# Preliminary Study for Branch Probability Estimation in Level 2 PSA with DICE and MELCOR

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**Abstract:** Since 2016, the Republic of Korea has established a systematic framework for preventing and mitigating accidents at nuclear power plants under accident management plans. A critical aspect of this framework is the tight collaboration between Deterministic Safety Analysis (DSA) for severe accidents and Probabilistic Safety Assessment (PSA) to ensure the achievement of quantitative safety goals. Level 2 PSA is evaluated using a combination of Containment Event Tree and Decomposition Event Tree for a more detailed analysis. The branches in these trees vary depending on severe accident phenomena and the success of safety functions. The branch probabilities are important for calculating the results of Decomposition Event Tree and Containment Event Tree.
This paper aims to demonstrate the process of estimating branching probabilities through dynamic event tree analysis, underscoring the method's applicability. DICE(Dynamic Integrated Consequence Evaluation), a dynamic event tree analysis tool developed by Kyung Hee University, has presented a procedure for confirming event sequence detail for design basis accidents. In this research, the integration with MELCOR and DICE using ACF(Analytical Control Function) has been completed. This integration is expected to facilitate the extraction of various implications from calculation results through large-scale simulation. The accuracy of DICE-MELCOR is verified by benchmarking it against the MELCOR standalone results. This study established a large-scale simulation environment using DICE-MELCOR, allowing for the investigation of various accident scenarios through the variability of accident scenarios.

**Keywords:** Dynamic Event Tree Analysis, Level 2 PSA, DICE-MELCOR, ACF

## 1. INTRODUCTION

In 2016, South Korea established a systematic framework for preventing and mitigating nuclear power plant accidents through the introduction of accident management plans as part of the amendment to the Nuclear Safety Act. According to the Act, the safety of power plants must be demonstrated through probabilistic safety assessment (PSA), with target criteria requiring new reactor designs to satisfy a core damage frequency (CDF) of 1e-5/year and a large early release frequency (LERF) of 1e-6/year. To achieve this, a Level 2 PSA for severe accidents is essential. Level 2 PSA evaluates the frequency and amount of radioactive material released into the environment due to core damage, which requires an analysis of severe accident phenomena. Severe accidents are conditions with high temperatures, high pressures, and core damage, making it difficult to understand and verify phenomena through empirical testing. Instead, phenomena are simulated using codes (e.g., MELCOR, MAAP), but uncertainties in phenomenology and a lack of experimental data introduce inherent uncertainties in the results.
To date, PSA has been a systematic method for demonstrating the safety of power plants and effectively mitigating accidents, with significant research conducted worldwide. However, some studies[1,2,3] point out that PSA has difficulty effectively reflecting (1) the nonlinear behavior of plant accidents, (2) the variability of accident scenarios due to equipment failures, (3) human actions over time, and (4) interactions among systems, humans, and plant states. Especially in Level 2 PSA, assigning branch probabilities to evaluate the final radioactive release amounts in the Dynamic Event Tree (DET) carries significant uncertainties due to uncertainties related to severe accidents, which remains an issue to be addressed[4,5,6].
The DET facilitates the integration process of DSA and PSA, supporting Level 2 PSA by analyzing realistic plant accident scenarios. The DET is a methodology that couples deterministic safety analysis-based physical models with probabilistic methods of plant systems to simultaneously consider the time-varying plant state and equipment effects. Notably, DET develops scenarios based on random equipment failures and human actions without predefining accident scenarios, allowing for a variety of accident scenarios to be identified. Additionally, discrete settings of random probability distributions enable re-evaluation of pre-conducted PSA calculations.

In this paper, we established a large-scale simulation environment by integrating the DET tool, DICE, with the MELCOR code, which can simulate severe accident phenomena. We analyzed the "RCS Fail" heading, which represents a severe accident phenomenon involving the failure of the RCS(Reactor Coolant System) boundary under high temperature and high-pressure conditions. To link DICE with MELCOR, we utilized MELCOR's ACF feature and generated accident scenarios based on the Monte Carlo Event Tree (MCET) method[7]. The goal of this preliminary to supplement Level 2 PSA by estimating branch probabilities through statistical processing of these scenarios.

## 2. DEVELOPMENT OF DICE-MELCOR

DICE is a tool developed by Kyung Hee University in South Korea that supports DET and has previously been used in conjunction with the regulatory verification safety analysis code (MARS-KS 1.5) to perform Level 1 PSA[8]. In this paper, we conduct research in conjunction with MELCOR to support Level 2 PSA. This chapter provides a brief explanation of DICE and introduces the method of linking it with MELCOR.

### 2.1 Structure of DICE

DICE consists of four modules: a physical module that simulates plant accident scenarios, a diagnosis module responsible for diagnosing plant conditions and activating appropriate equipment, a reliability module that simulates equipment failures and recoveries to handle equipment variability, and a scheduler that handles information exchange between these modules[9,10,11]. The recent research trends and application methods for each module are as follows.

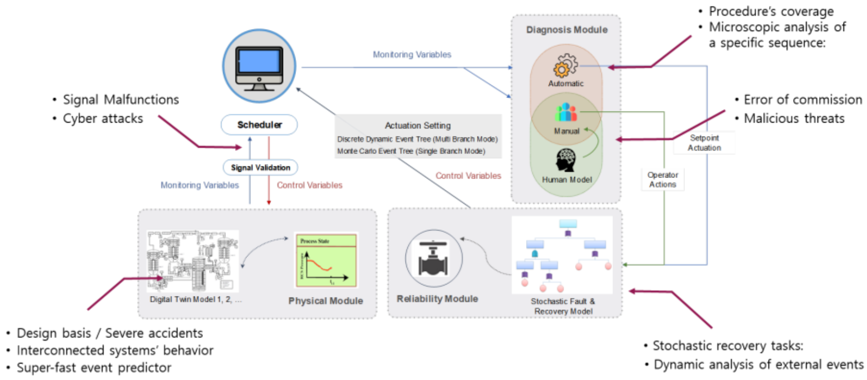


Figure 1. Schematic Figure of DICE

- Physical module: Utilizes MELCOR's ACF function for Level 2 PSA analysis.
- Diagnosis module: Separates the manual diagnosis module responsible for operator actions, allowing users to apply their desired model or methodology.
- Reliability module: Reflects equipment failures due to external events and is currently developing a separate external event module.

### 2.2 Coupling Methods in DICE-MELCOR

The physical module is
designed to simulate plant accident scenarios. In the past, when coupling with MARS-KS, it used the interactive variable function and linked via the DLL(Dynamic Link Library) method. The linking method with MELCOR varies depending on the version. While 1.8.x versions used the PVM(Parallel Virtual Machine) and MPI(Massage Passing Interface) methods, 2.2.x versions can be linked using the dynamic link program provided by MELCOR. In MELCOR 2.2.x, there are two linking methods[12]: using UDF(User-Defined Control Function) and ACF(Analytical Control Function). The following are the characteristics of each method:

| UDF | ACF |
|---|---|
| • Applicable from MELCOR version 2.1.6544 onwards.<br>• The number of user-defined functions is limited to 10.<br>• All UDF functions have 5 parameters.<br>• Suitable for expressing specific user functions, but cannot implement the exchange of variable values between MELCOR and other user programs. | • Provides all linking functions using the CF package.<br>• Suitable for implementing the exchange of variable values between MELCOR and other user programs.<br>• Allows linking variable values of each MELCOR package defined by the user with external user programs through "dynamic_link" in MELCOR input. |

The physical module must not only calculate to plant state but also transfer system monitoring variables to the diagnosis module through the scheduler. To check the full-scope variables of the plant, the linking was performed using the ACF. The following algorithm was implemented to allow real-time input and output of MELCOR CF(Control Function) values by selecting the monitoring and control variables in MELCOR's Control Function to link with DICE. Figure 2 is the pseudo-code for the ACF input data in MELCOR and its linkage with external programs, and Table 1 shows the MELCOR variables that can be linked with ACF.

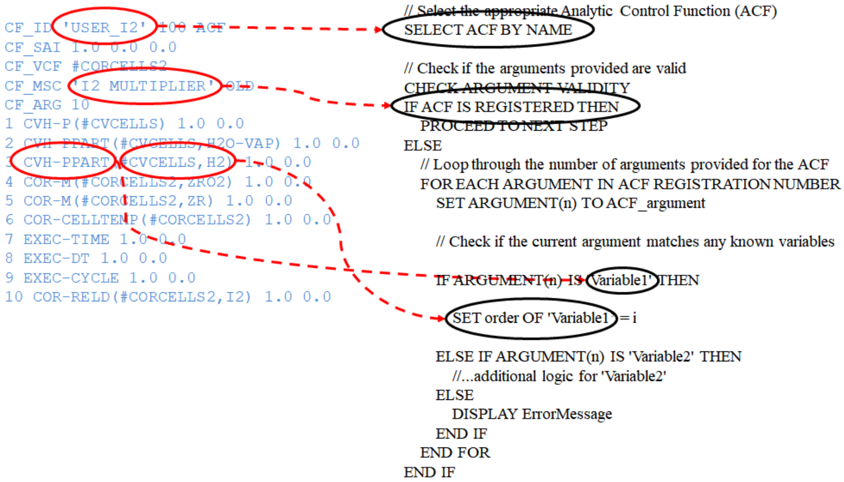

Figure 2. DICE-MELCOR coupling algorithm(using ACF)

Table 1. MELCOR Variables Available for ACF(Gray: Not Usable, Green: Under Update)[12]

| Package | Available Variable |
|---|---|
| CVH (Control Volume Hydrodynamics) | CVH-P, CVH-CPUT, CVH-ECV, CVH-PPART, CVH-TOT-E, CVH-VIRVOL, CVH-X, CVH-CVP, CVH-BETATA... |
| FL (Flow Paths) | FL-EFLOW, FL-I-MFLOW, FL-VEL, FL-MCH-TORQUE, MACCS-RHONOM, ... |
| HS (Heat Structures) | HS-CPUC, HS-DELM-POOL, HS-ITER-FREQ, HS-QFLUX-POOL, HS-TEMP, HS-CPUE, HS-DELM-STEAM, HS-RE-POOL, HS-QTOTAL-ATMS, HS-CPUR, HS-MASS-FLUX, ... |
| COR (Core Behavior) | COR-ZQ, COR-QCNV, ROD-DAM-FLAG, COR-TUQ, COR-CELLMASSFU, COR-VOLFRRAC, COR-RADHEATRATEHS, COR-H2MASSPROD, COR-CELLMASS, COR-CELLMASSCL, COR-CELLTEMP, COR-AXLHEATRATEHS, COR-ZROX-TLEFT, COR-TOTMASS, COR-CELLMASSCN, COR-MLTFR, ..., COR-VOL-FLU, COR-EMWR-RAT, COR-SS-DAMAGE, COR-VSTRESS, COR-HTC, COR-VOL-FLUB, ... COR-REL-ENGY-ERR, COR-M-LP, COR-MASS-DISCARD, COR-V-UP, COR-T-UP, COR-REL-ENGY-ERM, COR-M-UP, ... |
| RN (Radionuclide Behavior) | RN1-VCND, RN1-XMRLSER, RN1-MDT, RN1-GSDW, RN2-CPUC, RN2-VFLT-BUR, RN1-CPUC, RN1-TOTMAS, RN1-TMDTT, RN1-MMDD, RN2-CPUE, RN2-DFBUB-W, RN1-CPUE, RN1-TYCLAIR, RN1-TMDTR, RN1-GSDD, RN2-CPUR, RN2-DFBUB-A, RN1-CPUR, RN1-AMG, RN1-DHTOT, RN1-PH, RN2-CPUT, RN2-DFBUB-V, RN1-CPUT, RN1-VMG, RN1-DHCOR, RN1-IOP, RN2-AMFLT, RN2-DFBBT-W, RN1-ATMG, RN1-AML, RN1-DHCAV, RN1-IOT, RN2-RAFLT, RN2-DFBBT-V, RN1-ARMG, RN1-VML, RN1-DHDEP, RN1-IOD, RN2-VMFLT, RN2-DFBBT-A, RN1- |

| | |
|---|---|
| | VTMG, RN1-ADEP, RN1-DHATM, RN1-CAT, RN2-RVFLT, RN1-DEPHS, RN1-VRMG, RN1-VDEP, RN1-DHPOL, RN1-CAD, RN2-AMFLTS, RN1-TOTRES, RN1-ATML, RN1-ATMT, RN1-AMGT, RN1-TMCAT, RN2-VMFLTS, RN1-ARML, RN1-ATMR, RN1-CVCLT, RN1-TMCAR, RN2-FLT-QTOT, RN1-VTML, RN1-VTMT, RN1-TYCLT, RN1-MCA, RN2-FLT-QLOS, RN1-VRML, RN1-VTMR, RN1-CVTOT, RN1-MMDC, RN2-VFLT-TMP, RN1-XMRLSE, RN1-TMT, RN1-TYTOT, RN1-GSDC, RN2-VFLT-RAD, RN1-XMRLSET, RN1-TMR, RN1-MMDW, RN1-RESUSPND, RN2-VFLT-THR |

## 3. DICE-MELCOR CALCULATION

### 3.1. Code Coupling Validations

To verify the consistency between the standalone MELCOR results and DICE-MELCOR calculations, the steady state was evaluated from -2,000 seconds to 0 seconds. It was assumed that a loss of offsite power occurred at 0 seconds to perform the verification between DICE-MELCOR and standalone MELCOR.

Assumptions

- It is assumed that if power is not restored within 10 minutes after a loss of offsite power, it leads to a station blackout (SBO) event. Therefore, a loss of offsite power is initially assumed.
- After the loss of offsite power, the reactor must be successfully shut down to proceed to a station blackout event. Therefore, it is assumed that equipment such as reactor shutdown and reactor coolant pumps stop normally immediately after the event.

From 0 seconds to 100 seconds after the steady state, calculations are performed with all safety systems needed to mitigate the loss of offsite power and station blackout events set to be non-operational, except for the turbine-driven auxiliary feedwater pump. The left side of Figure 3. compares the peak cladding temperature results from standalone MELCOR and DICE-MELCOR calculations, while the right side shows the results when the turbine-driven auxiliary feedwater pump is activated at 0 seconds.

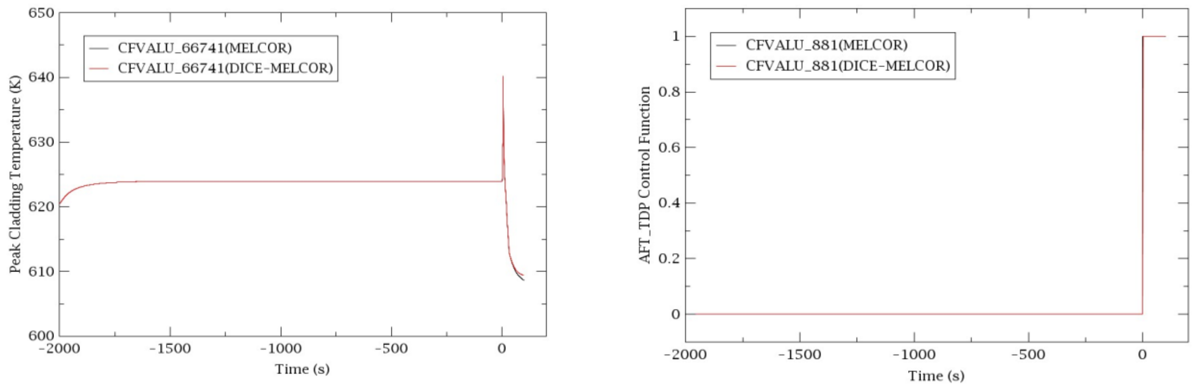


Figure 3. DICE-MELCOR/MELCOR Standalone V&V Result
(Left: PCT, Right: AFT_TDP Control Function)

### 3.2. L-M(Larson-Miller) Parameter

To estimate branch probabilities for the 'RCS Fail' category, which is RCS boundary breaks under high-temperature and high-pressure conditions, it is necessary to establish the criteria for RCS boundary failure. In this study, we use the pipe stress analysis model (PIPE-STR) and the Larson-Miller Creep Rupture model (LM-CREEP) embedded in MELCOR to evaluate creep rupture of the pressure boundary. The LM-CREEP function assesses cumulative damage based on the rupture time $t_R$ provided by the Larson-Miller Creep Rupture Failure model. The rupture time $t_R$ is expressed in Equation 1, where $P_{LM}$ is the Larson-Miller parameter, $T$ is the temperature of the thermal structure, and $C$ is a material property constant. The parameter $P_{LM}$ is expressed in Equation 2, where the values vary according to the material properties, and $t_R$ is defined by the PIPE-STR function. The PIPE-STR function, a function of pipe thickness and pressure, is defined in

Equation 3, where $P_i$ and $P_o$ represent the internal and external pressures of the pipe, respectively, and $R_i$ and $R_o$ represent the internal and external radius of the pipe, respectively.

$$t_R = 10^{(\frac{P_{LM}}{T} - C)} \tag{1}$$

$$P_{LM} = min[a_1 \log_{10}(\sigma_e) + b_1, a_2 \log_{10}(\sigma_e) + b_2] \tag{2}$$

$$PIPE - STR(t) = \frac{(R_o^2 + R_i^2)P_i - 2R_o^2 P_o}{(R_o + R_i)(R_o - R_i)} \tag{3}$$

$$LM - CREEP(t) = \int \frac{dt}{t_R(t)} \approx \sum \frac{\Delta t_i}{t_R(t_i)} \tag{4}$$

To evaluate the creep rupture of the RCS pressure boundaries, specifically the hot legs, pressurizer surge lines, and steam generator tubes, the LM-CREEP function was implemented for each pipe.

### 3.3 Case Study for RCS Fail Branches

Using DICE-MELCOR, two simulations were conducted with input settings designed to show distinct differences in the event of a station blackout.

First Simulation(CFVALU_79300_1st)
- Assumes a station blackout occurs at 0 seconds, and all safety systems become unavailable due to power loss despite the generation of engineering safety system activation signals. However, the turbine-driven auxiliary feedwater pump, powered separately by batteries, operates. The scenario continues with a failure to restore power, leading to a battery depletion and pump shutdown 7 hours after the incident.

Second Simulation(CFVALU_793002nd)
- Assumes a station blackout occurs at 0 seconds, with the operator immediately opening the atmospheric relief valve. The plant power is restored within an hour, enabling the safety systems to operate.

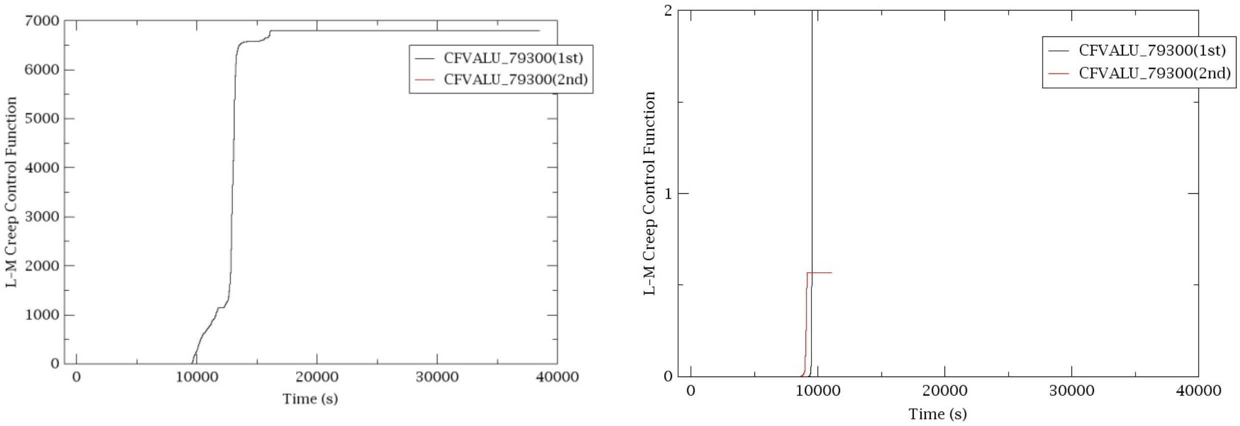


Figure 4. L-M Parameter for Hot Leg in Accident Scenario (Left: Original, Right: Enlarged)

In Figure 4, on the left side, it appears that the hot leg L-M Parameter in the second simulation does not increase. However, when scaled up (Figure 4, right side), it can be observed that the second simulation also rises to approximately 0.55. Since it does not reach 1, it is ultimately determined that the piping does not creep.

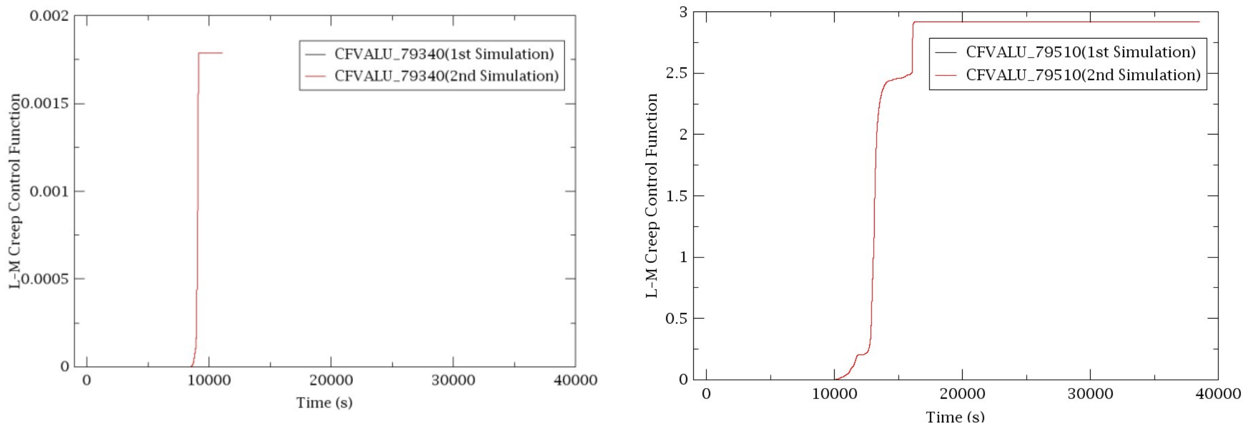


Figure 5. L-M Parameter for Surge Line and SG tube in Accident Scenario

(Left: SG tube, Right: Surge Line)

When comparing Figures 4 and 5, in the first simulation results, the L-M Parameter clearly reaches 1 in both the hot leg and the surge line. In Figure 5, the L-M Parameter reaches 1 first in the hot leg, indicating that the hot leg ruptures in this scenario. In the second simulation results, the L-M Parameter does not reach 1 in any range, resulting in an RCS No Fail outcome.

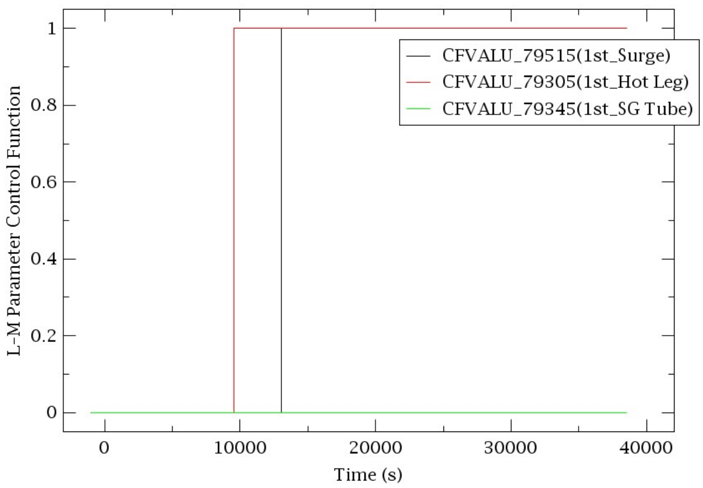


Figure 6. L-M Parameter for 1st Simulation

Figure 6 shows a Control Function that becomes true when the L-M Parameter exceeds 1, indicating the point of rupture. For example, if CFVALU_79510 represents the L-M Parameter value for the surge line, then CFVALU_79515 becomes true when it exceeds 1, indicating the rupture of the surge line. In Figure 6, it can be observed that approximately 10,000 seconds after the incident, the L-M Parameter for the hot leg reaches 1, and for the surge line, it reaches 1 at approximately 13,000 seconds. In the case of the steam generator, the L-M Parameter does not reach 1 by the end of the incident. Therefore, the hot leg ruptures before the surge line in this scenario, indicating a hot leg rupture accident. Similarly, in the second simulation, as shown in Figures 4 and 5, the L-M Parameter does not reach 1.

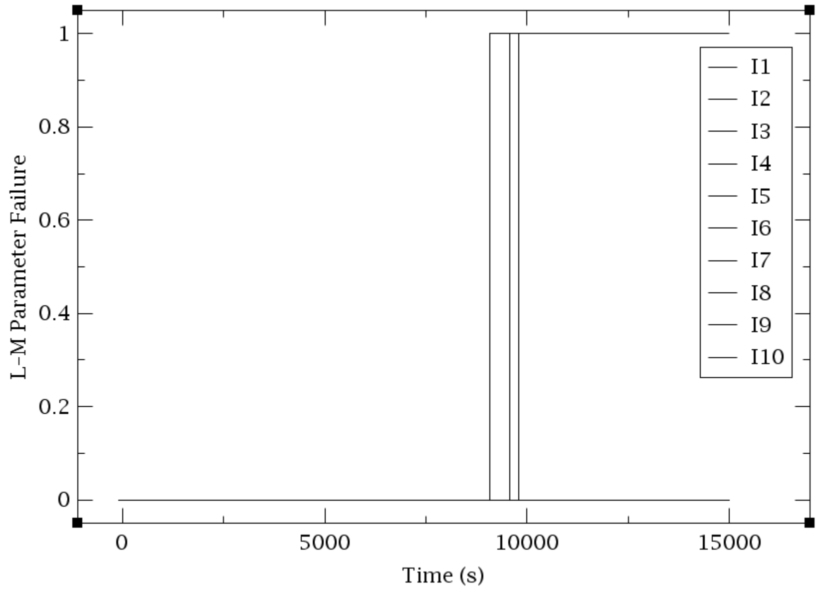


Figure 7. Multi-simulation results(Hot leg)

DICE-MELCOR can calculate multiple simulations simultaneously through parallel computing. Figure 7 shows 10 cases from a large number of simulation results. Among the 10 scenarios, 3 scenarios experienced hot leg creep rupture, suggesting that the branch probability of the example model can be estimated at 30%.

## 5. CONCLUSIONS

Level 2 PSA models severe accident phenomena using simulation codes due to inherent uncertainties. However, calculating branching probabilities for event trees remains challenging. To address this, this paper develops DICE-MELCOR, leveraging the DET method to support Level 2 PSA through large-scale simulations. By controlling MELCOR inputs and outputs with DICE using the ACF, the model randomly incorporates equipment failures and operator actions over time. V&V of DICE-MELCOR against MELCOR Standalone was conducted, and a case study on RCS Fail, a Level 2 PSA heading, was performed. Future work will involve grouping results from large-scale simulations to estimate branching probabilities for RCS Fail, thus enhancing Level 2 PSA. For future research, to achieve more accurate calculations, it is necessary to further improve the accuracy of the MELCOR model, increase the number of simulations, and perform additional statistical post-processing.

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