Task Analysis for Automatic Periodical and Surveillance Test with Machine Learning in Nuclear Power Plants

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1. Introduction

Nuclear Power Plants (NPPs) are facilities that require the highest reliability. NPPs are performing a lot of tests during normal operation and Overhaul (O/H). Operators, and maintenance workers of NPPs perform these tests to prove the safety of the NPPs and operate the plant safely. These tests are mainly Surveillance Test (ST), which is based on the Final Safety Analysis Report (FSAR), and the Periodical Test (PT), which is based on the Technical Specification (Tech-Spec).

Also, since the Fukushima Dai-ichi accident, there has been an emphasis on the safety of nuclear power plants globally. In addition, small modular reactors (SMR), which have strength in efficiency compared to the normal NPPs, real-time monitoring, and safe operation through Artificial Intelligence (A.I.) learning, have recently been in the spotlight. Furthermore, the International Atomic Energy Agency (IAEA) reported that human error was the main factor of accidents at nuclear power plants, and the Korea Atomic Energy Research Institute (KAERI) also reported that about 24% of accidents at nuclear power plants were caused by human error [1]. To increase safety by reducing human resources and human errors, it is necessary to study the potential of automating the tests carried out in NPPs.

In this paper, we classify and analyze the task of the Auxiliary Feedwater Pump test among the numerous tests performed in NPPs, as the initial process to automate the test.

2. Periodic and Surveillance Tests in NPPs

To safely operate NPPs, the operator checks the requirements of the FSAR and Tech-Spec. Tech-Spec of NPPs defines Limiting Conditions for Operation (LCO) and Surveillance Requirements (SR) to secure the safety of NPPs during Design Basis Accident (DBA) and satisfy the regulatory requirements of the FSAR [2].

The safety operation of NPPs is verified by performing the ST and PT, which are tests to prove whether the state of NPPs satisfies the requirements of FSAR and Tech-Spec. Simultaneously, the operator monitors the NPPs in real-time and performs tests at regular intervals.

Several tests conducted in NPP include; Overhaul (O/H) Test which is performed during preventive maintenance; Operate Performance Test, which is a test on equipment operating during normal operation; Operate Possibility Test which is a test on pieces of equipment in a standby state during normal operation of the power plant; Calibration Test which is correcting the measurement/monitoring equipment; and Core management Test which checks reactor core parameters. Through automation of these tests, which are the major tests carried out in the NPPs, human errors can be reduced and the safe operation can be approached by performing more accurate tests.

3. Auxiliary Feedwater System (AFWS) Pump Test

In NPPs, there is an important safety concept is called the Engineered Safety Features (ESFs), which is to limit plant/equipment damage and to mitigate the consequences of the accident. It is designed for accident response and mitigation [3]. The Engineered Safety Features Actuation Signal (ESFAS) provides signals to activate each system. There are 6-type ESF actuation signals, namely; Safety Injection Actuation Signal (SIAS), Containment Isolation Actuation Signal (CIAS), Main Steam Isolation Signal (MSIS), Auxiliary Feedwater Actuation Signal (AFAS), Containment Spray Actuation Signal (CSAS), Recirculation Actuation Signal (RAS) [4]. Nuclear power plants must prove the operability of these ESFs through tests.

Therefore, we will focus on the operability test of one of the ESFs called Auxiliary Feedwater System (AFWS).

3.1 The AFWS

AFWS is a safety system that supplies water to the Steam Generator (SG) until the Shutdown Cooling System (SCS) is connected when the Station Black-Out (SBO) occurs or Main FeedWater System (MFWS) cannot supply feedwater due to any event or accident. A simple flow path for AFWS is shown in Figure 1. It shows that AFWS consists of a main flow path that supplies water to the SG and a recirculation flow path for testing.
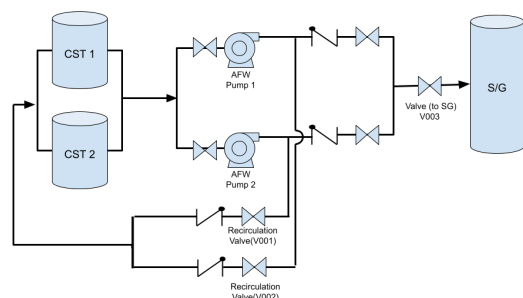

Figure 1. AFWS Simple Diagram

If the MFWS becomes unable to supply water, the AFAS signal will trigger the AFWS pump to operate. Then, the AFWS pump supplies feedwater from the Condensate Storage Tank (CST) to the SG through the main flow path. A check valve is installed to prevent a back flow of feedwater to the pump.

If the recirculation path do not exist, the feedwater is injected into the SG using the AFWS pump during the test in normal operation, and then the water level of the SG increases, supercooling occurs, and the NPP will be in a transient. Therefore, we need a recirculation flow path that can test the operability of AFWS pumps without supplying water to the SG is important.

3.2 The AFWS Pump Test Procedure

One of the basic precautions when perfuming every test is that operators have to check the initial test conditions and overall plant situation to make sure there are no problems before beginning the test. In addition, since there are several series of devices related to nuclear power plant safety due to diversity and multiplicity, they should not be checked at the same time. Each series is independently performed art a time during the test.

The main initial conditions to be checked in the AFWS Pump test are;
- Confirm that communication is possible between the Main Control Room (MCR) and the test location in the Local.
- Check the power supply of the test devices.
- Check the fuel tank level for driving a diesel engine.
- Perform filling and exhausting procedures to prevent water hammering when starting the pump.

After verification of these initial conditions demonstrates that the plant is in good condition to carry out the procedure, the pump operability test procedure begins. The test result is judged according to specific criteria, and if unsatisfied, the test is re-performed. However, if the test is consistently unsatisfactory, analyze the cause and additional steps written in the procedure are performed. This test procedure can be represented by the flowchart in Figure 2 and;

- Check that the valve arrangement is complete for testing.
- (MCR) Close the valve (to SG).
- (Local) Open the recirculation flow control valve by 1/4 turn.
- (MCR) Start the auxiliary feed water pump.
- (Local) Open the recirculation flow control valve and adjust the valve position to perform to suitable flow rate.
- If the pump is stable, record the following: Flow rate, inlet/outlet pressure and differential pressure, pump and motor vibration, recirculation pipe check valve state.
- (MCR) Stop the auxiliary feed water pump.
- (Local) Close the recirculation flow control valve.

- (MCR) Open the valve (to SG) to the pre-test position.
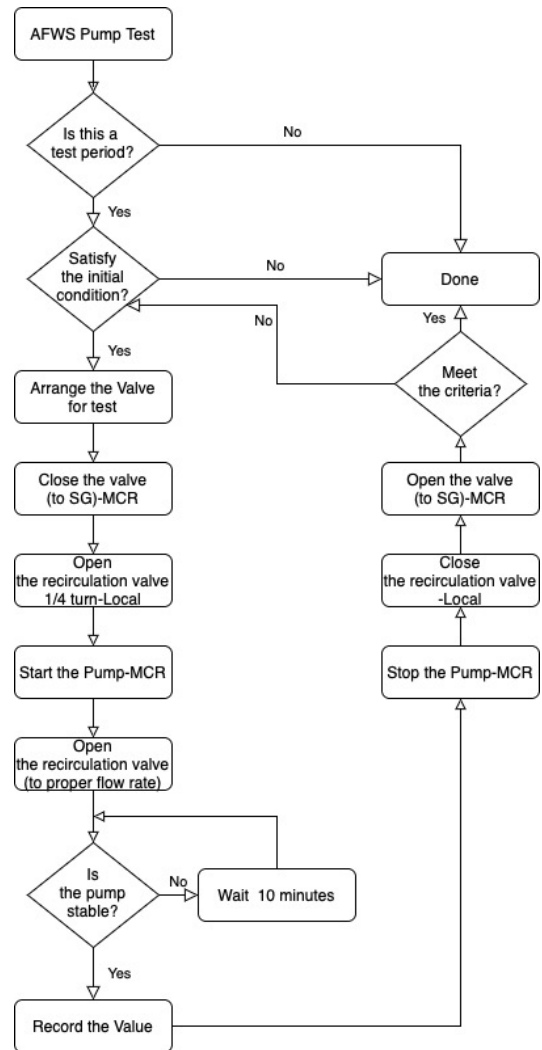
4. Task Analysis for Automatic PT and ST with Machine Learning in NPPs

4.1 Task Analysis

To automate the process of these tests, task classification is required first, and the task of the AFWS pump test can be classified as follows.

- Check the test period
- Check the initial condition
- Valve Operation (MCR)
- Valve Operation (Local)
- Equipment operation (pump, engine, etc.)
- Adjust the Valve position for the test
- Check the equipment
- Measure and record
- Confirm (satisfaction with the test result criteria)
- Alram to the operator (Test Pass or Fail)

In addition to the test procedure, it is necessary to determine whether the test in NPPs produces accurate results when the test is carried out with the task classification above. If an abnormal condition occurs, the test should be stopped and the operator should be given priority to manage the abnormal condition by using an alarm.

Table 1 shows the proper method to automate the test for each task. Most of the steps can be progressed using the if-then logic. Since most of the procedures performed in NPPs have a flowchart format. Even using the if-then logic, the operator's subjectivity and experience have a major influence on the task of checking the state of the device.

Table 1. Task Classification with automation Method

No.	Task	Method
1	Check the test period	If-then
2	Check the initial condition	If-then
3	Valve operation(MCR)	If-then
4	Valve operation(Local)	If-then
5	Equipment operation	If-then
6	Adjust the Valve position	DRL
7	Check the equipment	DRL
8	Measure and Record	If-then
9	Confirm	If-then
10	Alarm to operator	If-then

For example, after starting the pump, check that the pump is in a stable state and measure various values. At this time, the decision on the stable state of the pump is made based on the operator's experience and judgment.

In addition, when performing the exhaust procedure of the flow path to prevent water hammer, it will be influenced by the experience of the operator. For this reason, it is necessary to consider the experience of the operator even if the procedure in the flowchart format is performed with in the if-then logic. Machine learning of artificial intelligence can increase the reliability of the decision-making process based on the operator's experience and judgment.

Based on the classified tasks, we need to consider applying the automation methodology for each task. When deciding which methods is suitable for each tasks, we analyze each task. These tasks were also categorized into three types: Decision Making, Continuous Control, and Discrete Control.

Decision Making determines the strategies like the rate of power increase or the stable state of equipments; the subsequent control actions depend on this rate, although it does not include any control action. The continuous controls adjust component states over a range to realize specified target values for the given parameters, and the rules that govern the necessary adjustments cannot be described with simple logic. For example, adjusting the valve position to set proper flow rate of AFWS. In contrast, a discrete control involves the direct setting of a target value based on a binary condition, as in if-then logic. An example of a discrete control is as follows: open or close the valve, start or stop the pump [5].

Deep Reinforcement Learning (DRL) was deemed suitable for use as the continuous control module and a Long Short-term Memory (LSTM) network and applied a rule-based system (such as if-then logic) rule for the discrete control of components [5].

4.2 Limitations

Even if the procedure is made into a flowchart to automate the test of NPPs and the procedure can be performed through proper methods, there are clearly limitations.

First, it is a limitation of data acquisition. Some procedures that cannot be implemented through simulators or programs in the case of using actual values such as measuring device vibration. This part can be overcome to some extent if actual data from the power plant are available as research progresses. In the case of vibration measurement, it can be solved by installing a measuring device in the vibration measurement area.

Second, as mentioned in the introduction, static periodic tests of nuclear power plants are numerous and there are many types. Some tasks require real manpower to calibrate or replace equipment or components, and some procedures that require operator action such as checking directly on-site or operating local valves.

5. Conclusion

There are a lot of tests performed during normal operation or O/H in NPPs to operate safely, which are performed by operators or maintenance workers. IAEA and KAERI reported human errors are one of the main factors of an accident in NPPs. Also, with SMR in the spotlight, we need to automate these tests to reduce human errors and resources to improve the safety of NPPs. Among the numerous tests of NPPs, theAFWS pump operability test was selected, and tasks were classified and analyzed for the test. In this study, we need to use a flowchart, if-then logic and DRL to automate the ST and PT of NPPs. There are still limitations in automating the entire part of the test, but there are sufficient possibilities for automation by overcoming the limitations through various methods.

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