Intelligent Alarm Analysis of Pressurized Water Reactor Nuclear Power Plant Based on Multi - level Flow Model

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Abstract: Due to the intricate and interrelated nature of the nuclear power plant system, any anomaly can cascade into a flurry of alarms. Operators must adeptly assess the system's status amidst a deluge of alarm information and promptly implement appropriate mitigation measures. The substantial workload and mental strain involved predispose operators to errors in judgment and operation, thereby jeopardizing the safe operation of the nuclear power plant. To address these challenges, an intelligent alarm analysis method based on a multi-level flow model (MFM) is employed, facilitating the analysis of causal relationships between alarms. Specifically, a multi-level flow model of the primary auxiliary system, the Chemical and Volume Control System (RCV), in a Pressurized Water Reactor (PWR) nuclear power plant is formulated. By considering the alarm scenario of the RCV system triggered by multiple faults compounded during steady-state operation, the constructed multi-layer flow model is validated.

Keywords: Nuclear power plant; Multi-level flow model; Intelligent alarm analysis system

1. INTRODUCTION

Control room operators in nuclear power plants monitor and control plant operations, especially during fault and accident conditions, where they are tasked with identifying and intervening in faults and accidents. Operators typically rely on alarm information from the main control room to monitor the operational status of the nuclear power plant. They conduct alarm analysis, identify fault root causes, and implement emergency procedures with the assistance of alarm cards. A significant lesson from the Three Mile Island accident was that operators struggled to process a large volume of alarm information, known as alarm floods or avalanche alarms, within a short time due to human processing limitations[1].

Continuous advancements in computer technology, particularly in recent years, have seen remarkable achievements in AI technology. These advancements provide the foundation and impetus for the realization of intelligent nuclear power plants[2]. The introduction of intelligent alarm analysis systems into nuclear power plant control rooms has become a focal point. The intelligent alarm analysis system automatically analyzes alarms from the nuclear power plant system and equipment during abnormal working conditions. Based on identified cause alarms, it assists operators in locating fault locations and root causes, and provides solutions for fault or emergency handling. This ability to rapidly and accurately diagnose accidents provides significant support for plant operators in balancing safety and economic considerations.

Building on the intelligence nuclear power project, this study selected the reactor coolant system (RCP), chemical and volume control system (RCV), high-pressure feed water system (AHP), and low-pressure feed water system (ABP). It utilized the Multi-level flow model method to construct functional models describing the causal dependencies between alarm events, and promptly identified cause alarms using algorithms. Subsequently, fault locations and causes are identified, and the alarm analysis results are graphically displayed to provide decision support for operators. This study also demonstrates and verifies the industrial application capability of the Multi-level flow model.

2. RESEARCH PROGRAM

2.1. Research Objectives

The development of an intelligent alarm system project for the selected four systems should include over 600 alarm detection points and alarm cards. It is expected to achieve intelligent analysis, diagnosis, prediction, simplification, and filtering of a vast number of instantaneous alarms potentially occurring during nuclear power plant operations. This system will aid operators in swiftly identifying the overall alarm status, streamlining operation steps and response time for alarm identification, thus enhancing work efficiency. Simultaneously, the development of a performance evaluation tool for the nuclear power plant alarm system is undertaken. Additionally, research is conducted on the performance testing and human factor verification scheme of the intelligent alarm system prototype. The prototype undergoes verification in the simulator.

2.2. Research Method

This paper adopts a functional model-based alarm analysis method to overcome the shortcomings of traditional model-based methods, which often have high model requirements and slow diagnosis speeds [3]. The approach utilizes the Multilevel Flow Model (MFM) in the functional model, employing a symbolic modeling language to describe system interactions in terms of matter, energy, and information. This model is straightforward to establish and understand, allowing for the rapid acquisition of system knowledge in nuclear power plants. Additionally, a standardized symbolic language for multilayer flow models incorporates causal relationships between system functions, facilitating inference using software tools. In this paper, the MFM method is used to construct the functional model required for alarm analysis. The reasoning platform is established using C/C++ language to realize alarm reasoning, output graphical causal chains, and explain the reasoning results in detail, thereby aiding operators in judgment and decision-making based on alarm analysis results.

The Multi-Level Flow model, proposed by Professor Morten Lind of the Technical University of Denmark, was initially utilized as a human-machine interface technology for system monitoring and control. It has since evolved into an artificial system modeling method for analyzing the dynamic behavior of complex systems. The multilayer flow model is a goal-based system function model [4]. Based on the conservation principle, it describes the functional characteristics and interactions of the generation, transmission, storage, and consumption of matter, energy, and information in complex process systems. A function in the model is a highly abstract representation of a system, structure, or component with similar input-output relationships, reflecting the design intent and purpose of the system while describing the topology and behavior knowledge of the system. The goal-oriented characteristics of the multilayer flow functional model align with cognitive thinking habits and are highly comprehensible [5].

The MFM constructs models that describe energy flow and mass flow structures in physical systems at different levels of decomposition, using modules corresponding to functions and objectives, and representing them abstractly, independent of individual components of the physical system. MFM modeling is not only a representation method but also a powerful tool for analyzing and reasoning system performance [6].

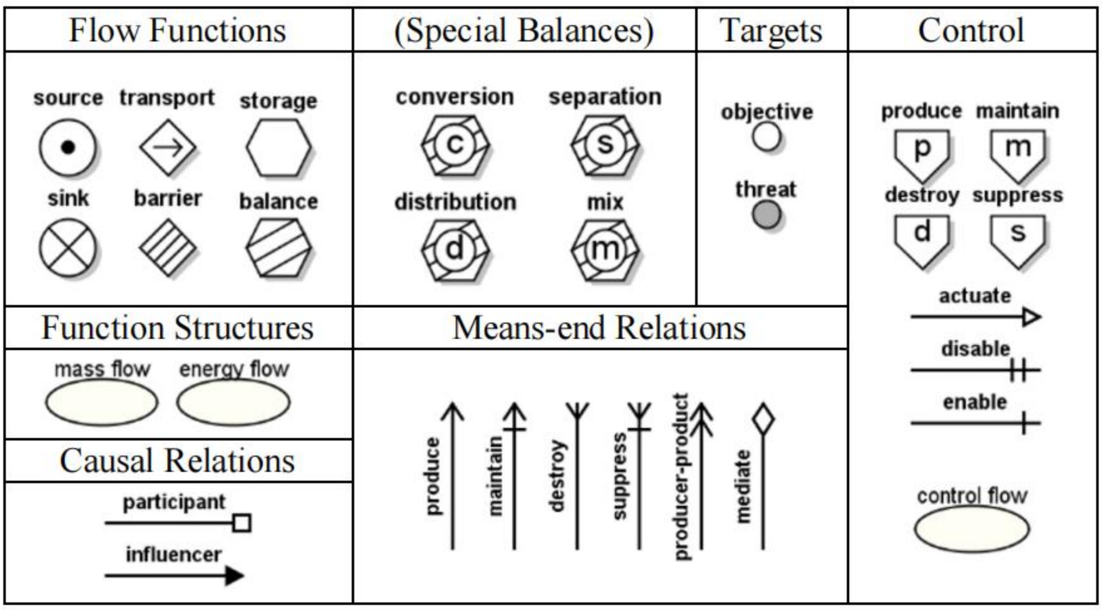

Figure 1. Multi-Level Flow Functional Modeling Elements

2.3. Research Process

Studying the operational data and alarm logs of the selected four systems, we analyze the pipelines and equipment deployed under steady-state operating conditions. Additionally, we review and draw the system flowcharts. Integrating the content of system alarm logs for comprehensive analysis, we thereby construct a multi-level flow model.

The multi-level flow model inference analysis employs dynamic operation data from nuclear power plants as parameters. Following the rules of the multi-level flow model" inference, it analyzes the potential effective alarm paths caused by faults and accidents, and outputs a table of effective alarm causality relationships. The multi-level flow inference engine inputs equipment malfunction information from the process flow into the multi-level flow model, inferring concise alarm causality relationships.

Applying the Multi-level flow model to streamline the logical relationships between system alarm logs, listing the sequence of alarm logic relationships combining alarm logs and multi-level flow model elements. Furthermore, utilizing existing multi-level flow model analysis engines to achieve "multi-level flow model" inference analysis and causality graph generation.

In this study, simulation and verification of selected typical scenarios are conducted using the full-range simulator simulation and verification platform. The alarm triggering situations are recorded, and the correlation between alarms is analyzed. A series of example alarm scenarios and event datasets are created and analyzed. The specific method steps are summarized as follows:

1. Initiation of Alarm Scenario: Insert the initial fault during the steady-state power operation stage, representing the known root cause.
2. Simulation of Alarm Sequence: Utilize the full-range simulator to simulate the alarm sequence resulting from the initial fault.
3. Analysis of Alarm Correlation: Integrate the alarm sequence, alarm card information, and system design data to analyze the correlation between alarm events. The steps for conducting alarm analysis are as follows:

   a) Organize the alarm sequence and examine the causes, consequences, and types provided in the alarm card.
   b) Combine system design data and system PICS screen to delineate the upstream and downstream relationships of system equipment, as well as the correspondence between alarm signals and system equipment.
   c) Analyze the data triggered by the alarm in conjunction with the previous steps to determine the transmission relationship between the alarm and the causal relationship chain.
   d) Compare the results with subsequent Multilevel Flow Model (MFM)-based alarm strategy analysis to verify its rationality and correctness.

3. MULTI-LEVEL FLOW MODEL CONSTRUCTION AND SIMULATION SCENARIO SETTING

3.1. System Power Operation

Taking the chemistry and volume control system (RCV) of a pressurized water nuclear power plant (PWR) as an example[7], the method of establishing a multilayer flow model of the system is illustrated.

The simplified RCV system power operation flow chart is shown in Figure 2.

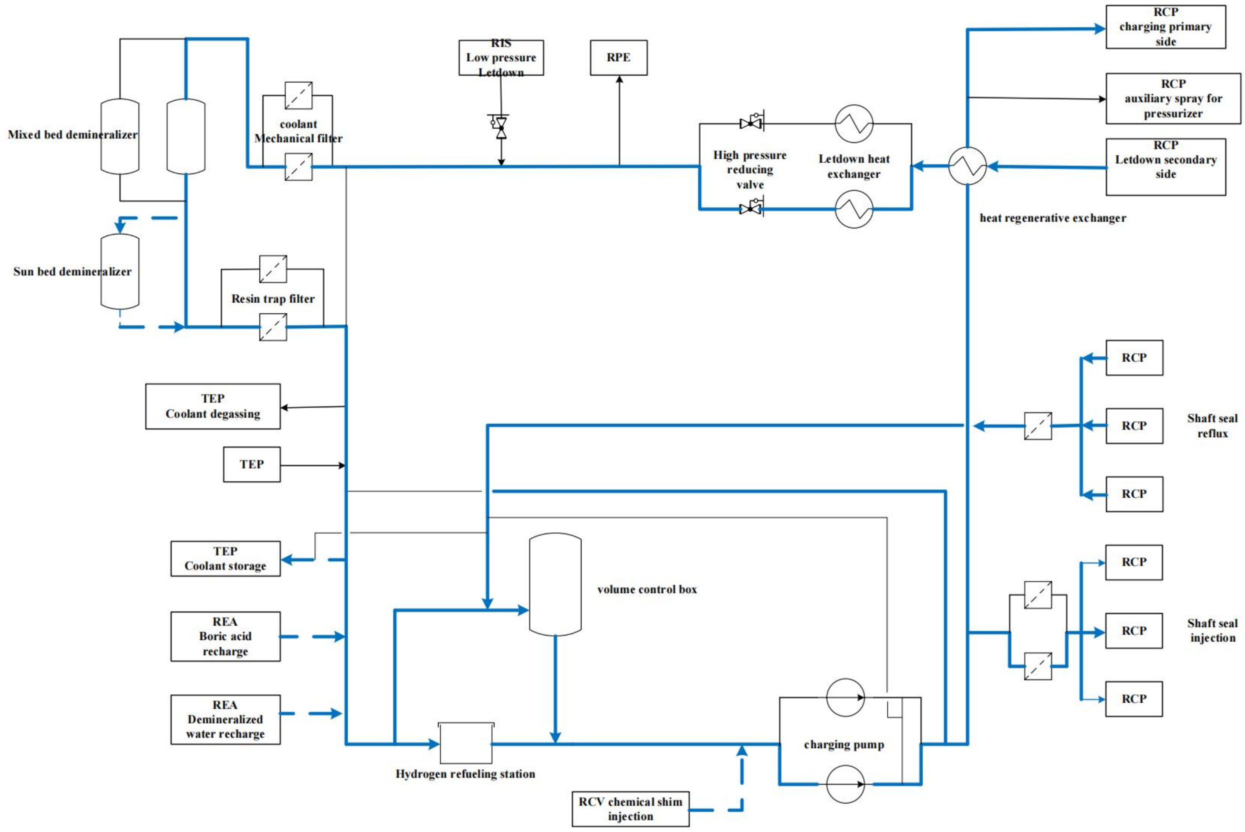

Figure 2. Power Operation Flow Structure of RCV System

Within this configuration, the blue pipeline denotes the power operation input pipeline, while the dashed line indicates operations contingent upon specific circumstances. In this setup, the unit necessitates the Reactor Engineering Auxiliary (REA) system to replenish water and boric acid to compensate for burn-up or leakage in the reactor coolant system, and to regulate the lithium content of the reactor coolant. The operational details are as follows:

1. Activation of one drain heat exchanger and one high-pressure reducing valve.
2. Initiation of the purification unit, operating at a flow rate of 25t/h.
3. Activation of one charging pump with a flow rate of 21.4t/h.
4. Normal operation of main pump shaft seal injection (5.4th), shaft seal reflux (1.8th), with pressurizer auxiliary spray isolation.
5. Non-activation of the charging pump small flow line.
6. Provision of supply lines for the REA system to remove brine and boric acid as per boron concentration regulation requirements.
7. Discharge of excess reactor coolant to the coolant storage tank of the TEP system in accordance with boron concentration regulation requirements.
8. Activation of the hydrogen refueling station.

3.2. MFM of RCV System

Figure.3 depicts the Multilevel Flow Model (MFM) [1] of the constructed RCV system, while Table 1 presents the pertinent goals and capabilities within the model. Notably, MFM adeptly organizes system knowledge along two interconnected axes: "means-end" and "part-whole". Along the "means-end" axis, MFM employs goals and functions to delineate the system as a nexus of material, energy, and information flows, elucidating both the operational and functional aspects encompassing the generation, transmission, and consumption of resources. This approach not only captures the operational dynamics and functional attributes of the system but also underscores the overarching objectives and interdependencies inherent in its functions.

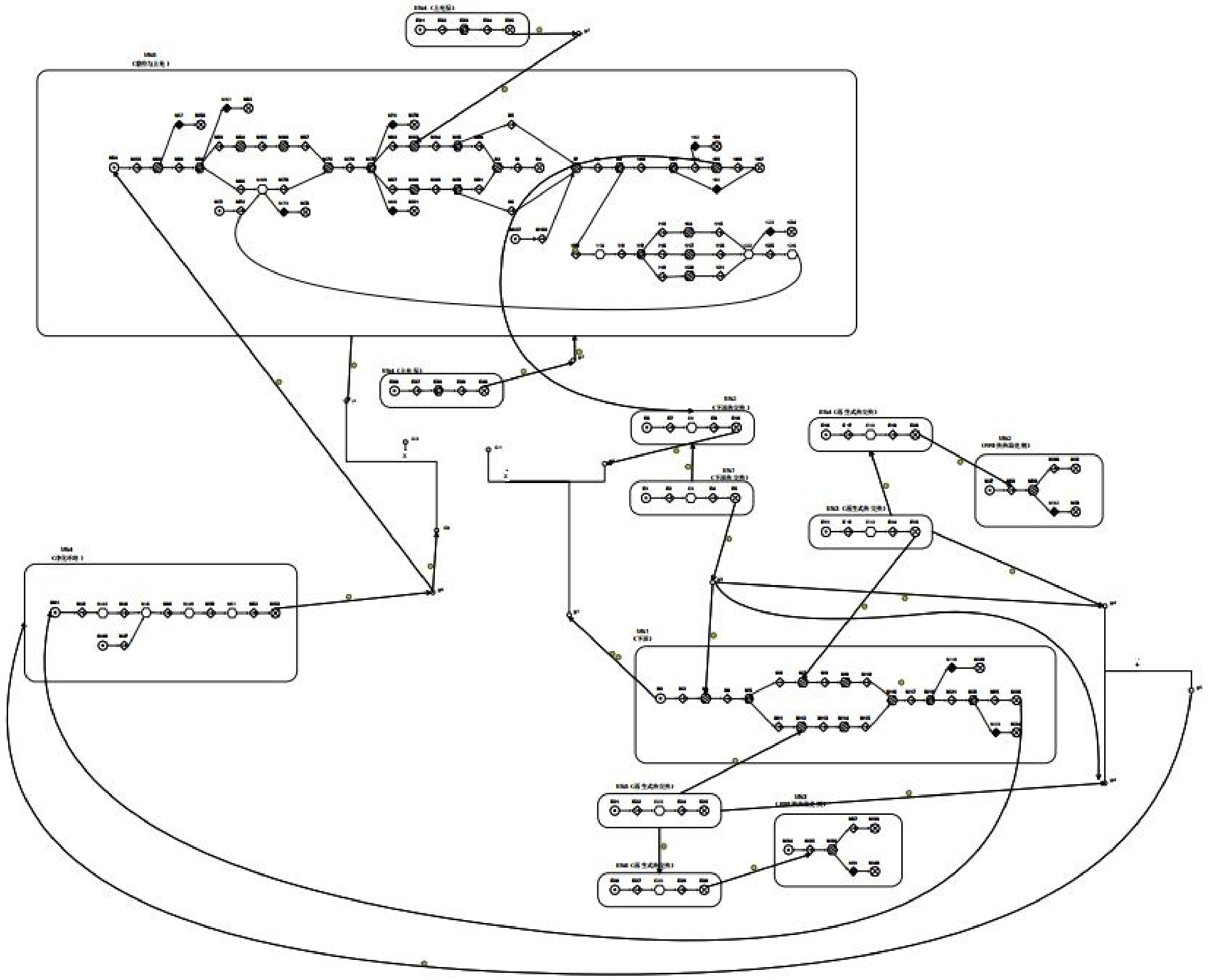

Figure 3. MFM of RCV System

Along the "part-whole" axis, MFM illustrates the hierarchical relationship between "unit" and "system", where a "unit" can be conceptualized as a microcosm of the broader "system", which, in turn, comprises multiple interconnected "units". By amalgamating these "units" into the holistic "system", MFM encapsulates more comprehensive and abstract functionalities, facilitating the representation and analysis of system knowledge across various levels of abstraction. This versatile approach to system knowledge representation enables MFM to tackle complex system challenges with enhanced flexibility and adaptability.

The causality table for multi-layer flow model and alarm list analysis is as follows:

Table 1. Causal Logic Table（portion）

	Result	M1	M2		M3	M4	M5	M6	M7	M8		M9	M10
Cause	Alarm card number			3RCV6021KA-						3RCV1031KA-			
M1		1	0	0	0	0	0	0	0	0	0	0	0
M2		0	1	0	1	0	0	0	0	0	0	0	0
	3RCV6021KA-	0	0	1	0	0	0	0	0	0	0	0	0
M3		0	0	0	1	1	0	0	0	0	0	0	0
M4		0	0	0	0	1	1	0	0	0	0	0	0

M5		0	0	0	0	0	1	1	0	0	0	0	0
M6		0	0	0	0	0	0	1	1	0	0	0	0
M7		0	0	0	0	0	0	0	1	0	1	0	0
M8	**3RCV1031KA-**	0	0	0	0	0	0	0	0	1	0	0	0
		0	0	0	0	0	0	0	0	0	1	1	0
M9		0	0	0	0	0	0	0	0	0	0	1	1
M10		0	0	0	0	0	0	0	0	0	0	0	1

Instructions:

1. Row headings and column headings correspond to all alarm events;
2. The row title corresponds to the cause event.
3. Column headings correspond to result events;
4. If a cause event causes a result event, the cell value corresponding to the cause event row and result event column is 1, otherwise it is 0.

In the actual application process, if a certain element or test point is only related to itself, the point must be a result alarm, and its rows and columns can be eliminated in the actual analysis.

3.3. Simulation Scenario And Alarm List

According to the design objectives and requirements of the simulator, the simulation range, fidelity and simulation boundaries of various power plant operating conditions are evaluated and determined. In general, plant systems related to the plant control room operator should be included in the simulation scope of the simulator regardless of whether the system is monitored and controlled in the control room. Systems directly related to nuclear safety and power production at the plant must be fully simulated in detail. Other power station auxiliary systems shall be allowed to perform partial simulation or value logic simulation in accordance with the requirements of the relevant operation of the main control room.

Based on the characteristics of the RCV system and the characteristics of the power plant operator interview and the simulation machine test, the alarm scenarios of the failure of the capacity control box of the RCV system, the loss of the charge pump successively, and the rejection of the relief valve were adopted, and the alarm list was generated as shown in the following Table 2.

Table 2. Alarm List

Serial Number	Alarm Card Code	Description
1	3RCV3236KA	Capacity control tank 3220BA- Liquid level L4
2	3RCV3035KA	Capacity control tank 3220BA- Liquid level L5
3	3RCV6821KA	The overcharge flow is low
4	3RCV1313KA （Alarm recovery）	The difference between the charge flow and the discharge flow is h igh when the first column is used
5	3RCV7521KA （Alarm recovery）	The shaft seal return line is incorrectly configured
6	3RCV1423KA	Low discharge pipe flow
7	3REA5251KA （Alarm recovery）	REAS recharge flow deviates from the set value
8	3RCV7118KA	Low injection flow of shaft seal
9	3RCV7327KA	RCP2110PO- shaft seal injection flow L2
10	3RCV7337KA	RCP3110PO- shaft seal injection flow L2
11	3RCV7137KA	RCP1110PO- shaft seal injection flow L2
12	3RCV5002KA （Alarm recovery）	The switch operation of the upper charge pump is faulty

13	3RCV1318KA （Alarm recovery）	The first column is put into use and the top charge pump is out of service
14	3RCV3227KA	Volume control box 3220BA- Low pressure
15	3RCV1415KA	Safety valve 1415VP- not fully closed

4. SYSTEM VERIFICATION

The system correctness test is a comprehensive test of the entire system application. Based on the application scenario (simulated by the simulator or simulator), the comprehensive test case data (including operator response actions) conforming to the application scenario is set to verify the system. The test results should be consistent with the expected results.

4.1. Alarm Analysis

Initial operating condition: The initial operating condition is the steady normal operating condition. The capacitors system ensures that the pressurizer water level is at the programmed level through charging and discharging, and completes the volume control, chemical control and shaft seal water supply of the reactor coolant system. At this time, the excess letdown, low pressure letdown, low pressure letdown return water and auxiliary spray lines are isolated.10s later, manually insert the rupture fault of the capacity control box 3220BA into the analog machine, and set the rupture size to 15. Due to the small rupture size and slow response, set the rupture size to 20.6 at 39s and 100 at 4:14s respectively. Due to the breach, the liquid in the container 3220BA continues to leak, and then the liquid level continues to drop. When the liquid level is ≤ 0.6m, the alarm of "3RCV3236KA container 3220BA-liquid level L4" is triggered; when the liquid level is ≤0.4m, the alarm of "3RCV3035KA container 3220BA-liquid level L5" is triggered.

As the upstream input of the upper charge pump, the liquid leakage of the capacity control box will lead to the reduction of the upper charge flow. When the flow rate is less than or equal to 10t/h, the alarm of "low 3RCV6821KA upper charge flow" will be triggered. In this case, the upper charge flow is less than 10t/h, the lower discharge flow is higher than 8.8t/h, and it is not in the water entity operation mode, so the alarm of "High difference between the upper charge and lower discharge flow when the first column of 3RCV1313KA is put into use" is triggered.The 8411VP is initially open and controlled by the pressure of the charging loop. Due to the rupture of the capacity control box, the pressure drops, resulting in the 8411VP closing, which triggers the alarm of "wrong configuration of the 3RCV7521KA shaft seal return line"."3RCV1313KA column 1 discharge discharge when the difference between the charge and discharge flow is high", resulting in automatic isolation of the discharge pipeline, thus triggering the "3RCV1423KA discharge pipe flow is low" alarm;

When the tank level drops to a low level, the reactor boron and water recharge system (REA) will provide demineralized and deoxygenated boron water to the tank to ensure the chemical control function of the tank, resulting in "the theoretical calculated value of demineralized water flow rate deviates too much from the actual measured value of the sensor 5251KM-". Therefore, the alarm of "3REA5251KA REAS recharge flow deviates from the set value" is triggered;Overcharging pump 1 is the upstream device for filling shaft seals. Due to the failure of "stator grounding" of pump 1 when RCV overcharging pump is inserted in 6 minutes and 17 seconds, the overcharging pump 1 stops running, resulting in the decrease of shaft seal injection flow rate. When the flow rate is less than 4.2t/h, the alarm of "Low 3RCV7118KA shaft seal injection flow rate" is triggered."Low injection flow rate of 3RCV7118KA shaft seal" leads to a decrease in the flow rate of shaft seal injected into the main pump. When the flow rate of shaft seal injected into the main pump is less than 1.4t/h, Trigger the "3RCV7327KA RCP2110PO-shaft seal injection flow L2" alarm, "3RCV7337KA RCP3110po-shaft seal injection flow L2" alarm, "3RCV7317KA RCP1110po-shaft seal injection flow L2" alarm;Since the "stator grounding" fault of pump 1 was followed by the "stator grounding" fault of pump 1 after the RCV upper charge pump was inserted, the "stator grounding" fault of pump 2 was inserted after the RCV upper charge pump was inserted at 6 minutes and 22 seconds, so the alarm of "3RCV5002KA upper charge pump switching operation Fault" was triggered. At this time, the 1314VP is still in the open state, and when the two charging pumps are in the shutdown state for more than 1min, the alarm of "3RCV1318KA Column 1 discharge operation, the upper charging pump is stopped" will be triggered.

As the liquid level of the container decreases rapidly, the pressure of the container decreases. When the pressure is <0.09MPa.a, the alarm of "3RCV3227KA Container 3220BA- low pressure" is triggered. Due to 8 minutes 18s, the insertion of the RCV relief valve 1415VP "reject" failure triggered the "3RCV1415KA relief valve 1415VP- not fully closed" alarm.

4.2. Construction Of Standard Answers

According to the description of the RCV system, the combing of the causes and consequences of the alarm card, and the analysis of simulation scenarios, the correlation diagram of alarm events can be drawn as shown in Figure 4. below. Among them, the red border oval identifier represents the inserted equipment failure, the dashed border oval identifier represents the hidden alarm event (that is, not the alarm card event, but the cause event listed in the alarm card), the rectangular identifier is the alarm card event, the filling color is the alarm card color, and the green border square identifier is the identified root cause alarm. The solid arrows are definite alarm event causation (from cause to effect), and the dashed arrows are uncertain alarm event causation (from cause to effect).

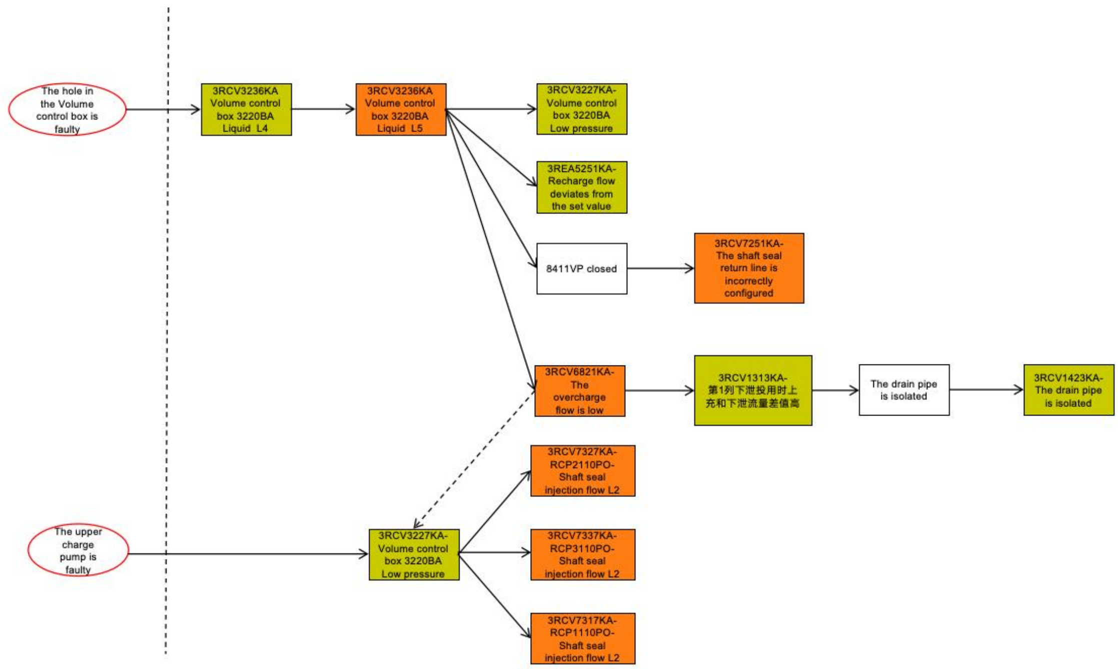

Figure 4. Construction of Standard Answers

4.3. comparison of results

According to the inference algorithm, the sent alarm event is causally inferred, and the causality alarm event is given, and the causality diagram is shown as follows.

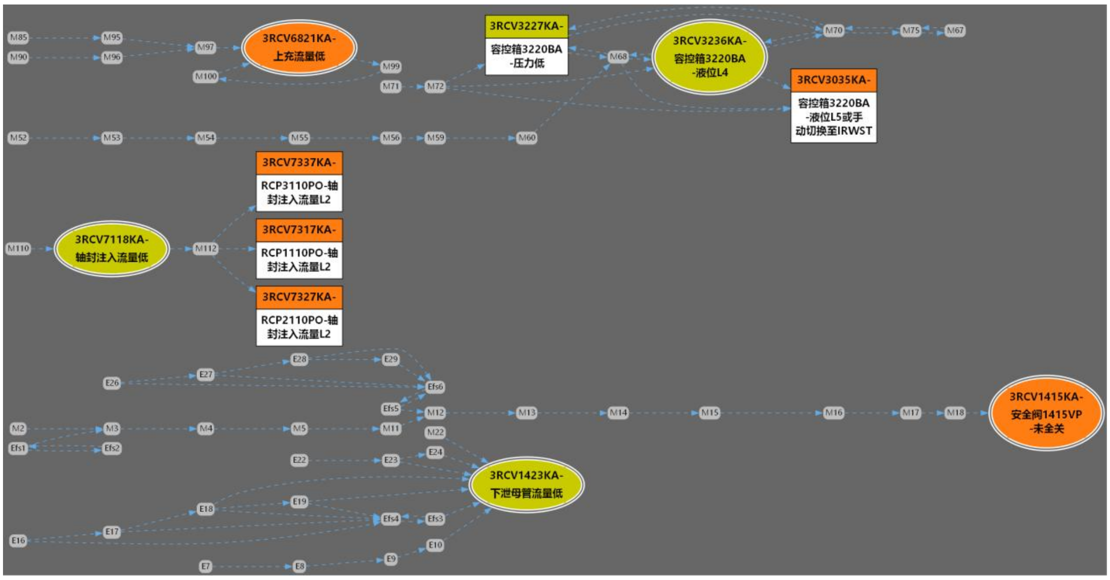

Figure 5. Alarm Event Correlation Diagram of RCV System

Compared with the standard answers, the results are as follows:

1. Within the verifiable range of this case model, the accuracy rate is 100%
2. For the five alarms shown in the following Table 3 in this case:

Table 3. Alarm List Not Included

Serial Number	Alarm Card Code	Description
1	3RCV1313KA （Alarm recovery）	The difference between the charge flow and the discharge flow is h igh when the first column is used
2	3RCV7521KA （Alarm recovery）	The shaft seal return line is incorrectly configured
3	3REA5251KA （Alarm recovery）	REAS recharge flow deviates from the set value
4	3RCV5002KA （Alarm recovery）	The switch operation of the upper charge pump is faulty
5	3RCV1318KA （Alarm recovery）	The first column is put into use and the top charge pump is out of service

Among them:

3RCV1313KA- When the first column is put into use, the difference between the charge and discharge flow is high; 3RCV7521KA- shaft seal return line configuration error; 3RCV5002KA- Charge pump switching operation failure; 3RCV1318KA- The first column of the discharge pump is put into use and the charge pump is shut down, which is a system control alarm, and is not included in the multi-layer flow model and inference algorithm at present.

REA5251KA-REAS recharge flow deviation from the set value is an alarm for other systems, which is not within the analysis scope of the current capacitor system and the other three systems.

Therefore, the causal diagram obtained according to the inference algorithm does not contain the above five alarms.

5. CONCLUSION

In this paper, the chemical and volume control system of PWR nuclear power plant is taken as an example to illustrate the modeling application of multi-level flow model (MFM). Taking RCV system as an example, the multi-layer flow model of the system is constructed, and the alarm list is generated and analyzed by the algorithm. At the same time, the multi-scene fault superposition mode was set in the full-range simulator, the standard answer was constructed for the generated alarm list, and the correctness was verified with the cause-and-effect diagram generated by the intelligent alarm system. The conclusion was drawn that the accuracy rate was 100% within the verifiable range of the case model.

The follow-up study will study and verify the other three systems according to the method described in the paper, improve the intelligent alarm system, and study the human factor verification scheme.

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