construct a strategic implementation roadmap for Korea. Specifically, this paper aims to: (i) dissect the functional dependencies and feedback mechanisms in mature international safety case architectures; (ii) critically evaluate the structural gaps in Korea's 2016 preliminary framework against modern regulatory demands; and (iii) formulate an actionable, phased strategy to establish a legally compliant, traceable, and socially acceptable Korean safety case.

2. Terminology

2.1. High-level radioactive waste disposal

HLW is defined as radioactive waste containing alpha-emitting radionuclides with half-lives of 20 years or longer at a concentration of at least 4,000 Bq/g and having a heat generation rate of at least 2 kW/m^3. Spent nuclear fuel designated for disposal is a representative form of HLW [7].

Deep geological disposal entails placing HLW in engineered structures within stable geological formations at depths typically ranging from 300 to 1,000 m. This approach aims to permanently isolate radionuclides from the biosphere and human access [6]. In practical repository concepts, the waste is encapsulated within corrosion-resistant, mechanically robust disposal canisters surrounded by low-permeability buffer materials (e.g., bentonite) before being emplaced in the host rock.

2.2. Safety case

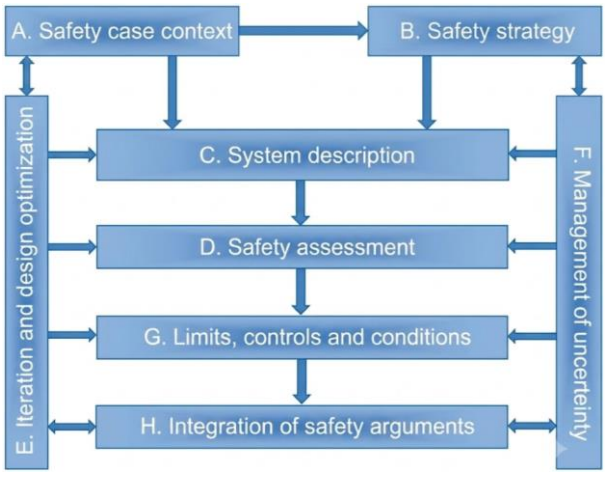

Fig. 1. Components of the safety case [2].

According to the International Atomic Energy Agency (IAEA), a safety case is defined as a collection of arguments and evidence that supports the safety of a facility or activity [2]. For radioactive waste disposal, it provides an integrated framework comprising the safety

case context, safety strategy, system description, safety assessment, uncertainty management, design optimization, and supporting scientific and technical evidence [2]. Korean regulatory criteria similarly require the demonstration of disposal safety to be supported by multiple lines of evidence [6].

3. Comparative Review of International Safety Case Development Processes

3.1. United States

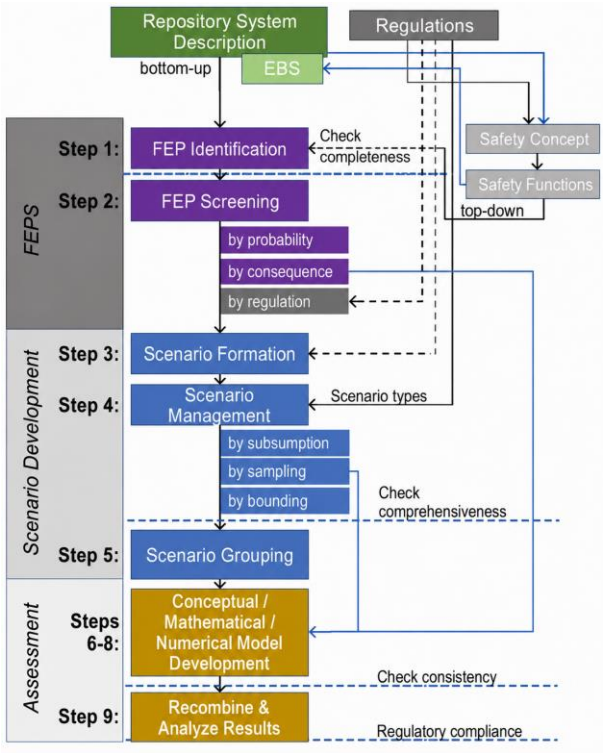

Fig. 2. Safety case development for a geological radioactive waste repository [8].

The U.S. safety case framework, synthesized from an international review of geological repository program led by Sandia National Laboratories, features a structured, dual-directional architecture as shown in Figure 2. It employs a bottom-up analytical process that flows from disposal-system information to Features, Events, and Processes (FEPs) analysis, scenario development, and performance assessment, while simultaneously applying top-down guidance derived from regulatory requirements, safety concepts, and safety functions [8].

The process begins with the repository system description, including the host-rock environment, engineered barrier system, and relevant design information. Based on this description, safety-relevant FEPs are identified using international and program-specific FEP catalogs and are subsequently screened according to their probability, consequences, safety functions, and regulatory relevance. The retained FEPs are then combined during scenario development to construct expected and alternative repository evolutions and what-if cases. These scenarios are managed and grouped according to their consequences, failure mechanisms, timing, and event sequences to establish a comprehensive final scenario set. In the assessment stage, each scenario is translated into conceptual, mathematical, and numerical models, and the calculated results are analyzed individually or recombined and compared with applicable regulatory criteria.

The principal strength of this approach is its rigorous traceability and transparency, ensuring a continuous logical link from repository-system information through FEP screening, scenario development, numerical modeling, and final regulatory evaluation, while completeness and consistency are checked throughout the process.

3.2. Switzerland

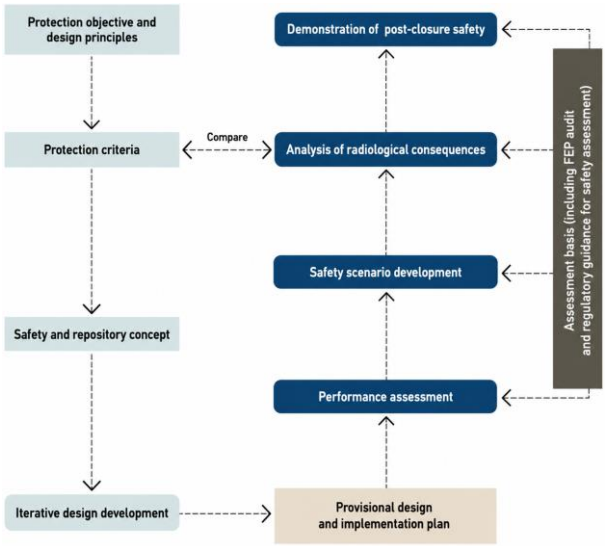

Fig. 3. Workflow for the post-closure safety case [9].

The workflow in Figure 3, developed by the Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra) in support of Switzerland's general license application, systematically integrates repository concept and design development with performance assessment, scenario development, radiological consequence analysis, and the final demonstration of post-closure safety [9]. A defining feature of the Swiss framework is its explicit feedback loop, through which assessment outcomes systematically inform ongoing repository design modifications and data collection priorities.

This entire process is anchored by a comprehensive assessment basis comprising scientific data, domain knowledge, and modeling tools, as follows:

- Conceptualization and Iterative Design: Top-level protection objectives inform safety criteria, which in turn guide the development of safety and disposal

concepts. These concepts are refined iteratively through design optimization.

- Performance Assessment and Scenario Formulation: Performance assessment verifies whether the repository's intended safety functions are maintained over time and identifies potential degradation mechanisms. Findings are then used to formulate safety scenarios that depict expected system evolutions as well as alternative what-if cases.
- Radiological Impact Analysis and Safety Demonstration: Quantitative dose and risk analyses evaluate compliance with regulatory protection criteria. The final safety demonstration synthesizes quantitative results with multiple lines of supporting evidence to confirm overall system robustness.

3.3. Japan

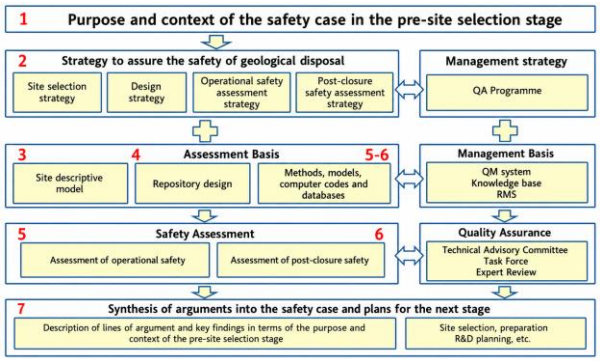

Fig. 4. Structure of the NUMO safety case at the pre-siting stage [11].

The pre-siting safety case framework developed by the Nuclear Waste Management Organization of Japan (NUMO) is shown in Figure 4. It was designed to establish a generic, adaptable structure applicable prior to final site selection. It combines technical assessment streams with institutional management systems.

The framework defines the purpose and context of the safety case and integrates safety strategy, assessment basis, safety assessment, management and quality assurance, and planning for subsequent program stages as follows:

- Safety Strategy and Assessment Basis: The safety strategy outlines approaches for site selection, repository design, operational safety, and post-closure safety assessment. The assessment basis integrates site descriptive models, repository design information, assessment methods, models, computer codes, and databases.
- Integration with Institutional Management: NUMO explicitly incorporates managerial components—such as corporate strategy, a quality assurance program, a quality management system, a knowledge base, a requirements management system, and expert review—directly into the safety case structure.

The resulting safety arguments not only demonstrate technical feasibility under generic conditions but also directly guide preparations for site selection and future R&D planning. The principal feature of the Japanese approach is the integration of technical assessment with management and quality assurance at the pre-siting stage, together with the direct use of safety case findings to guide subsequent site selection and R&D [10,11].

3.4. Korea

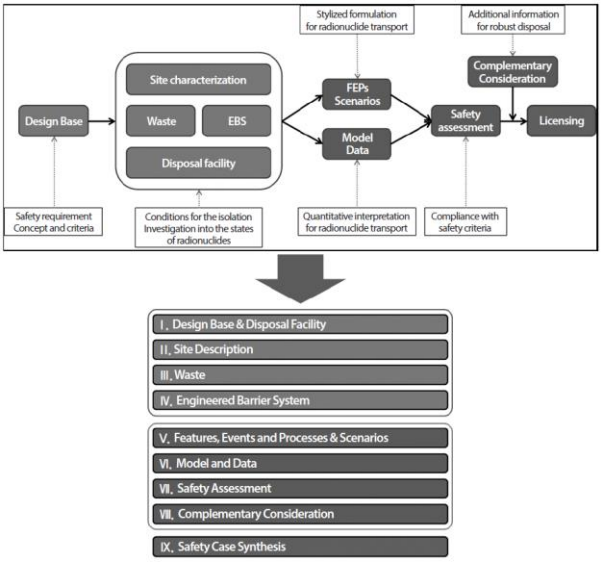

Fig. 5. Restructured safety case report framework proposed by KAERI [12].

Figure 5 shows a safety case framework proposed by KAERI in 2016 for developing a deep geological disposal concept for pyroprocessing waste using research results and site data obtained from the KAERI Underground Research Tunnel (KURT) [12]. Unlike a licensing safety case prepared by a repository implementer, this framework was research-oriented and intended to establish the disposal-system concept, organize the technical basis for safety, and identify future R&D requirements [12].

The design basis defines the safety requirements, disposal concept, and assessment criteria. Site characterization, waste, the engineered barrier system, and the disposal facility provide the principal description of the disposal system and its isolation conditions. FEPs and scenarios represent possible repository evolutions, while models and data provide the quantitative basis for radionuclide-transport analysis. Safety assessment evaluates compliance with the specified safety criteria, and complementary considerations provide additional evidence supporting the robustness of the disposal system. These elements are organized into nine report sections covering the design basis and disposal facility, site description, waste, engineered barrier system, FEPs and scenarios, models and data, safety assessment, complementary considerations, and safety case synthesis [12].

The principal feature of the Korean framework is the systematic restructuring of existing research results into a safety case format linking disposal-system information, scenarios, models, safety assessment, and supporting evidence. It also provides a basis for improving the reliability of safety-assessment input data and identifying research needs for subsequent development of the national disposal program [12].

4. International Comparison of Regulatory Requirements

The comparison presented in Section 3 should be complemented by an explicit regulatory benchmark. International guidance and national regulatory requirements do not prescribe a single safety case template; rather, they generally require a staged, evidence-based demonstration in which the safety strategy, assessment basis, safety assessment, uncertainty management, design optimization, and integration of safety arguments remain traceable throughout the repository lifecycle. This distinction is important for Korea because its research-oriented framework must ultimately be converted into a licensing-grade safety case with clear acceptance criteria, regulatory decision points, and a controlled evidence base.

At the international level, SSR-5 requires the preparation and iterative updating of a safety case and supporting safety assessment throughout the development, operation, and closure of a disposal facility. SSG-23 provides detailed guidance for integrating safety arguments, assessment results, uncertainty management, limits and controls, and multiple lines of reasoning. GSR Part 5 addresses predisposal radioactive waste management and is therefore most relevant to interfaces involving waste characterization, processing, storage, and acceptance rather than to the disposal safety case itself. Accordingly, the Korean framework should explicitly distinguish binding safety requirements, assessment assumptions, and supporting evidence and maintain traceability from each regulatory requirement to the relevant claim, evidence, model, and conclusion [1,2,13].

The NRC regulatory framework illustrates the importance of a criteria-led licensing basis. For the proposed Yucca Mountain repository, 10 CFR Part 63 establishes post-closure performance objectives addressing multiple natural and engineered barriers, individual protection, human intrusion, groundwater protection, and performance assessment. Although Part 63 is site-specific, it demonstrates the value of linking regulatory performance objectives to FEPs, scenario classes, model abstractions, parameter treatment, and compliance calculations. For geologic repositories other than Yucca Mountain, 10 CFR Part 60 provides a broader regulatory reference. A Korean safety case should therefore include a requirement-to-evidence matrix, an auditable FEP-screening record, documented model-support and software-quality-assurance arrangements, and explicit treatment of alternative conceptual models and bounding analyses [14,15].

Canada provides a particularly useful benchmark because CNSC REGDOC-2.11.1, Volume III, Version 2 is organized directly around the safety case. It addresses the safety case context, safety strategy, disposal-system description, safety assessment, uncertainty management, iteration and design optimization, limits, controls and conditions, monitoring and surveillance, institutional controls, and integration of safety arguments. The post-closure assessment is further structured around scenarios and time frames, assessment models, and interpretation of results. These elements suggest that the Korean framework should add an explicit monitoring and surveillance strategy, criteria governing the role of active controls relative to passive safety, and a formal process for evaluating the safety significance of new information [16].

In the United Kingdom, the regulatory architecture should be described as joint rather than attributed to a single organization. The Office for Nuclear Regulation regulates nuclear safety, security, safeguards, and radioactive-material transport, whereas the Environment Agency regulates environmental protection and radioactive-substances permitting in England. The two regulators conduct joint early-stage scrutiny to prepare for future licensing and permitting. A Korean licensing approach should therefore clearly define the interfaces among nuclear safety, environmental protection, safeguards, transport, and planning and land-use authorization and should integrate radiological assessment with broader environmental and institutional safety arguments [17].

Finland provides a mature example of stepwise implementation. STUK Guide YVL D.5 applies across site investigation, design, construction, operation, closure, and the demonstration of long-term safety. It requires operational safety to be addressed in preliminary and final safety analysis reports and long-term safety to be demonstrated through a safety case. During operation, a periodic safety review is required at least once every 15 years, and the safety analysis report and safety case must be updated to reflect its results. Korea should similarly maintain two linked but distinct demonstrations: an operational safety analysis for the pre-closure period and a post-closure safety case for long-term safety, with clearly defined interfaces for waste acceptance, criticality safety, thermal management, reversibility, closure, and safeguards [18,19].

Japan's program is also instructive for the pre-siting stage. NUMO developed a generic safety case to demonstrate the feasibility of geological disposal and to support staged site selection and future safety case development. However, this pre-siting safety case does not replace the site- and facility-specific safety demonstration that will be required when the project advances to regulatory review. It should instead identify the information needed to resolve site-specific

Table I: Comparative matrix of international safety case frameworks and implications for Korea.

Feature/ Dimension	United States (SNL/DOE)	Switzerland (Nagra)	Japan (NUMO)	Korea (KAERI 2016)	Proposed Strategy for Korea
Primary Objective	Compliance demonstration and support for regulatory licensing	General license application and repository design optimization	Pre-siting feasibility demonstration and preparation for site selection and R&D	Research-oriented framework and pyroprocessing-waste disposal concept development	Site-specific safety demonstration for regulatory review and licensing
Structural Flow	Bottom-up FEP-to-model process coupled with top-down criteria	Iterative loop between assessment and design refinement	Integrated framework combining technical and institutional components	Linear nine-section report structure	Closed-loop iteration linking assessment, design, and quality assurance
Traceability	High: rigorous FEP-to-scenario mapping	High: assessment-basis documentation	Moderate to high: requirements management system	Low to moderate: primarily static report structure	High: requirement-to-evidence and data-to-model-to-decision traceability
Uncertainty Management	Quantitative sensitivity analysis and parameter screening	Multiple lines of evidence and scenario analysis	Knowledge base and expert judgment integration	Qualitative or basic treatment of parameter uncertainty	Multiple lines of evidence and an integrated uncertainty management system
Institutional Integration	Quality assurance and NQA-1 compliance	Quality management system	Full QMS/RMS and corporate strategy integration	Limited: focused primarily on technical assessment	Full integration of QA/RMS and stakeholder interfaces

uncertainties, criteria for progressing through site-selection stages, and R&D needs for subsequent decisions. Korea should therefore introduce a stage-specific safety case plan defining the purpose, level of conservatism, evidentiary maturity, and regulatory deliverables for screening, site investigation, construction, operation, closure, and subsequent regulatory decisions [10,11,20].

On the basis of these benchmarks, the following additions are recommended for a future Korean national safety case: (i) a regulatory-requirement-to-evidence traceability matrix; (ii) a claim–argument–evidence structure supported by independent review and configuration control; (iii) a formal uncertainty register identifying uncertainty type, safety significance, resolution path, and residual treatment; (iv) explicit criteria for scenario completeness, model selection, model validation, and code quality assurance; (v) separate but integrated operational and post-closure safety demonstrations; (vi) a monitoring, surveillance, and closure-decision strategy; (vii) a graded approach to multiple lines of evidence, including natural analogues, laboratory experiments, in situ testing, and conservative or bounding analyses; (viii) clearly defined regulatory interfaces and decision points; and (ix) periodic safety case updates triggered by new site data, design changes, operating experience, or revised regulatory requirements. These additions would make the framework more suitable for regulatory review while preserving its value as an R&D integration tool.

5. Comparative Analysis and Synthesis

Despite differences in program maturity, geological conditions, and regulatory environments, international approaches to safety case development share a common framework. They begin by defining safety objectives and the disposal concept, followed by the establishment of an assessment basis that integrates site characterization, waste characteristics, engineered barrier systems (EBS), validated models, and supporting data. Repository performance is then evaluated through systematic scenario development and quantitative safety assessment. Finally, uncertainty is addressed through multiple lines of evidence, robustness evaluation, and iterative feedback that supports repository design optimization, site characterization, R&D activities, and subsequent regulatory and programmatic decision-making [8–12].

Accordingly, despite differences in implementation, international frameworks are consistently built upon four fundamental pillars:

- Clear specification of safety objectives and the disposal concept.
- A robust assessment basis integrating site characterization, waste characteristics, engineered barrier systems, validated models, and supporting data.

- Systematic scenario development and quantitative safety assessment to evaluate long-term repository performance.
- Integrated management of uncertainty through multiple lines of evidence, robustness evaluation, and iterative feedback into repository design, R&D, and decision-making.

Therefore, the safety case should be regarded as an iterative, transparent, and traceable framework that integrates technical information, assessment results, safety arguments, and decision-making throughout the repository development process.

The comparative analysis also provides several implications for Korea. The United States approach emphasizes maintaining transparent traceability from FEP screening through scenario development, model formulation, and regulatory evaluation [8]. The Swiss approach demonstrates the importance of strengthening feedback between safety assessment and repository design while integrating multiple lines of evidence into the overall safety argument [9]. The Japanese approach highlights the need to define the role and objectives of the safety case at each program stage and to use identified uncertainties to prioritize subsequent site investigations and R&D activities [10,11].

Although the safety case framework previously developed by KAERI incorporates the principal technical elements, a future national framework should further strengthen its regulatory applicability by establishing explicit methodologies for uncertainty management, evidence evaluation, decision criteria, regulatory interfaces, and periodic updates throughout the repository development process [12].

The comparative matrix presented in Table 1 highlights that international safety case frameworks are converging toward performance-based and risk-informed regulatory paradigms while preserving the fundamental principles of defense-in-depth and independent regulatory oversight. The analysis suggests that Korea should develop a safety case framework that reflects domestic regulatory requirements while incorporating internationally recognized best practices. Such a framework would improve regulatory consistency, enhance licensing efficiency, and strengthen public confidence in the development and implementation of deep geological disposal.

6. Conclusions

The management of high-level radioactive waste is one of the major challenges in Korea. To address this challenge, a systematic framework for deep geological disposal should be established together with a safety case that integrates the disposal concept, scientific and engineering evidence, safety assessment, and supporting arguments. This study reviewed safety case development approaches in the United States, Switzerland, and Japan and compared them with the previous Korean framework.

In addition, the comparison of international regulatory requirements shows that a licensing-grade safety case must be more than a compilation of technical studies. It must provide an auditable claim–argument–evidence structure, separate pre-closure and post-closure demonstrations, explicit management of uncertainty and model validity, defined monitoring strategies and closure decision criteria, and stage-specific regulatory interfaces. These elements are reflected to varying degrees in IAEA guidance and in the regulatory practices of the NRC, CNSC, ONR/EA, STUK, and NRA.

The United States approach emphasizes traceability from FEP identification to scenarios, models, and regulatory evaluation. The Swiss approach closely links protection objectives, repository design, performance assessment, and supporting evidence, while the Japanese approach integrates technical assessment with management and quality assurance and uses safety case findings to guide subsequent site selection and R&D. The previous Korean framework included the principal technical components but was developed primarily from a research perspective. Therefore, future safety case development in Korea should strengthen traceability, uncertainty management, feedback between assessment and design, integration of multiple lines of evidence, and periodic revision in accordance with the progress of the national disposal program.

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