Development of COmputerized Severe Accident Information AID for NPP

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1. Introduction

In the event of a severe accident at a Nuclear Power Plant (NPP), various Emergency Response Organizations (ERO) such as the Technical Support Center (TSC), Emergency Operations Facility (EOF), Operating Support Center (OSC), and Severe Accident Fast-response Expert Team(SAFE-T) are activated. These organizations implement a range of actions, including system initiation, operation, and shutdown, based on the Severe Accident Management Guideline (SAMG). Such actions play a critical role in maintaining the integrity of the reactor and the containment building [1,2].

However, severe accident scenarios are inherently complex and unpredictable. The need for coordination across multiple organizations, combined with high workload and time pressure, subjects plant operators and ERO to extreme psychological and cognitive stress. Consequently, the risk of human error, such as judgment failures, procedural omissions, or delays can increase significantly [3,4].

Unlike Emergency Operating Procedures (EOPs), which are highly proceduralized, the SAMG emphasizes strategy based decision-making. TSC is required to assess the accident conditions, select the most appropriate mitigation strategy, and communicate it to the Main Control Room (MCR) operators [2]. This process entails setting priorities, evaluating the effectiveness of potential strategies, and identifying alternative actions making the overall decision-making process more demanding and complex [5,6].

To address these challenges, Artificial Intelligence (AI) has emerged as a technology in the nuclear domain. AI is adept at modeling the nonlinear and complex behaviors of nuclear systems, enabling high-accuracy predictions and diagnostics. In the high-stress, uncertain context of a severe accident, AI-based support systems can alleviate the cognitive load on operators and mitigate human error. By providing predictive modeling and real-time analysis, these systems can enhance situational awareness, support the pre-assessment of mitigation strategy impacts, and facilitate more timely and informed decision-making [7,8].

This study introduces the Computerized Severe Accident Information AID for NPP (COSAIN), a novel support system developed to enhance the implementation of SAMG. We detail the system's design principles, key functionalities, and its potential to improve operator performance during severe accident conditions.

2. Identification of Key Technologies for COSAIN

This section presents the procedure and results of identifying key technologies to support the implementation of SAMG. The derivation of these technologies was conducted systematically according to a step-by-step analytical framework. In this study, particular focus was placed on the Mitigation-03 guideline, and the research outcomes are primarily centered on supporting this specific SAMG strategy through digitalization.

2.1 Analysis of SAMG and Its Linkage with Calculation Sheets

The first step in identifying the key technologies involved a systematic analysis of the SAMG, specifically the Control, Mitigation, Monitoring, and Termination guidelines. For each guideline, the required mitigation systems and key plant parameters were identified. Based on this analysis, the strategic action items and their corresponding calculation sheets were examined to understand the structural linkage between procedural steps and supporting technical data.

This analysis aimed to clarify the actual flow of information utilized by operators and ERO, and to understand the information based decision-making framework. As a result, essential parameters for SAMG execution were extracted, including safety parameters, severe threat parameters, and termination parameters. In addition, the entry conditions for each guideline were systematically identified.

For example, the Mitigation-03 guideline is initiated when the core exit temperature exceeds 371.1 °C. This guideline involves the implementation of severe accident mitigation strategies using various safety systems, including the Safety Injection System (SIS), Chemical and Volume Control System (CVCS), Containment Spray System (CSS), Shutdown Cooling System (SCS), and so on.

Furthermore, during the execution of Mitigation-03, Calculation Sheets 01 through 04 are closely integrated with the guideline. These sheets serve as critical decision-making aids by supporting assessments of strategy implementation feasibility and determining the priority of candidate actions.

2.2 Analysis of SAMG Operational Strategy

To analyze the operational strategies of SAMG, various severe accident scenarios were simulated using the Modular Accident Analysis Program (MAAP). Among these, the Large Loss of Coolant Accident (LLOCA) scenario characterized by coolant loss and a consequent rise in core exit temperature was selected as the representative case for this study.

In the LLOCA scenario, the loss of primary system coolant leads to a rapid increase in core temperature, eventually meeting the entry conditions for severe accident management and triggering the need for SAMG execution. Due to this direct correlation with SAMG activation, the scenario was deemed appropriate for detailed analysis in this research.

Based on the selected scenario, the information required to operate systems and components under SAMG was identified. Specifically, all necessary parameters, system conditions, and operational states for the activation of each component were identified and analyzed in detail. This process enabled a quantitative identification of the technical requirements essential for implementing mitigation strategies in actual accident conditions.

2.3 Derivation of key Technologies for COSAIN

Based on the results of the two preceding analyses, a total of eight key technologies (KT) were identified to support the effective implementation of SAMG. These technologies were proposed as key components in the design of the Human-System Interface (HSI) for COSAIN.

KT-1) Real-time Monitoring of Safety and Severe Threat Parameters: Provides real-time monitoring, trend visualization, and alerts for critical plant parameters to enhance operator situational awareness.

KT-2) Real-time Monitoring of SAMG Termination Conditions: Supports decision-making by continuously monitoring plant status against predefined termination criteria.

KT-3) Equipment Availability Support: Displays the real-time availability of mitigation-related equipment, visualizing its operability status based on system-level analysis.

KT-4) SAMG BISI (Bypassed and Inoperable Status Indication): Presents a simplified overview of system lineups in a mimic format, highlighting unavailable components within a flow path for rapid recognition of operational constraints.

KT-5) Prediction of Plant Parameters: Employs AI models to forecast key plant parameters with uncertainty estimation up to two hours in advance.

KT-6) Mitigation Action-based Prediction: Predicts future plant trend based on a selected mitigation action, allowing operators to pre-assess the effectiveness and potential side-effects of a selected strategy before implementation.

KT-7) Dynamic Calculation Table: Integrates real-time data and operator inputs into a digital format to support complex calculations required for strategy execution, improving usability and response efficiency.

KT-8) Plant Database (DB): Functions as the central data hub, collecting and sharing real-time plant data across all COSAIN modules to ensure synchronized information access.

3. Derivation of Functional Requirements and Functional Design of COSAIN

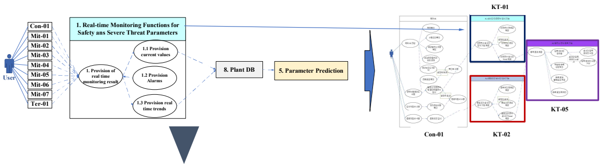
This section presents the process of defining functional requirements and developing the functional design for the COSAIN HSI. Functional requirements were identified using Use Case Diagrams (UCDs), while the functional design was systematically developed using the IDEF0 (Integration Definition for Function Modeling 0) methodology. While this process was applied to all eight key technologies, this paper uses "Real-time Monitoring of Safety & Severe Threat Parameters" (**KT-1**) as a representative example to provide a detailed analysis of its functional structure and requirements.

3.1 Design of Use Case Diagram for Functional Requirement Derivation

The UCD is a component of the Unified Modeling Language (UML) that visually represents how a system interacts with external users (actors). A UCD clearly illustrates the relationship between the system's functions (use cases) and the actors who use them. It is commonly employed during the system analysis and design phases of software development and serves as an effective method for visually expressing system requirements [9, 10].

In this study, a UCD was designed to illustrate the **KT-1**. The function comprises the following three primary capabilities: 1) Real-time display of current values, 2) Alarm generation when threshold values are exceeded, 3) Provision of parameter trend information.

This function is utilized in the Control Guideline to monitor safety and severe threat parameters, and in the Mitigation Guideline, it is applied to assess entry conditions, monitor ongoing plant states, and determine termination criteria. The UCD for this function, along with related functions and the derived sub-functions, is illustrated in Fig. 1.



No.	Identified Function
1	Provision of real-time monitoring results for safety and severe threat parameters
1.1	Providing current values of parameters
1.2	Providing parameter alarms
1.3	Providing real-time trends of parameters

Fig. 1. Use Case Diagram Result for KT-1.

3.2 IDEF0 Modeling for Functional Design

IDEF0 is a function-based modeling method used to structurally represent systems and visualize the interactions between functions. It defines function execution flows based on the ICOM (Input, Control, Output, Mechanism) framework, where inputs enter from the left, controls from the top, mechanisms from the bottom, and outputs exit to the right [11, 12].

In this study, the **KT-1** was selected as the target, and a detailed functional design was conducted for the three previously identified requirements. The value display function automatically collects parameter data from the plant database, serving as input for both alarms and trend analysis. The alarm generation function compares current values against predefined thresholds based on SAMG settings and generates alerts accordingly. The trend information function provides not only current and historical data but also predicted values using AI- and MAAP-based forecasting models.

The IDEF0 model for this function is illustrated in Fig. 2.

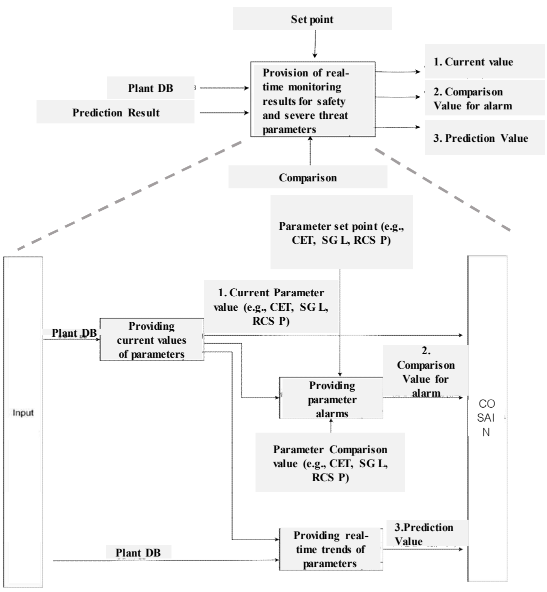


Fig. 2. IDEF0 Result for KT-1.

4. Design of COSAIN Interface

The COSAIN proposed in this study is a HSI designed to support the execution and operation of the SAMG. COSAIN provides a structured digital interface that assists emergency response teams and operators in decision-making during severe accident conditions. The COSAIN interface consists of the following seven main screens:1) COSAIN Main 2) Mitigation Main, 3) Equipment Selection within a Mitigation Guideline, 4) Plant Parameter Prediction Based on Selected Mitigation Means, 5) COSAIN BISI, 6) Dynamic Calculation Sheet, and 7) Summary View for Overall Plant System Status Monitoring.

Each interface screen is designed to guide users through the procedural and strategic aspects of SAMG execution, while also visualizing critical plant data and predictions to enhance situational awareness and reduce operator burden.

4.1 COSAIN Main

The COSAIN Main interface provides real-time access to key information for SAMG execution. It collects and visualizes safety parameters, severe threat parameters (**KT-1**), and termination criteria (**KT-2**) from the plant database (**KT-8**). To support proactive decision-making, historical data and AI-based predictive graphs (**KT-5**) are also displayed. From this interface, users can navigate to each Mitigation Guideline via selection buttons on the left. Fig. 3 shows the COSAIN Main Interface.

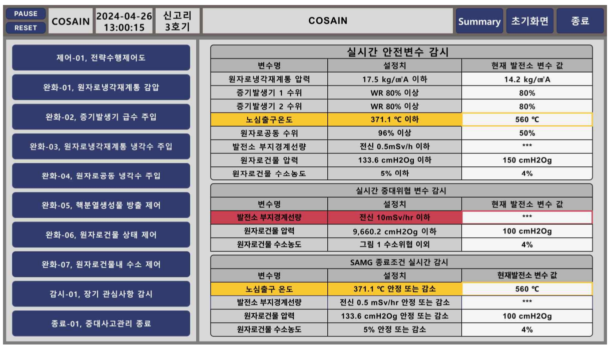


Fig. 3. COSAIN Main Interface

4.2 Mitigation Main

This interface provides integrated access to all information required to execute a specific mitigation strategy. It displays entry conditions, severe threat parameters (**KT-1**), available mitigation systems (**KT-3**), and currently selected actions. It also includes navigation buttons to key functional modules such as Plant Parameter Prediction (**KT-6**), BISI (**KT-4**), and the Dynamic Calculation Sheet (**KT-7**). A simplified system schematic visualizes all relevant systems, with component availability status indicated by a three-color code: Green (Available), Red (In Use), or Gray (Unavailable). For active systems, the interface graphically illustrates the flow path, enabling intuitive assessment of system operations. Fig. 4 shows the Mitigation Guideline Main Interface.

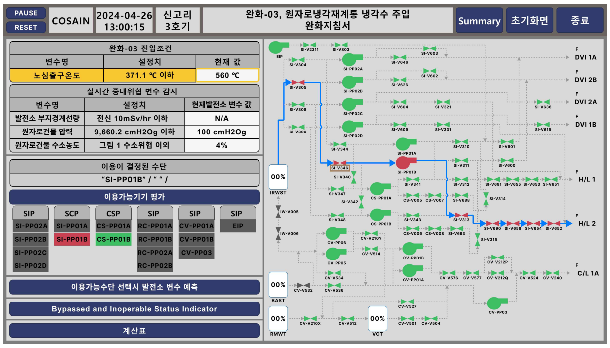


Fig. 4. COSAIN Mitigation Guideline Main Interface

4.3 Equipment Selection within a Mitigation Guideline

This interface supports the assessment of equipment availability (**KT-3**) required by a mitigation guideline, allowing users to select appropriate equipment for strategy implementation. Equipment status is denoted by symbols: "●" (Available), "X" (Unavailable), or "***" (Data Not Available). The evaluation results are shown in a status panel, and if a device is available, users can select a "Use" button to incorporate it into the strategy. When an equipment's status is changed via the BISI interface (**KT-4**), that information is automatically synchronized, and the availability status on this interface is updated accordingly. Fig. 5 shows the Equipment Selection Interface.

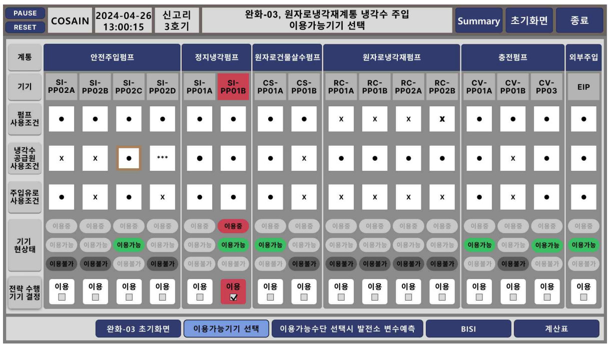


Fig. 5. COSAIN Equipment Selection Interface

4.4 Plant Parameter Prediction Based on Selected Mitigation Means

This interface implements the Mitigation Action-Based Prediction technology **(KT-6)**. It provides AI-based forecasts of key plant variables, simulating the expected plant response if a selected mitigation system were applied. This technology integrates Autoformer, Temporal Convolutional Network (TCN), Variational Autoencoder (VAE), and conditional generative models to provide real-time predictions of NPP system trends, incorporating the impact of mitigation actions [13]. The results are presented graphically, categorized into two groups: 1) parameters indicating successful strategy execution, and 2) parameters indicating potential negative impacts. For instance, a case might illustrate the predicted results of applying pump SI-PP02A during an LLOCA scenario. This feature supports a more quantitative and objective evaluation of mitigation options prior to implementation. Fig. 6 shows the Plant Parameter Prediction Interface.

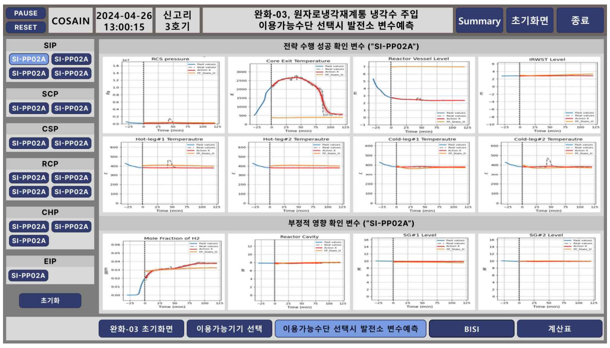


Fig. 6. COSAIN Plant Parameter Prediction Interface

4.5 COSAIN BISI

This interface provides a visual representation of equipment lineups (**KT-4**) within plant systems to support strategy selection. Unlike traditional EOP BISI, which assesses individual components, COSAIN's BISI offers comprehensive information for the entire flow path in a mimic-style interface. This allows users to quickly identify which components within a flow path may be causing operational limitations. Moreover, any devices overridden in the BISI interface are automatically reflected in the Equipment Selection interface. Fig. 7 shows the SAMG BISI Interface.

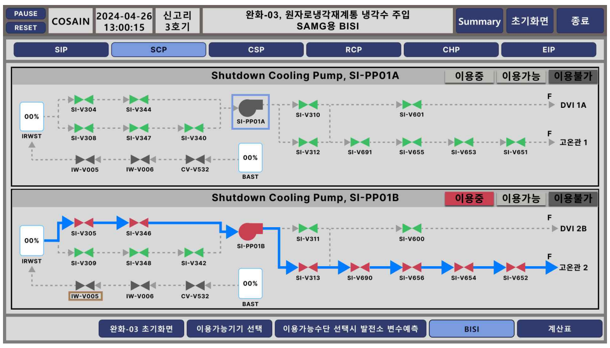


Fig. 7. COSAIN SAMG BISI Interface

4.6 Dynamic Calculation Sheet

The Dynamic Calculation Sheet (**KT-7**) is designed to enhance user convenience by utilizing real-time data for SAMG-related calculations. The left side of the interface displays key input parameters in real time, while the right side visualizes corresponding data trends through graphs. These graphs incorporate historical data and AI-based predictions, enabling a more informed assessment of variable behavior over time. Fig. 8 shows the Dynamic Calculation Sheet Interface.

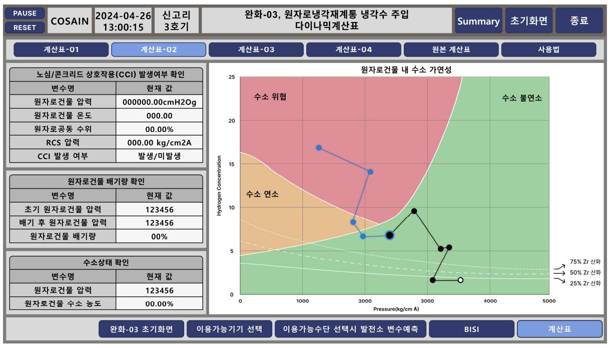


Fig. 8. COSAIN Dynamic Calculation Sheet Interface

4.7 Summary

The Summary interface provides a comprehensive overview of the current status of all equipment relevant to SAMG, based on the availability evaluations (**KT-3**) conducted within each mitigation guideline. From this interface, users can also directly access each guideline, allowing for centralized monitoring and streamlined navigation. Fig. 9 shows the System Status Summary Interface.

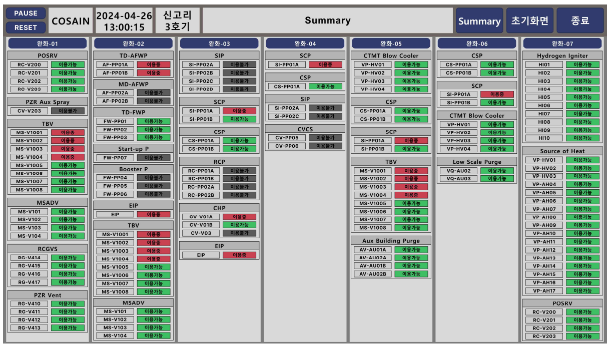


Fig. 9. COSAIN Summary Interface

5. Conclusions

This study proposed the design and key components of COSAIN, a digital support system developed to enhance the execution of SAMG during severe accident conditions.

COSAIN integrates real-time plant data to support decision-making by ERO and MCR operators. It provides key functions required for implementing mitigation guidelines, including safety parameter monitoring, equipment selection, strategy impact prediction, and calculation support. In particular, the system incorporates AI models trained on MAAP-based accident scenarios, enabling the prediction of future plant behavior and pre-assessment of strategy effectiveness prior to execution.

Key features such as BISI, the Dynamic Calculation Sheet, and AI-based forecasting are designed to reduce the cognitive burden on users and improve situational awareness in high-stress environments.

Future work will focus on developing a prototype applicable to real-world operating conditions and conducting user evaluations to verify the practical effectiveness and usability of the system.

Acknowledgement

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REFERENCES

[1] International Atomic Energy Agency (IAEA). Severe Accident Management Programmes for Nuclear Power Plants: Safety Guide. IAEA Safety Standards Series No. NS-G-2.15, Vienna, 2009.
[2] Cho, J., Lee, S.H., Kim, J., & Park, S.K. Framework to model severe accident management guidelines into Level 2 probabilistic safety assessment of a nuclear power plant. Reliability Engineering & System Safety, 217, 2022.
[3] U.S. Nuclear Regulatory Commission (NRC). The Effects of Stress on Nuclear Power Plant Operational Decision Making and Training Approaches to Reduce Stress Effects. NUREG/CR-6127, Washington, D.C, 1994.
[4] OECD Nuclear Energy Agency (NEA). The Human Factor in Nuclear Power Plant Operation. OECD-NEA, Paris, 1988.
[5] U.S. Nuclear Regulatory Commission (NRC). Emergency Response Procedures and Guidelines for Beyond Design Basis Events and Severe Accidents (NEI 14-01, Rev. 1). Washington, D.C., 2016.
[6] OECD Nuclear Energy Agency (NEA). Severe Accident Management. CSNI/R(2001)7, Paris, 2001.
[7] M. Najar and H. Wang, Enhancing Nuclear Power Plant Safety and Reliability: Integrating Explainable AI for Operator Performance Optimization, Proceedings of PSAM17 & ASRAM2024, Sendai, Japan, 2024.
[8] E. Gursel and A. Khojandi, Using Artificial Intelligence to Detect Human Errors in Nuclear Power Plants, Nuclear Engineering and Technology, vol. 55, no. 2, pp. 456–467, 2023.
[9] M. Fowler, UML Distilled: A Brief Guide to the Standard Object Modeling Language, Addison-Wesley, 3rd ed., 2003.
[10] K. El Miloudi and A. Ettouhami, A Multiview Formal Model of Use Case Diagrams Using Z Notation: Towards Improving Functional Requirements Quality, Mathematical Problems in Engineering, vol. 2018, Article ID 6854920, 2018.
[11] D. F. Martin, Integration Definition for Function Modeling (IDEF0), National Institute of Standards and Technology (NIST), FIPS PUB 183, Gaithersburg, MD, 1993.
[12] A. Chari, An IDEF0 Modelling Approach to Enhance Manufacturing Value Chain Resilience, Chalmers University of Technology Research Publication, pp. 1–18, 2023.
[13] Hyojin Kim et.al., Action-based prediction for Nuclear Power Plants at Severe Accident. KNS Autumn Meeting, Korea, 2025