Research on the Automatic Generation Method of Dynamic Event Tree Scene Based on SBLOCA

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ABSTRACT

Dynamic Event Trees are used in the safety analysis of Nuclear Power Plants for the effective modeling of complex accident scenario evolutions. However, traditional Dynamic Event Trees analysis is challenged by the significant dependence on expert knowledge for branch node selection, leading to reduced modeling efficiency. This study introduces an automatic Dynamic Event Trees generation method for Nuclear Power Plants accident scenario modeling. The method utilizes system code input deck of the accident and integrates logical algorithms (logical algorithms written according to the writing rules of accident card) to automate the construction of accident Dynamic Event Trees models. The efficacy of this approach was demonstrated through the automatic generation of small break loss of coolant accident scenarios, using the Chinese double-loop pressurized water reactor as a case study. The results show that this method can automate the generation of accident scenarios and identify safety characteristics of accidents. This support for operational optimization and safety decision-making in Nuclear Power Plants.

Keywords: Dynamic event tree; Small break loss of coolant accident; Accident scenario modeling; Automatic generation metho; Nuclear safety assessment

Ⅰ. Introduction

The dynamic event tree (DET) method enhances the traditional event tree by considering time and comprehensively simulates the possible consequences of an accident through the coupling of system codes and random response model of nuclear power plants. At present, this field has attracted widespread attention and is being actively investigated[1-2]. The DET method has been successfully applied to analyze different types of nuclear accidents[3-4]. Amirsortani[5] analyzed the station blackout (SBO) accident and established a DET model using RAVEN coupling RELAP5. By considering the number of available safety systems, operator action time, and AC power recovery time, the core damage frequency (CDF) of SBO was obtained. Jang[6] analyzed the steam generator tube rupture (SGTR) accident and developed a DET generation program DPRA-SGTR using PASCAL language. CDF was estimated by analyzing operator behaviors and safety system failures. Sun [7] analyzed the small break loss of coolant accident (SBLOCA) using the DET method and found that the safety of the core cannot be guaranteed by relying only on the normal input of a column of medium pressure injection. Using the DET method to establish time-dependent branches for branch nodes such as the steam assisted feedwater system and AC power restoration, Chen [8] analyzed the SBO accident and found that an increase in the operating time of the steam assisted feedwater system can extend the time window for power restoration. Moreover, there exist an upper limit to the power restoration time. If the upper limit is exceeded, core damage is inevitable.

However, in most applications, the DETs are manually branched based on expert knowledge and judgment. This often leads to inconsistency in the selection of branch nodes among different DET analysts for the same accident scenario, this results in incomplete DET modeling and analysis. Therefore, an automatic DET generation method is proposed in this paper and demonstrates it using a case study of the SBLOCA analysis for the typical double loop pressurized water reactor in China (CNP300).

In this paper, Section 1 provides a brief literature review of DET method and identifies the current problems. Section 2 introduces the DET method and represent the automatic DET-based analysis method. In Section 3 the model CNP300 used for case study is introduced. Section 4 analyzes the model developed using the DET-based automatic analysis method to obtain the core damage probability and compared with the results calculated in Literature 7. Section 5 summarizes this paper and provides directions for future work.

Ⅱ. DET-based automated analysis method

DET generates a series of event sequences containing time-dependent changes based on certain branching rules, and determines the evolution path of the system or component by determining the branching conditions. When the branching conditions are met, it will cause the system or component to evolve on different branching paths, thereby obtaining a set of event sequences to generate a DET branching model. DET branch types are divided into demand type failure branch and operation type failure branch. Demand type failure branch refers to the branch where the function of the system or component has not been successfully achieved, as shown in Root1 in Figure 1. The probability of successful action is p_1, and the probability of unsuccessful action is $1 - p_1$. Operational failure branch refers to the branch where a system or component is successfully deployed, but operational failure occurs, i.e. the system or component fails to complete its corresponding action within the specified task time period. The branch shown as Root2 in Figure 1, assuming that the operating time of the system or component satisfies the probability density function $F(x)$, the probability of operational failure occurring at t_1 is $F(t_1)$, the probability of operational failure occurring at t_2 is $F(t_2) - F(t_1)$, and so on. If no operational failure occurs, the probability is $1 - F(t_1)$.

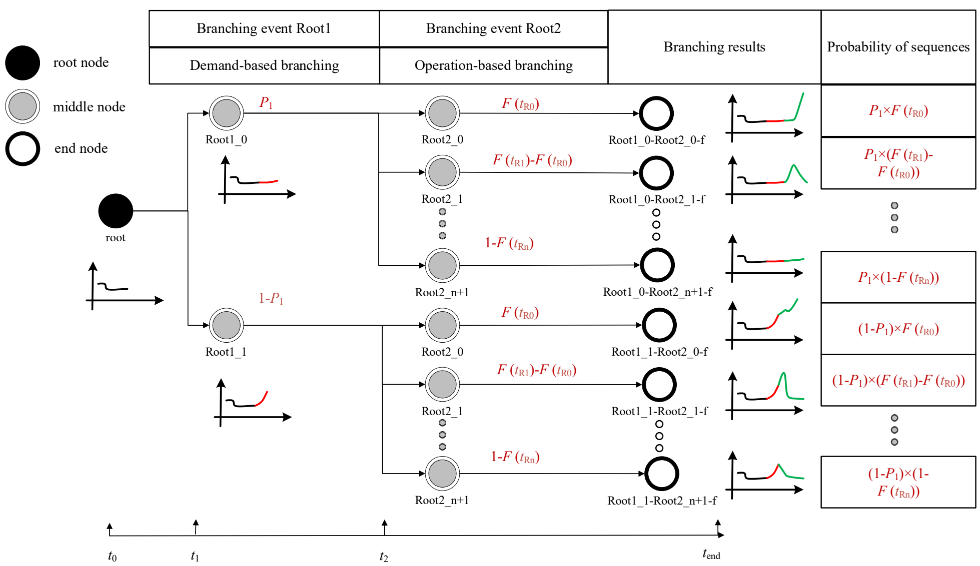

Figure 1. Schematic diagram of DET structure for state evolution of nuclear power plant [8]

When conducting DET analysis on nuclear power plant accidents, the accident card is important because it is an important carrier for accident simulation, and the writing of the accident card follows the rules on the thermal software manual. The content of the card includes time information, control signals, and systems or components. Since the control signals in the accident card directly provide action signals for the system or components, finding the control signals on the card is equivalent to finding the branch nodes in the DET. However, in the actual analysis process, due to the presence of some intermediate signals in the control signal, which do not directly affect the actions of the system or components, but assist in the transmission of control signals, it is necessary to isolate these intermediate signals and retain those that directly affect the system or components during modeling. Based on the above analysis, a method for automatic analysis based on DET is proposed, and the specific flowchart is shown in Figure 2:

1. Read all control signals: Extract all control signals from the corresponding accident card according to the rules in the thermal software manual used.

2.Classification of control signals into valid control signals and intermediate signals: Scan each line of the accident card, screen the read control signals one by one, and determine whether they are directly used by the system or components. If yes, it is determined to be a valid control signal and retained; No, it is judged as intermediate signal and isolated.

3.Create branching objects based on the type of part being controlled and its failure mode: Targeted modeling is conducted based on the identified different component types and their failure modes, as shown in Table 1.

4. Conduct DET analysis based on the modeling object.

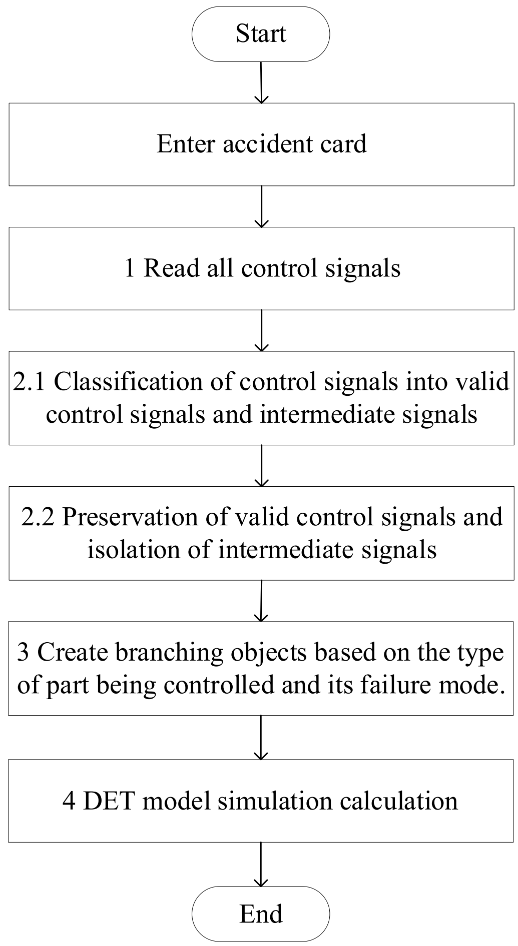

Figure 2. Flow chart of automatic analysis method

TABLE I. Modeling Object

Component Type	PFMEA	Demand Failure/Operational Failure
tmdpvol	No failure mode	simulate according to users' needs
tmdpjun	No failure mode	
valve	refuse to open/close	demand Failure
pump	start failure/operation failure	operational Failure
accum	refuse to open/close	demand Failure

As the DET module of advanced Coupling Platform for Advanced Risk Simulation (CARS) is used for DET analysis [9], the DET module principle of CARS software is shown in Figure 3. When the module monitors the action of the system or components, two branches will be generated, one is to maintain the original action, and the other is the opposite action. Therefore, based on the DET module of advanced CARS software and combined with the above methods, this paper develops an automatic analysis software.

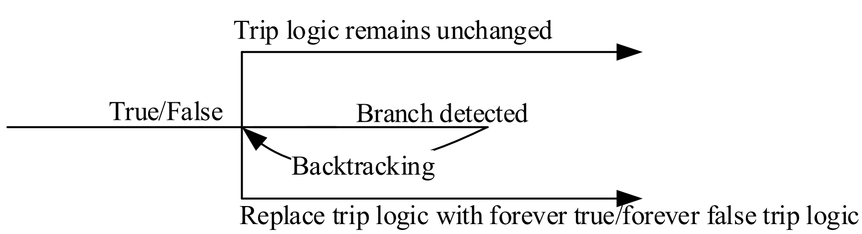

Figure 3. Schematic diagram of DET module of CARS software [9]

Ⅲ. Modeling of SBLOCA

In this paper, the double loop pressurized water reactor (CNP300) is selected as the modeling object, and the model node diagram is shown in Figure 4. The model is mainly divided into two parts: primary and secondary circuit. The main system equipment includes pressure vessel, reactor coolant pump, steam generator, pressurizer, safety injection system and other dedicated safety systems. The primary loop is mainly composed of two complete loops and reactor core. Each loop includes cold pipe section, hot pipe section, main coolant pump, SG primary side and other components and equipment. The break is set in the cold pipe section with an area of 43cm^2.

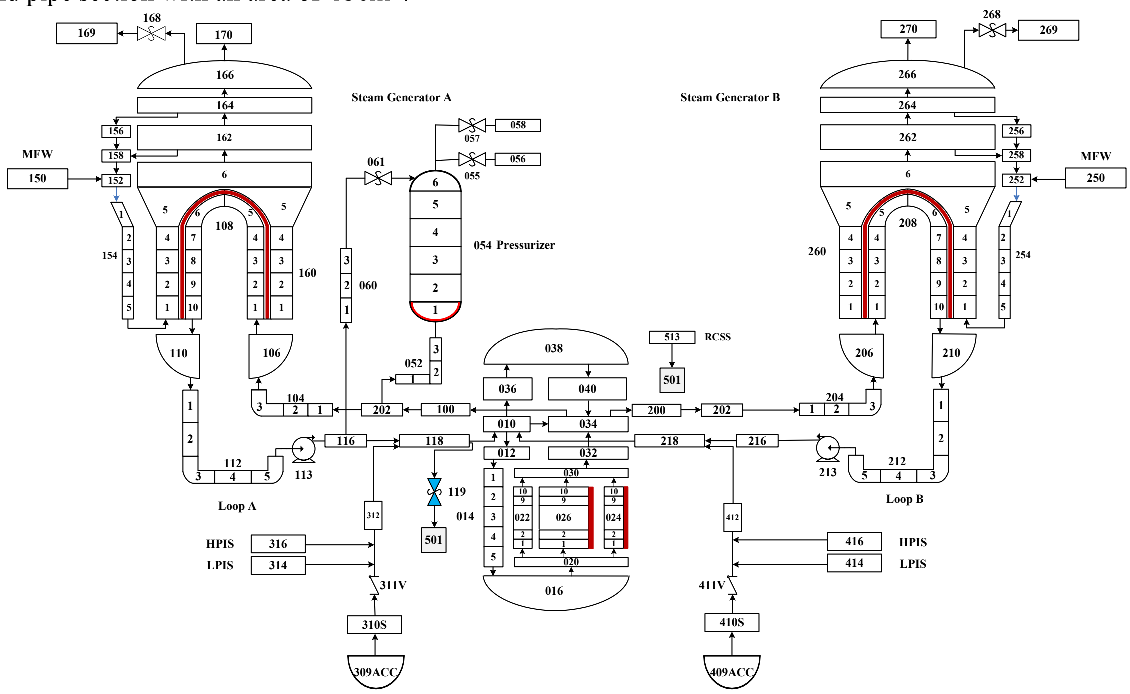

Figure 4. CNP300 model modulization

Ⅳ. Result analysis

Ⅳ.A DET sequence analysis

The SBLOCA established in Section 3 is analyzed using the DET-based automatic analysis method proposed in Section 2, and a total of 35 control signals are identified, 14 valid control signals are retained according to the rules and compared with the manual identification to conclude that there is no error in the identification. Then the model is built according to the component type and failure mode. The modeling object is shown in Table 2, and the modeling results are shown in Figure 5. The total core damage probability is calculated based on the modeling results and the equipment reliability data report of China nuclear power plant [8].

TABLE 2. Modeling Object of SBLOCA

System/Component	Component Type	Trip	Demand Failure/Operational Failure
Reactor Coolant Pump(RCP)	pump	501	operational failure
Main Steam Isolation Valve(MSIV)	valve	615	demand failure
Main Steam Relief Valve(MSRV)	valve	618	demand failure
Pressurizer Spray Valve(PSV)	valve	603	demand failure
Pressurizer Relief Valve(PRV)	valve	606	demand failure
Pressurizer Safety Relief Valve(PSRV)	valve	609	demand failure
First Column of High Pressure Injection System(HPIS)	tmdpjun	612	demand failure
Second Column of High Pressure Injection System(HPIS)	tmdpjun	614	demand failure
First Column of Medium Pressure Injection System(MPIS)	accum	403	demand failure

Second Column of Medium Pressure Injection System(MPIS)	accum	411	demand failure
First Column of Low Pressure Injection System(LPIS)	tmdpjun	402	demand failure
Second Column of Low Pressure Injection System(LPIS)	tmdpjun	410	demand failure
Containment Spray System(CSS)	tmdpjun	401	demand failure
Rupture Valve(RV)	valve	404	demand failure

(Note: The failure time of the reactor coolant pump during operation is 1 hour and 1.6 hours)

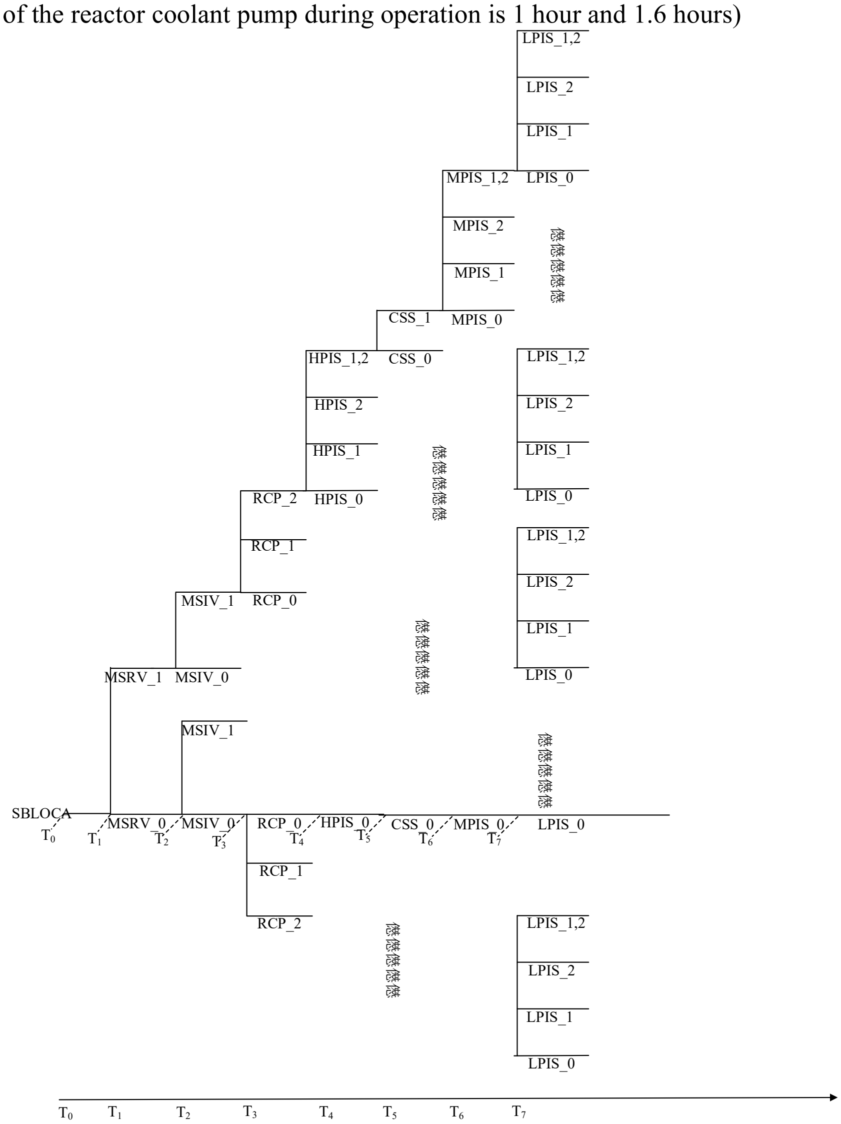

Figure 5 SBLOCA DET Model

In Figure 5, HPIS is explained as an example, HPIS_0 represents that two columns of high pressure injection system are available and can be put into operation normally, HPIS_1 represents that only the second column of high pressure injection system is available and can be put into operation normally, HPIS_2 represents that only the first column of high pressure injection system is available and can be put into operation normally, and HPIS_1,2 represents that columns of high pressure injection system are not available.

In this paper, Peak Cladding Temperature (PCT) is chosen as the key safety parameter. Therefore, comparing the maximum PCT during the accident process with the safety limit of 1477K can clearly reflect whether the core remains intact during the overall development of the accident.

The DET automatic analysis method was used to analyze SBLOCA, generating a total of 739 sequences. This paper used the coupled CARS software, and the branch calculation taken about 14 hours in total. Among them, 98 sequences failed to complete the whole process calculation due to insufficient transient stability of the model. For these 98 sequences, a two-step approach is taken. The first step is to reasonably infer incomplete sequences based on the already calculated sequences. The second step is to treat all sequences that cannot be reasonably inferred based on the already calculated sequences as invalid sequences. The probabilities of each branch node are shown in Table 3 [10].

TABLE 3 Demand Type Branch Node Probability

Branch Node	main steam isolation valve has failed to close	main steam release valve has failed to open	safety shell spray system has failed to operate
Node Probability	7.51E-04	4.35E-05	2.126E-03
Branch Node	High pressure injection system failure	medium pressure injection system failure	low pressure injection system failure
Node Probability	2.585E-03	5.26E-08	2.635E-03

The cumulative probability density distribution function for the operating time of the operating type branch reactor coolant pump is

$$F(t) = 1 - e^{-\lambda t_n} \tag{1}$$

In the equation (1), λ is an exponential distribution constant, and the λ of the reactor coolant pump is $\lambda = 4.25E - 6$[10].

Among the 641 fully calculated sequences, 45 sequences have a maximum PCT exceeding the safety limit; Among the 98 sequences that could not be fully calculated, 42 were deemed invalid, resulting in a total of 87 invalid sequences. Therefore, the core damage probability is $6.84E - 18$. The sequence with the greatest impact on failure is shown in Table 4.

TABLE 4 Maximum Impact Sequence

Sequence	PCTMAX	Failure Probability
root-614_1-612_1-403_1-402_1-410_1	1869.5	2.43E-18
root-614_1-612_1-411_1-410_1-402_1	3317.3	2.43E-18

(Note: root-614_1-612_1-403_1-402_1-410_1 represents two columns of high pressure injection system failure, the first column of medium pressure injection system failure, and two columns of low pressure injection system failure; Root-614_1-612_1-411_1-410_1-402_1 represents two columns of high pressure injection system failure, second column of medium pressure injection system failure, and two columns of low pressure injection system failure)

According to the automatic DET analysis method, an SBLOCA study identified two sequences with the highest core damage probability. These two sequences differ only in the number of loops where the medium pressure injection system fails; consequently, their physical parameter evolution is identical. As they were identical, the first sequence was selected for analysis in this paper. Figures 6, 7, 8 and 9 give the graphs of key security parameters of this sequence over time.

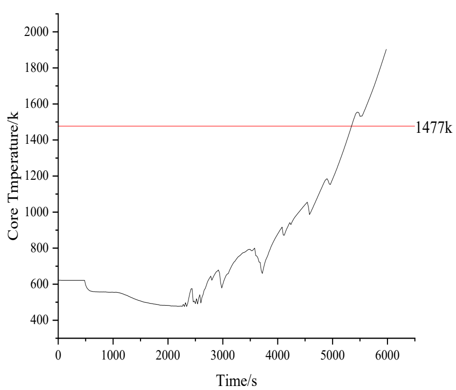

Figure 6 Core Temperature

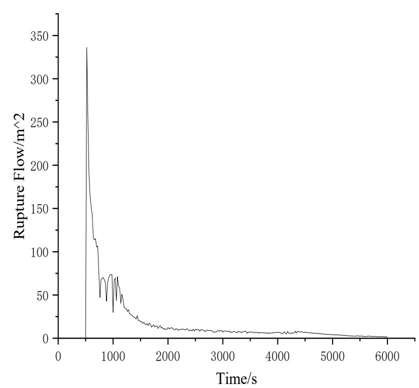

Figure 7 Rupture Flow

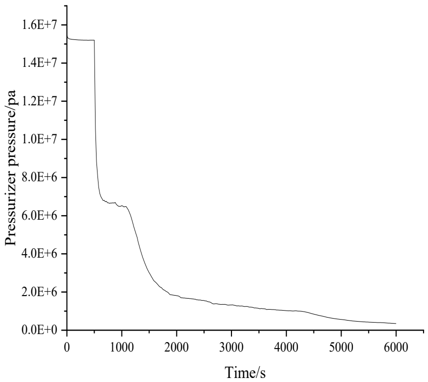

Figure 8 Pressurizer Pressure

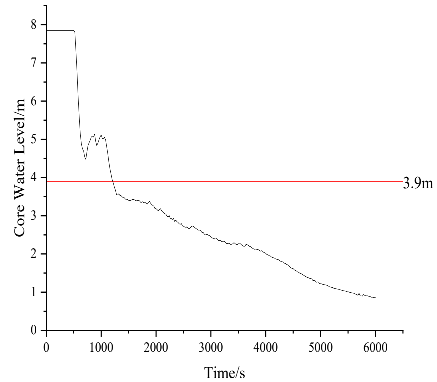

Figure 9 Core Water Level

When the small breach in the cold tube section appeared, as shown in Figures 7 and 8, the core coolant was continuously ejected from the breach into the containment, which resulted in a continuous drop in pressurizer pressure. As the coolant kept spraying out of the breach and there was no coolant replenishment to the core. As shown in Figure 9, the core level will continue to drop. When the pressurizer pressure is less than 4.9 MPa, there will be a column of medium pressure injection, but the coolant injected into the core is difficult to make the core submerged, so although the injection of medium pressure injection has a mitigating effect on the accident, it is difficult to maintain the decreasing level of the core, which leads to further exposure of the core, and then leads to the increasing temperature of the core, as shown in Figure 6. The result was that the core temperature exceeded the safety limit and the core melted down. In summary, the case of only one column of medium pressure annealing input will result in a prolonged core exposure during the accident process, with the PCT rising all the way up and eventually exceeding the safety limit.

Ⅳ.B Comparative analysis

As shown in Table 5, Literature 7[7] used DET to analyze SBLOCA, mainly studying the impact of different injection system inputs on accident mitigation. The calculation results generated a total of 64 branches, among which the maximum PCT of 3 branches exceeded the safety limit, namely, only the first column of medium pressure injection can be put into operation normally, only the second column of medium pressure injection can be put into operation normally, and all injection systems fail, all of which will cause core meltdown.

This paper uses the developed automatic analysis method based on DET to analyze SBLOCA. It not only studies the impact of different safety injection system inputs on accident mitigation, but also investigates the impact of other equipment failures on accident mitigation. The calculation results generated a total of 739 branches, of which 87 branches had a maximum PCT exceeding the safety limit, 3 failed branches were the same as those calculated in Literature 7 and the remaining 84 failure branches are composite failure scenarios not covered by traditional methods. For example, if the main steam relief valve fails to open and two columns of high pressure and medium pressure injections cannot be put into operation normally, it will cause the maximum PCT of the core to exceed the safety limit, resulting in core meltdown.

The above differences primarily stem from variations in the application of dynamic event trees in nuclear accident analysis. When using DET, users must manually specify branch nodes to construct the accident DET model. The authors of Literature 7 focused their research on the impact of different operational states of high-, medium-, and low-pressure injection systems on accident mitigation. Given this research direction, other equipment failure factors were not considered. In contrast, the accident scenario automatic generation method based on DET employed in this paper uses the accident system code input file as a basis and leverages integrated logical algorithms to comprehensively identify all simulable equipment in the input file, thereby achieving the automatic construction of the accident DET model. As a result, this paper can not only study the role of different operational conditions of high-, medium-, and low-pressure injection systems in accident mitigation but also fully consider the impact of failures in other equipment, Deeply analyze possible accident scenarios with low probability of occurrence but serious consequences, leading to differences between the two methods.

Table 5 Comparison of Literature 7

Method	Literature 7	automated analysis method based on DET
Number of simulated devices	6	14

Types of simulation equipment	2	4
Number of Branches	64	739
Number of Failure Sequences	3	84

Ⅴ. Conclusion

This work developed an automatic DET analysis method and applied it to SBLOCA of CNP300. The proposed method can automatically generate accident scenarios and reduce the requirement of expert knowledge. In addition, it can provide a more comprehensive analysis of the dynamic responses of NPPs during accidents.

In the case of SBLOCA with a rupture area of $43cm^2$ in the cold pipe section, if the failure of the main steam relief valve opening is combined with the failure of the two high-pressure injections and the failure of the medium pressure injections, it is not sufficient to ensure the safety of the reactor core only by the normal operation of the two low pressure injections; therefore, it is necessary to pay attention to the situation that only the two low pressure injections can be put into operation normally after the occurrence of the SBLOCA.

There are still some deficiencies in this paper. For example, in the discrete method of running failure branches, this paper chooses 1 hour and task time to discrete. In fact, for the running failure branch, its discrete time is at any time of the task time, so this problem will be studied later.

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