Development of Post-processing Method for Extracting Success Criteria in Dynamic Event Tree Analysis

Yongjoon Lee[a], Yuntae Gwak[a], Dohun Kwon[a], Gyunyoung Heo[a*]
[a]Kyung Hee University, Gyeonggi-do, Republic of Korea
[*]: corresponding author, gheo@khu.ac.kr

Abstract: Event tree (ET) analysis, one of the key components of Probabilistic Safety Assessment (PSA), is a method of analyzing the progress of accidents by dividing scenarios into success/failure when specific conditions (physical variables, device operation, etc.) are met. Looking at the ET generation process, after analyzing variables affecting the event sequence through Deterministic Safety Analysis (DSA), conservative success criteria are established based on simulation results. Next, the probabilities of the end states are calculated by combining the success or failure of the success criteria, which is called the quantification process of PSA. On the other hand, Dynamic Event Tree (DET) analysis including transition of event sequence, can discover new insights into success criteria by simultaneously performing DSA during the PSA quantification process. Dynamic Integrated Consequence Evaluation (DICE), developed by Kyung Hee University, can perform DET analysis using the Monte Carlo Event Tree (MCET) method. Due to the characteristic of Monte Carlo simulation, event scenarios can be flexibly explored by reflecting the variability of related variables, and various success criteria can be extracted by creating branching points depending on whether the device is operating. However, post-processing method is needed to organize the simulation results of the MCET method to analyze the variables affecting the event sequence to group scenarios, automatically classify the operation of the device, and extract the success criteria accordingly. The purpose of this study is to develop a post-processing method for extracting success criteria in DET analysis using DICE. Analysis of obtaining the event sequences was conducted utilizing MARS-KS (as a physical module in DICE). Post-processing algorithms and outcomes are then presented, which extract success criteria based on device operation in simulations. As a case study, this research presents process of converting the MCET results into binary ET used in conventional PSA using a post-processing method that extracts success criteria in Large Break Loss of Coolant Accident (LBLOCA).

Keywords: Probabilistic Safety Assessment, Event Tree, Dynamic Event Tree Analysis, Success Criteria

1. INTRODUCTION

Probabilistic Safety Assessment (PSA) plays a crucial role in the safety evaluation of large-scale facilities such as nuclear power plants. Event Tree (ET) analysis, one of the key components of PSA, is a method of analyzing the progression of accidents by dividing scenarios into success or failure based on specific conditions (physical variables, device operation, etc.). The point at which a scenario branches based on the fulfillment of certain conditions is referred to as a 'branching point.' Traditional ETs utilize expert knowledge to predefine the sequence in which multiple branching points will occur.

Examining the ET generation process, variables affecting the event sequence are first analyzed through Deterministic Safety Analysis (DSA), and then conservative success criteria are established based on simulation results. This process involves using expert knowledge to analyze variables influencing the event sequence, setting success criteria based on simulation outcomes, and constructing the ET accordingly. The success criteria derived from expert knowledge may lead to an optimistic assessment, but it is often a conservative judgment when compiling the ET based on the physical outcomes of the system's end state.

On the other hand, DET analysis using Dynamic PSA can obtain new insights into success criteria by performing DSA in real-time during the PSA quantification process.

When performing DET analysis, the combination of transition states and time steps in complex systems increases exponentially, leading to practical difficulties in generating and analyzing DETs [1]. Due to these characteristics, a separate post-processing algorithm is necessary to organize simulation results, analyze variables affecting the event sequence, group scenarios, automatically classify device operations, and extract corresponding success criteria.

To support user interpretation of the large-scale results from DET analysis tools, various methods such as the K-shortest-paths algorithm and fuzzy C-means clustering algorithm have been applied [2,3,4].

The purpose of this study is to develop a method for extracting success criteria based on the operational state of devices by utilizing post-processing algorithms that leverage the characteristics of Monte Carlo simulation in DICE. The DET analysis tool, DICE, is currently coupled with MARS-KS and MELCOR to calculate physical variables, providing a basis for analyzing and extracting success criteria by reflecting simulation results in real-time. As a case study, the analysis to obtain event sequences was conducted using MARS-KS (the physical module in DICE), and success criteria were extracted from the results of LBLOCA, Design Basis Accident (DBA). This study focuses on presenting the process of converting DETs generated using DICE into the binary ET format used in traditional PSA and automatically extracting success criteria.

2. SUCCESS CRITERIA FOR DYNAMIC EVENT TREE ANALYSIS

2.1. Success Criteria

The ET in PSA is a process of identifying significant accident sequences that lead to core damage based on initiating events for large-scale nuclear facilities. Depending on the initiating events, headings are established to organize the corresponding safety systems and operator action timings needed to maintain the plant's end state in a safe condition. Success criteria are then determined based on the number of operating devices and the timing of operator actions for each heading. A binary ET format, which includes this information, organizes accident sequences to provide information about the end state, indicating either safety or failure (core damage in Level 1 PSA).

Examining the process of generating a binary ET, variables affecting the event sequence are analyzed through Deterministic Safety Analysis (DSA). Based on simulation results, conservative success criteria are then established. In the quantification process of PSA, the probabilities of end states are calculated by combining the success or failure of these success criteria. For example, in a Level 1 PSA accident sequence analysis, the necessary safety functions required to keep the core in a safe condition for each initiating event are identified. The required safety systems and operator actions are organized as headings of the ET. The accident scenarios are then logically constructed in a binary tree format by branching based on the success or failure of each heading. The next step involves identifying the systems required to maintain the safety functions mentioned earlier, defining these systems as ET headings, and determining the success criteria and operational timings for each system based on the initiating events. Key considerations include time, function, and system dependencies. Typically, the headings are arranged in chronological order of the relevant system operations. Once the systems, success criteria, and heading order for each initiating event are determined, all possible accident sequences are logically derived based on the success or failure of these headings. For DBA (Level 1 PSA), this process ultimately concludes with either core damage or safe reactor shutdown. By utilizing expert knowledge to analyze variables affecting the event sequence, setting success criteria based on simulation results, and constructing the ET accordingly, this method effectively organizes and quantifies the possible outcomes.

2.2. Dynamic Event Tree Analysis

DET analysis is another approach of traditional PSA, evaluating how a system responds and evolves over time, and how dynamic situations impact the event sequence. With advancements in computing power and numerous methodologies, the DET has become possible to dynamically perform safety assessments of complex systems to solve large-scale problems, such as nuclear power plants. While DSA assumes the failure of specific systems in a deterministic manner, DET analysis simultaneously incorporates both deterministic and probabilistic features. In other words, DET analysis integrates (couples) the concepts of DSA and PSA. It can construct various event sequences, or scenarios, which include the success, failure, and recovery of devices, considering the entire progression from the initial occurrence of an accident to its end state. By simulating the entire process, DET analysis takes into account the system's states and variables according to the flow of event transitions, providing a more realistic analysis of the accident progression.

2.3. Dynamic Event Tee Analysis Tool - DICE^{TM}

DICE is a tool that supports DET analysis. DICE facilitates DET analysis by supporting two methods: the Dynamic Discrete Event Tree (DDET) method, which uses a multi-branching mode, and the Monte Carlo Event Tree (MCET) method, which uses a single-branching mode. The DDET method has a relatively deterministic nature, achieved through the grouping of variability into probability distributions. In contrast, the

MCET method generates more probabilistic results by individually sampling random numbers from the probability distributions. To implement the DDET and MCET methods, DICE couples several independent modules: the physical module, diagnostic module, reliability module, and scheduler. Each module plays an independent role and interacts with each other to generate branches [5].

As shown in Figure 1, after the occurrence of an initial event, branching rules are determined by the diagnostic module. Branches such as t_1 and t_2 are generated by automatic diagnosis, while t_3 is generated by manual diagnosis. The branches created by automatic diagnosis differ from those generated by manual diagnosis. Branches generated through automatic diagnosis are primarily determined by the number of flow paths in the safety system (since the MARS-KS code, the physical module, is used, branches are created based on the number of flow paths). On the other hand, branches created by manual diagnosis involve setting the operator's action time by the user, creating branches from immediate action to time-based intervals, or considering operator non-response. The branching points are generated by considering these factors and obtaining the operator action failure rates from the reliability module.

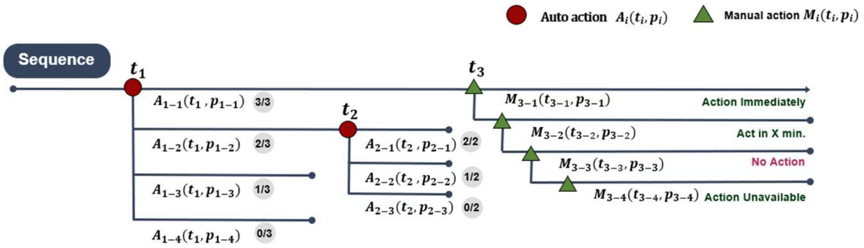

Figure 1. Example of Branch Generation in DICE

3. POST-PROCESSING METHOD

The single-branching mode of DICE, due to the characteristics of Monte Carlo simulation, allows flexible exploration of event scenarios by reflecting the variability of related variables. It generates branching points based on whether the device is operating and extracts various success criteria. In a previous study, author demonstrated the method to extract conditional success criteria, when, user select physical variables and setpoints of the end state. Scenarios were able to be then sequentially classified based on the number of devices and operator action times [6]. This approach can be successfully applicable to DBAs such as LBLOCA (guillotine break) which does not have complicated operator actions in its ET.

In this study, this is extended such that DETs generate branches based on the operational status of devices and operator action times, leading to transitions in event sequences. Figure 2 is a flow chart for organizing the results of the DET analysis tool to extract success criteria.

First, the results of the DET analysis tool are organized to construct the DET, which is the process of STEP 1. Then, in STEP 2, from the extensive DET results, similar event sequences are grouped by backtracking the headings from the end state. In STEP 3, user-defined engineering margins are applied to convert the grouped DET into a binary ET format. Finally, in STEP 4, success criteria are extracted for each heading in the binary ET. The flow chart is composed of these steps, with detailed explanations provided below.

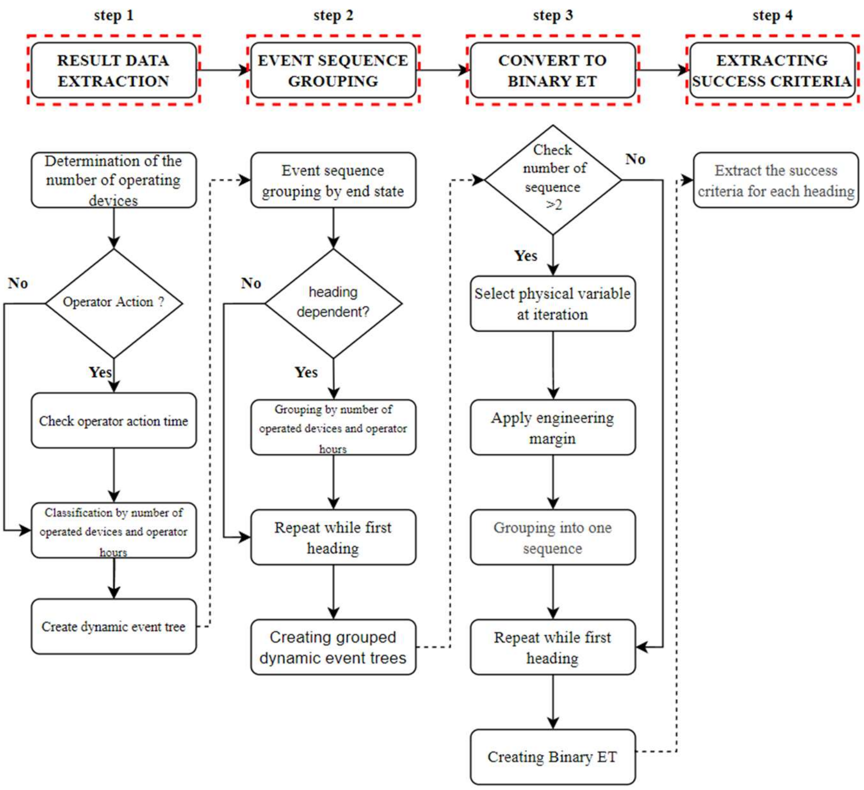

Figure 2. Post-Processing Method Flow Chart

STEP 1: RESULT DATA EXTRACTION

Since the branching point in the DET analysis tool are generated based on the number of operating devices and operator action times, the DET is created by organizing and classifying the number of operating devices, operator actions, and operator action times from the first heading to the end state.

STEP 2: EVENT SEQUENCE GROUPING

To group similar event sequences in the DET, start from the end state and assess whether the branches divided at each heading impact the event sequence. Then, backtrack the event sequences to the headings before the initial event, repeating this process.

STEP 3: CONVERT TO BINARY ET

To generate a binary ET, during the grouping process in STEP 2, event sequences were grouped based on the number of operating devices and operator action times. However, if the branches being grouped affect the previous or subsequent headings, they are not grouped but maintained as separate branches. To generate a binary ET, during the grouping process in STEP 2, event sequences were grouped based on the number of operating devices and operator action times. However, if the branches being grouped affect the previous or subsequent headings, they are not grouped but maintained as separate branches. This means that the branches are grouped into more than three event sequences. The diagnostic module of DICE generates branches based on variables related to physical phenomena when unfolding scenarios. Therefore, applying user-defined engineering margins, group the more than three grouped event sequences into two for each heading repeatedly, creating a traditional PSA ET format.

The diagnostic module of DICE generates branches based on variables related to physical phenomena when unfolding scenarios. Therefore, applying user-defined engineering margins, group the more than three grouped event sequences into two for each heading repeatedly, creating a traditional PSA ET format.

STEP 4: EXTRACTING SUCCESS CRITERIA

Finally, the information obtained from the ET includes the end state of the event sequence, the trend of important variables over time for each event sequence, and the status of systems or devices, and operator actions impacting the event sequence over time. By using this information from the generated binary ET, success criteria for each heading are extracted.

Figure 3 illustrates an example of converting a DET, which branches based on the number of operating devices and the timing of operator actions, into a binary ET. In this example, a total of 12 event sequences are grouped into 4 event sequences, creating a format similar to that of a traditional PSA ET.

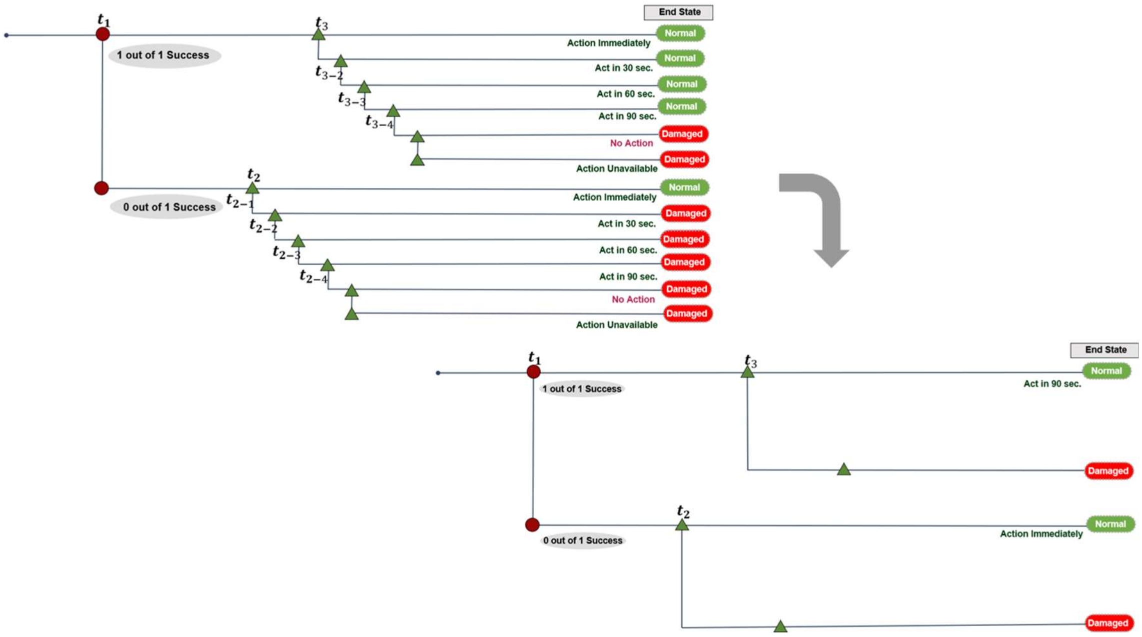

Figure 3. Example of Grouping Using the Post-Processing Method

4. CASE STUDY

A reference model for extracting success criteria is presented using a hypothetical 3-loop reactor model in DICE's physical module, MARS-KS. For the LBLOCA, the MCET method with 100 iterations was used. The case study model involves a 6-inch Cold Leg Break LBLOCA in a hypothetical 3-loop reactor, which includes LPSI (Low Pressure Safety Injection) and SIT (Safety Injection Tank). The branching points were set at the start of LPSI injection and the start of SIT pump operation.

The pump operation was set to begin when the pressure in the three steam lines dropped below 12.5 MPa, and the SIT injection initiation was set when the pressure in the three accumulators fell below 4.3 MPa. Because the actual failure rates of SIT and the LPSI pump are used in the analysis, and each device's real failure rate data would make it difficult to reflect accident scenarios, the failure rates of each device were increased. The total number of LPSI pumps SIT paths are three. Due to the structural characteristics of a nuclear power plant, in the event of LOCA caused by a cold leg break, the actual injection into the cold leg containing the break differs from the branching signal and the actual injection from a thermal-hydraulic perspective. For instance, even if the branching signal indicates that all three LPSI pumps have been injected, in reality, only two out of the three pumps inject. Therefore, to propose a method for extracting success criteria, the analysis was conducted based on the actual injection into the intact cold leg from a thermal-hydraulic perspective, distinguishing it from the branching signal. Figure 4 shows a graph of the CT (Cladding Temperature) using the reference model. Although the mission time continues up to 525 seconds, the injection times for LPSI and SIT are approximately 23 seconds and 31 seconds respectively, so the scale was adjusted. Figure 4 shows the CT change graphs using the reference model. Although the mission time continues up to

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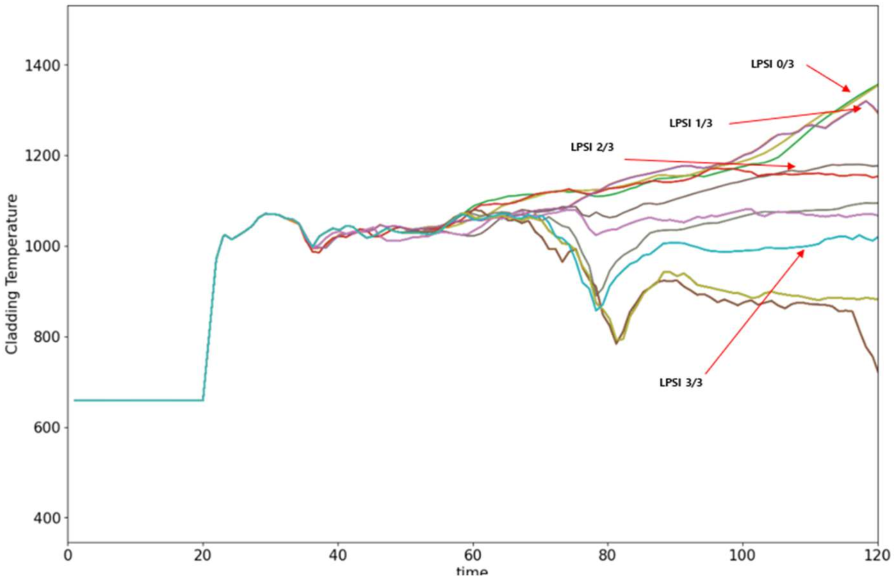

Figure 4. 100-branch CT graph using DICE

In this study, STEP 1 was applied to organize the results, and then the DET was constructed. Subsequently, STEP 2 was applied to the results of the DET to group similar event sequences by backtracking the headings from the end state in the order of SIT and LPSI. This process generated a DET as shown in Figure 5.

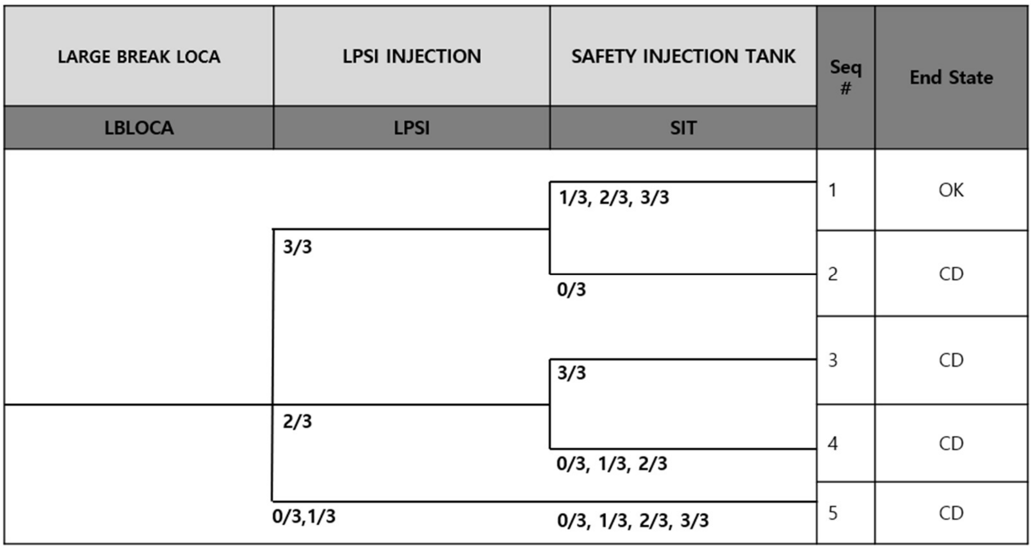

Figure 5. Dynamic Event Tree Grouped by Backtracking Headings

Examining the DET in Figure 5, when 2 out of 3 LPSI pumps are injected, the event sequences diverge based on the SIT injection, which restricts the extraction of success criteria using a binary ET. Therefore, according to the process in STEP 3, a margin of 100°C was applied to the CT of the third event sequence, and it was grouped with the fourth event sequence. This resulted in the creation of a binary ET format as shown in Figure 6.

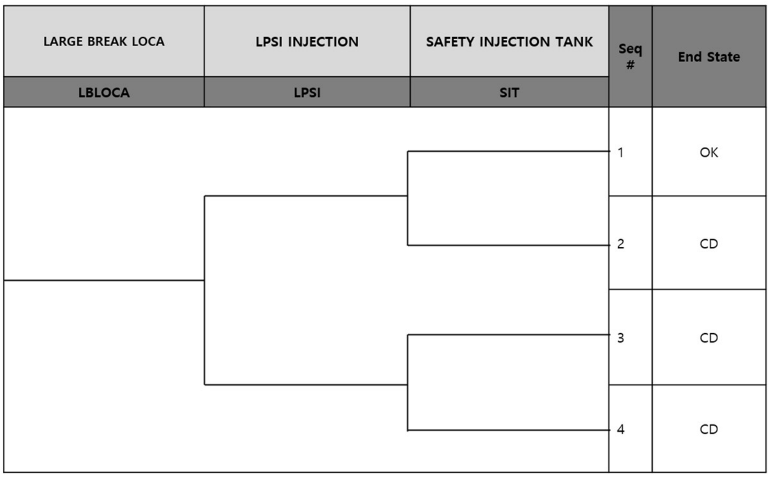

Figure 6. Binary ET with Margin Applied to Cladding Temperature

By applying the STEP4 of post-processing method, the success criteria for the LBLOCA case were extracted. The success criteria for the LPSI are that at least 2 out of the 3 LPSI pumps inject into the intact cold leg. For the SIT, the success criteria are that at least 1 out of the 3 SITs inject into the intact cold leg.

5. COLCLUSIONS

This study confirmed the potential of supporting traditional PSA ETs by converting DETs generated using DICE into Binary ETs and extracting success criteria. The analysis was conducted using MARS-KS, the physical module of DICE, to obtain event sequences. By applying the post-processing method to an LBLOCA, the success criteria for each safety system were extracted and converted into the traditional PSA ET format.

The success criteria of the binary ETs, which were previously extracted by alternating between PSA and DSA, were extracted using DICE, a DET tool that integrates the strengths of PSA and DSA.

Currently, a methodology for operators' actions has been developed, but operators' actions time was not analyzed in this paper. In the next study, we plan to analyze operators' actions and running failures by modeling them. Although resolving questions about the basis for applying the CT margin during the grouping process will incur significant costs. Future research will aim to incorporate substantiated references for applying engineering margins during the grouping process. Additionally, efforts will be made to address the state explosion problem of DET tools by reducing computation time, ultimately improving the efficiency of DET analysis.

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