

LLM-Supervised Framework for Determining Operator Available Time

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1. Introduction

In conventional probabilistic safety assessment (PSA), high-pressure safety injection (HPSI) is generally modeled as a simple success/failure branch. Unlike failure to start (FTS), which occurs on demand, failure to run (FTR) occurs after successful initiation; thus, plant conditions at the failure time may affect how urgently aggressive cooldown (ASC) must be initiated [1]. ASC is a recovery strategy used during a small-break loss-of-coolant accident (SLOCA) when HPSI is unavailable [2,3]. To better represent the time-dependent interaction between HPSI FTR and the time available for ASC, a detailed success boundary may therefore be needed. Constructing this boundary, however, requires a large number of repeated thermal-hydraulic (TH) code calculations.

The use of large language models (LLMs) in nuclear-engineering applications, including automated system modeling, has become an active research area [4,5]. This study develops an LLM-supervised automation framework for analyzing the time available for operator action and the associated success boundary. The framework supports TH input generation, case execution, simulation review, error recovery, and systematic boundary identification. By automating tasks that would otherwise be performed manually, the framework provides a practical means of identifying timing-dependent success boundaries.

2. Methods and Results

2.1 Scenario Scope

The case study examined how the time available for an operator to initiate ASC changes with break size and HPSI FTR time under SLOCA conditions. For the present analysis, the mission time was set to 24 h. Both HPSI trains were credited until a common FTR, and the model also credited one low-pressure safety injection (LPSI) train, two safety-injection tanks (SITs), and one atmospheric dump valve (ADV) for each steam generator. The target cooldown rate was modeled as approximately -55.6 K/h. The TH calculations were performed using the MARS-KS code [6]. A simulation case was classified as OK only if it reached the 24-h mission time and maintained the peak cladding temperature (PCT) below 1477 K. A case was classified as core damage (CD) when the PCT reached 1477 K.

2.2 Development of the LLM-Supervised R2-TH Framework

Figure 1 summarizes the developed framework. The plant nodalization, code manuals, steady-state input, and scenario description are used to generate a base accident input; however, the target accident deck was not provided to the LLM. The LLM checks source consistency and performs a short smoke run. If syntax errors occur, it rechecks the source materials, corrects the input, and repeats the run until the code executes normally. The base accident model was then confirmed through an independent comparison of the human and LLM-prepared inputs.

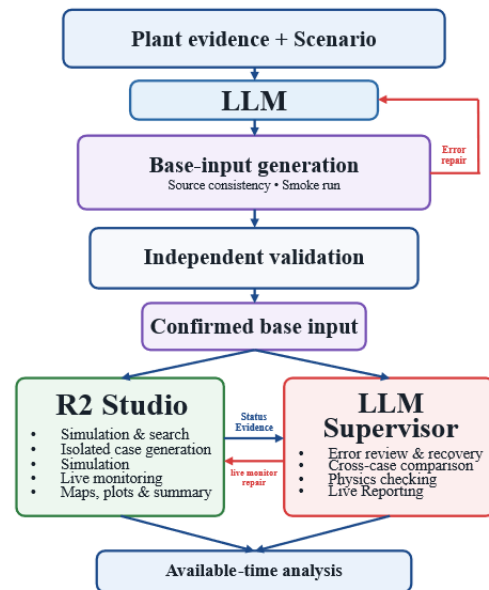


Fig. 1. LLM-supervised R2-TH framework.

Starting from the confirmed input, R2 Studio deterministically generates and executes isolated cases while displaying live status and estimated completion time. It searches the target parameter space to identify the success boundary, after which the results are classified and used to generate maps and summaries. In parallel, the LLM supervisor monitors R2 Studio and automatically retries cases that encounter transient execution errors, such as Windows access violations. If execution fails because of an input syntax error, the LLM corrects the syntax in real time without altering the physical variables and requeues the corrected case.

Also, as the simulations proceed, it compares results across cases in real time and reports their trends and physical consistency.

2.3 Case Study

The proposed framework was applied to determine the HPSI operating threshold and the time available for operator initiation of ASC. For each break size (B), T_{th} was defined as the earliest HPSI FTR time for which the case remained OK without ASC. Physically, T_{th} is the minimum time for which HPSI must remain available before FTR so that CD can still be avoided without ASC. Under this condition, natural depressurization can subsequently lower the primary-system pressure to the setpoints for LPSI and SIT injection. For a given break size and HPSI FTR time, T_{avail} was defined as the maximum time after HPSI FTR within which ASC could be initiated and the case would still be classified as OK. It therefore represents the operator action window for ASC.

For the 1.5-in SLOCA, as shown in Fig. 2, T_{th} was determined to be 14.6 h, approximately 12 h later than that of the 2.0-in case. This difference appears to be associated with the slower depressurization for the smaller break, which delays LPSI and SIT injection and requires HPSI to remain available longer.

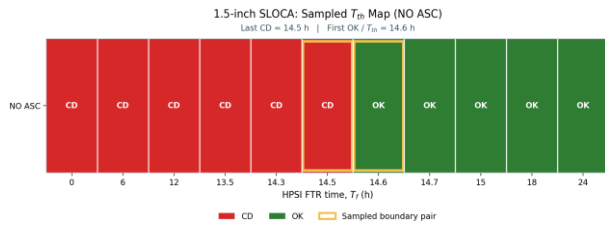


Fig. 2. Example of T_{th} determination for a 1.5-in SLOCA.

From the perspective of the time available to the operator, T_{avail} for the 1.5-in case increased as HPSI FTR occurred later, as shown in Fig. 3. Also, the 1.5-in case generally provided a longer time window for ASC initiation than the 2.0-in case. This behavior appears to reflect the slower response and more gradual progression of the smaller-break transient. Taken together, these results show that the operator action window depends on the plant state at HPSI FTR and provide a time-dependent representation of the success boundary for subsequent operator-action modeling.

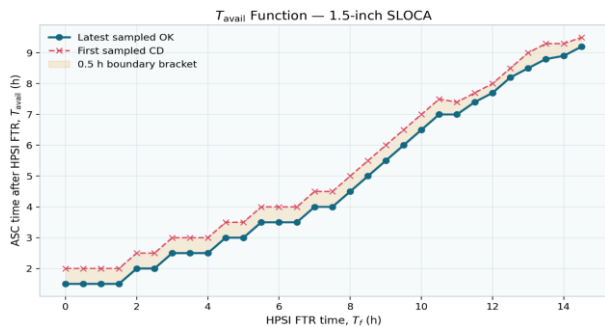


Fig. 3. Example of T_{avail} determination for a 1.5-in SLOCA.

3. Conclusions

This study developed an LLM-supervised R2-TH framework to automate success-criterion analysis for assessing the time available for operator action. The framework covers the workflow from TH input generation to operator available time evaluation and reduces the manual burden associated with large timing studies. Comparison of the LLM-prepared and human-prepared inputs showed that they produced matching simulation results. Application of the framework to the SLOCA cases further showed that T_{th} depends on break size, while T_{avail} varies with both break size and HPSI FTR time. Future work will extend the validation to a broader range of accident scenarios, introduce LLM-guided adaptive sampling near the success boundary, and develop a quantitative method for incorporating the resulting success-boundary functions into PSA models.

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