Study and Optimization of Full Flow Test Method for Core Safety Injection System

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Abstract: Due to the high pressure safety injection full-flow test of the nuclear power plant core safety injection system (RIS), there are problems such as the limit of the pump starting condition, the “blind adjustment” of the valve flow, the test logic defect, and the number of unqualified tests, etc. This research has improved the test principle and operation steps of the RIS high pressure safety injection full-flow periodic test, and describes in detail the comparison between the new scheme and the existing RIS high pressure safety injection full-flow test scheme, and the actual verification effect. The research results show that the optimized RIS high pressure safety injection full-flow test has the advantages of simple logic, easy operation, high qualification rate, and short test period, and it is worthy of popularization and application in this reactor type.

1. Introduction

To ensure safe operation of the safety injection system (RIS) [1-3] in pressured water reactor (PWR) nuclear power plants, system flow measurement tests are usually performed to ensure that the parameters like system flow and pressure meet the requirements of design [4]. Among all these tests, the RIS high-pressure safety injection full-flow test is the regular test that affects nuclear safety and the statutory test supervised by the Ministry of State Security. However, experience in the operation of PWR nuclear power plants shows that this type of test has many shortcomings and needs further research: 1) it is infeasible to stop the bump to adjust the flow during the test, and hence the times of pump start and stop often exceed the standards; 2) it is not achievable to observe and judge whether the test result meets the standards, and there is no basis for “blind adjustment” of the valve flow; 3) it is not feasible to identify the reasonable range of the total flow of the testing pump during the test, leading to multiple times of failure in the final test. To solve these problems, it is necessary to analyze the safe and stable operation of existing PWR nuclear power stations and the design of new nuclear power plants.

To remedy the defects of flow-flow tests of RIS high-pressure safety injection systems, this paper probed into the principles of full-flow tests of RIS high-pressure safety injection, optimized the test operation code and procedures, and put forward optimization strategies of “flow adjustment without stopping the pump”, “judging whether the test meets the standard by the flow”, and “identifying the most reasonable range for the total flow of the first test pump”.

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2. Test method analysis

2.1. Test principle
Figure 1 shows the working principle of the full-flow test for RIS high-pressure safety injection. Specifically, during the refueling and overhaul period of the nuclear power plant, the RIS high-pressure safety injection pumps (RCV001/002/003PO) are started successively, and through the water transfer loop, the cooling water in the refueling tank (PTR001BA) is injected to the reactor pit. Meanwhile, the flow in each pump and the three parallel branch pipes is measured, the result of which is based on to judge whether the test meets the standard so that we can confirm whether the reactor core makeup capacity under the fault conditions meets the requirements.

![Test Schematic Diagram](image)

Fig. 1 Test Schematic Diagram

2.2. Acceptance criteria
The acceptance criteria for the full-flow test of RIS high-pressure safety injection are as follows: with the set water transfer loop in the system, the pumps of RCV001PO, RCV002PO and RCV003PO are boosted successively. According to Formulae (1), (2), (3) and (4), the flow (Q) of each pump is calculated, the elevation corrected value (ΔH) of the reactor pit and PTR001BA is obtained, the flow mismatch value (A) of three branch safety injection pipes and the error of measured values (dA) by meters is calculated. When the operating points of H and Q of the three pumps fall within the dashed lines in Figure 2 and the value of (A+dA) for the three branch pipes ≤4.5%, it is considered that the test meets the standard.

\[
Q_j = \frac{(N - N')S}{t} \quad (1)
\]

\[
ΔH = \frac{n + n'}{2} - \left( \frac{N + N'}{2} + 1.02 \right) \quad (2)
\]

\[
A = 150 \times \left( \frac{3q_1}{q_1 + q_2 + q_3} - 1 \right) \quad (3)
\]

\[
dA = 25\sqrt{6} \times \left( \frac{q_{\text{max}}}{q} \right)^2 d\Delta P \quad (4)
\]

Where \( Q_j \) is the calculated value of injection flow (\( m^3/h \)), \( N \) is the water level of the PTR001BA tank before the test (\( m \)), \( N' \) is the water level of the PTR001BA tank after the test (\( m \)), \( n \) is the water level of the reactor pit before the test (\( m \)), \( n' \) is the water level of the reactor pit after the test (\( m \)), \( S \) is the inner area of the PTR001BA tank (\( m^2 \)), \( t \) is the test time (\( h \)), \( ΔH \) is the corrected elevation of the reactor pit and the PTR001BA tank (\( m \)); \( q_1 \), \( q_2 \) and \( q_3 \) are the flow
values of the three safety injection branch pipes, respectively \( (m^3/h) \); \( q_{\text{max}} \) is the range of the meter indicator \( (m^3/h) \); and \( d\Delta P \) is the accuracy of the meter indicator.

2.3. Test procedures and challenges
The full-flow tests on the three pumps, RCV001/002/003PO, should be performed separately, and collaboration is necessary during the test that have complex procedures. The major uncertainties and challenges are as follows:

Limited by the test conditions, the pumps need to be stopped each time to record the water level of the reactor pit \( (n) \), and if the test result \( (\Delta H, Q) \) does not meet the standard, the pump needs to be restarted and the pump flow needs to be adjusted, after which the pump must be stopped to check whether the test result meets the standard again. The three pumps are important nuclear pumps. If the tests constantly fail to reach qualified results, the repetitive start and stop operations of the pumps will exceed the standard (the maximum times for continuous starts of the pump is 6 times under the cooling state and 5 times under the heat state). When the values are recorded, the test must be stopped, which lengthens the working period of the test. In the existing test methods, it is impossible to adjust the flow without stopping the pump, which accounts for a demerit of these methods.

According to the test procedures, during the test of the first pump, the flow of the three branch pipes \( (q_1, q_2, \text{ and } q_3) \) does not meet the acceptance criteria of \( (A+dA) \). In practice, it is necessary to adjust the opening degree of the manual regulating valve to adjust the flow of three branch pipes. This process is “blind adjustment”, which is only according to experience and repeatedly start and stop the pump to adjust the flow, and this is not conducive to the test. In existing test methods, it is not obtainable to judge whether the test result meets the standard by direct observation, which accounts for another demerit of these methods.

During the test of the second and third pumps, it is not allowed to adjust the flow by the manual regulating valve. If the flow of the second and third pumps fails to meet the acceptance criteria, the full-flow test for all the three pumps fail, and the test must be performed again. In the existing methods, it is not feasible to identify the most reasonable range for the full flow of the test pump, which accounts for another defect of the existing test methods.

3. Optimization of test methods

3.1. Test method to adjust the flow without stopping the pump
As Figure 2 shows, when \( \Delta H \) changes between -6.1 m and 16.4 m, the maximum change in \( \Delta Q \) is 0.9 m\(^3\)/h. If the impact of \( \Delta H \) on the flow \( Q \) is not considered, pump flow adjustment can be realized without stopping the pump. Thus, to realize pump flow adjustment without stopping the pump, the acceptance criteria for \( Q \) can be optimized into a range of \((140.9\text{m}^3/\text{h} \sim 144.6 \text{ m}^3/\text{h})\), as shown in Figure 3. In this
case, the flow Q will meet the acceptance criteria if the value of $\Delta H$ falls within the range from -6.1 m to 16.4 m, and hence the flow can be adjusted without stopping the pump.

![Fig. 3 Optimized Test Acceptance Criteria for ($\Delta H$, $Q$)](image)

3.2. Test method to judge whether the test meets the standard through direct observation of the flow

As the Formulae (3) and (4) in Section 1.2 show, $q_{max}$ and $d\Delta P$ are known parameters of the device in the test. To achieve a method to judge whether a test meets the standard through direct observation of the flow, iterative calculation of the values can be performed: when $\max(q_1, q_2, q_3)-\min(q_1, q_2, q_3) \leq 1.2$, the formula $A+dA \leq 4.5\%$ holds. Therefore, when the flow is adjusted by the adjustment valve, it only needs to check whether the flow of the three branch pipes meets the formula $\max(q_1, q_2, q_3)-\min(q_1, q_2, q_3) \leq 1.2$, and can judge whether the test meets the acceptance criteria: $A+dA \leq 4.5\%$. This method can avoid “blind adjustment” and save much time in the test.

3.3. Test method to identify the most reasonable range of the total flow of the first test pump

As the original test method shows, the flow cannot be adjusted by the manual regulating valve when the second and third pumps are under tests, so the test results of the second and third pumps are not controllable. To make the result controllable, it is necessary to refine the acceptance criteria of the test flow of the three pumps based on modification of the criteria as specified in Section 3.1.

The flow values of the three pumps are set as $Q_1$, $Q_2$, and $Q_3$. If $Q_1>Q_2>Q_3$, and they all meet the acceptance criteria, the ideal distribution of $Q_1$, $Q_2$ and $Q_3$ in the acceptance criteria is as shown in Figure 4. In the first test of the pump, the flow $Q_1$ is adjusted to a range within the upper 1/3 of the corrected acceptance criteria (140.9 m$^3$/h ~ 144.6 m$^3$/h), the test flow of the second pump $Q_2$ will be within the central 1/3 of the acceptance criteria, and the flow of the third pump $Q_3$ will fall within the lower 1/3 of the acceptance criteria. Thus, the results of the second pump and third pump turns from an uncontrollable state to an indirectly-controllable state, which will considerably increase the success rate of the three pumps at one time.

![Fig. 4 The Most Reasonable Area Diagram of Pump Flow](image)
4. Test process optimization
The optimized full-flow test method for the reactor core safety injection system can greatly reduce the operation steps, and improve the success rate of the test at one time. The major content is as follows, and Figures 5 and 6 show the test procedures before and after the optimization.

(1) The optimized system does not need multiple persons to read the values on site. Instead, it is only necessary to read the flow of the pumps and the three branch pipes;
(2) During the test, we do not need to stop the pump to record the data;
(3) We only need to adjust the flow while testing the first pump. When the first pump test result meets the standard, the results of the second and third pumps also meet the requirements.

![Fig. 5 Flow Chart of Test before Optimization](image1)

5. Real-world application and benefits
By comparing the number of tests and the testing period before and after the optimization of the full-flow test method for reactor core safety injection, we found that the average testing time reduced from 3 h before optimization to 1.5 h after optimization, and the minimum testing time could be 1 h. For each round of overhaul of the reactor unit, the testing time for the key paths reduces by 1.5 h on average, so through calculation based on the hourly power generation of millions of reactor unit, and the reduction in the testing time could be reduced by over several hundred thousand RMB for each unit every year. Besides, the one-time qualification rate after the optimization considerably exceeded that before the optimization.

6. Conclusions
This paper introduces and analyzes a method for optimizing the full-flow test of safety injection systems of the reactor core in megawatt-level pressured water reactor nuclear power plants. Feasible suggestions for optimization have been proposed. Practice in real nuclear power plants for years have proved that the full-flow test method for reactor core safety injection system after optimization is more convenient and has a higher test success rate than previous ones. It can also reduce the testing time and has high economic efficiency.

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