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Proposal of a Pre-Test for Optimizing LCSR Testing in Korean NPPs

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1. Introduction

In nuclear power plants, Resistance Temperature Detectors(RTDs) are critical sensors for monitoring Reactor Coolant System(RCS) temperature. Their signals are directly used in the plant protection system to calculate Departure from Nucleate Boiling Ratio and to initiate automatic reactor trips during abnormal events. If RTD response is too slow, these safety actions may not occur in time, risking plant safety. Therefore, regulatory bodies require RTD response times to remain under 8 seconds at normal operating pressure and temperature (NOP/NOT).

The standard method for testing response time is the Loop Current Step Response (LCSR), which allows in-situ testing without removing sensors. However one of the formal LCSR tests is conducted at NOP/NOT conditions during the heat-up stage at the end of an overhaul. If an RTD fails at this stage, the plant must cool down, repair or replace the RTD, and reheat the RCS again, resulting in significant delay and economic loss.

2. Background

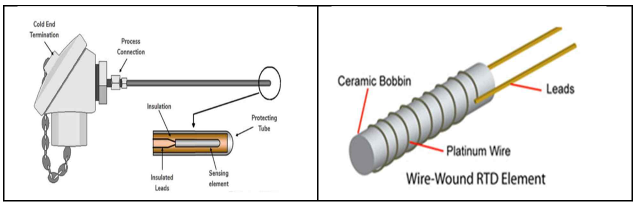


Fig. 1. Structure of a typical RTD assembly

RTDs are platinum-based devices that provide accurate and stable measurements. In Korean standard nuclear plants, 24 RTDs feed into the protection system, where response time must meet the 8-second requirement.

Historically, the plunge test was the standard method. In this method, the RTD is removed from the plant and plunged into a temperature-controlled bath, and the time constant is measured as the time for the output to reach 63.2% of the final value after a step temperature change. Although the idea is easy to understand, the plunge test had several drawbacks: removal of sensors exposed workers to radiation, laboratory conditions (e.g., atmospheric pressure, mild temperature) did not represent reactor environments, and results had to be extrapolated with large uncertainties.

To overcome these issues, the LCSR (Loop Current Step Response) method was developed by EPRI[1]. LCSR test applies a step electrical current to the RTD in place, generating internal heating, and records the transient response while the RTD remains installed in the RCS. This allows testing under actual operating pressure, temperature, and flow.

Although the direction of heat transfer differs (external fluid to RTD in plunge test, internal heating to fluid in LCSR), the governing transient equations are mathematically equivalent. Both can be represented as multi-exponential step responses, and the time constant extracted is the same physical quantity. Extensive validation confirmed that LCSR and plunge test results agree within about 10% accuracy, which is acceptable for regulatory purposes. For this reason, LCSR has been approved by regulatory authorities worldwide as the standard in-situ method for verifying RTD response time[2].

3. Field Challenges

In Korean plants, two formal LCSR tests are carried out per overhaul period: the first at the beginning of the overhaul under NOP/NOT conditions, and the second at the end of the overhaul, also under NOP/NOT, for replaced RTDs. If the second test fails, the plant must undergo another cooldown and reheating sequence.

For example, in an OPR1000 unit, if a failure occurs during the final LCSR test at the end of the overhaul, the restart process is severely delayed. By applying the proposed pre-test method instead of relying solely on the current process, the plant could reduce the delay by approximately 60 hours, preventing unnecessary repetition of cooldown and heat-up stages.

Table 1: Comparison of Process With and Without Pre-Test

	Current	**With Pre-test**	**difference**
Process	100℃ ↓(27.5hr) NOP/NOT ↓(38hr) Ambient Temp. for maintenance ↓(37.5hr) NOP/NOT	100℃ ↓(5.5hr) Ambient Temp. for maintenance ↓(37.5hr) NOP/NOT	**60 hrs**
Duration (hr)	**103**	**43**	

Using the following equation, the delay can be translated into an estimated economic loss:

Loss=P×t×1000×S

where P is plant power (MW), t is delay (h), and S is system marginal price (KRW/kWh), the economic loss is about 7.7 billion KRW for a 1000 MW unit with a 60-hour delay at 128.33 KRW/kWh(mainland rate in 2024).

Importantly, many failures are not due to inherent RTD defects but simple installation problems, such as debris inside thermowells or poor insertion.

Hashemian proposed a pre-test during cold shutdown[3], in which not only the replaced RTDs but also the unreplaced RTDs are tested. By comparing the response time trends of the entire RTD population, outliers could be identified, allowing early detection of installation or degradation issues. However, this method requires significant manpower and time during the busy overhaul period, and the interpretation of outliers can be subjective, depending on the evaluator's judgment.

4. Optimal Pre-LCSR Testing

This study proposes a simpler pre-test. The concept is to apply the same formal LCSR procedure earlier in the heat-up phase, under conditions where coolant flow is stable but before reaching full NOP/NOT. Instead of subjective curve comparisons, the proposed pre-test directly measures the response time of only the replaced RTDs using the same procedure as the formal LCSR.

4.1 Timing of Pre-Test

The optimal time is immediately after the third RCP startup (~100 °C, 25~27 kg/㎠ A). At this stage, coolant flow is established in almost all loops, making it possible to conduct the test because stable flow is required to measure response time properly.

4.2 Simplified RTD Modeling

To predict RTD response times, the following equation is used[4]:

$$\tau = \frac{\rho c r_o^{\,2}}{2k} \ln\left(\frac{r_o}{r_i}\right) + \frac{\rho c r_o}{2h}$$

where ρ is density, c is specific heat, r_o is the outer radius of sensor assemly, r_i is the radius of the sensing tip, k is thermal conductivity of sensor assembly, and h is heat transfer coefficient of film. This equation is valid under the assumption that the RTD can be modeled as a homogeneous cylinder.

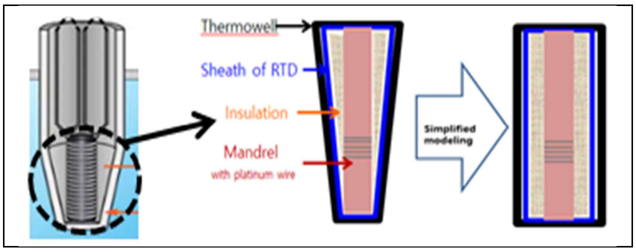


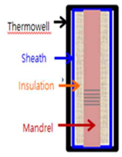
Fig. 1. RTD Structure Simplification.

Real RTD assemblies are tapered and multi-layered, consisting of thermowell, sheath, insulation, and mandrel. To apply this equation, the geometry was simplified into a homogeneous cylindrical model. Layer thicknesses were estimated using 82 sets of manufacturer LCSR data (average response time ≈ 4.0 s) with a Python differential evolution algorithm. This enabled calculation of equivalent thermal properties and response times under different conditions.

Table 2: Process for Simplified RTD Modeling

Step 1	Use outline drawings and available documents → Roughly estimate the thickness range of each layer
Step 2	Randomly assign each layer thicknesses within the estimated ranges
Step 3	Apply homogeneous cylindrical equivalent model using assigned layer thicknesses → Calculate response time under lab conditions (76 °C, atmospheric pressure, 1 m/s)
Step 4	Compare the calculated response time with 4.0 s
Step 5	Repeat Step 2 ~ Step 4 until the error is minimized

The optimization process was repeated 30 times, and in all runs, similar thickness values for each layer were consistently obtained. The representative results are summarized below.



Layer		thermowell	sheath	insulation	mandrel
Thickness[m]		0.002045	0.00066	0.000315	0.00174
Manufacturer test	ρ (kg / m³)	7163.3904			
	c(J / (kg•K))	580.49478			
	k(W / (m•K))	15.677882			
Pre-test	ρ (kg / m³)	7154.1237			
	c(J / (kg•K))	589.45255			
	k(W / (m•K))	15.981521			
NOP/NOT test	ρ (kg / m³)	7078.5582			
	c(J / (kg•K))	641.01931			
	k(W / (m•K))	18.116121			

Fig. 2. Layer Thicknesses and Equivalent Thermal Properties.

4.3 Acceptance Criterion

At NOP/NOT, the model predicted about 3.2 s response time under ideal condition. Since the regulatory limit is 8 seconds, some degree of degradation is acceptable, and the allowable degradation corresponding to 8 seconds can be represented as a reduction in thermal conductivity. This is because the primary cause of response time degradation is the deterioration of internal characteristics within the assembly. When k was reduced until τ reached 8.0 s, the conductivity dropped by about 36.5%.

Applying this degradation factor to pre-test conditions yielded:

- Ideal pre-test: 3.18 s
- With degradation: 8.429 s

Therefore, the acceptance criterion for pre-test is set at 8.429 s; hower, a conservative 8.0 s limit is recommended to ensure safety..

4.4 Results Summary

The proposed pre-LCSR test should be conducted immediately after the third RCP startup, when coolant flow is established in most loops. At this timing, nearly all RTDs can be tested under representative but moderate conditions.

The RTD assembly was simplified into a homogeneous cylindrical model, and layer thicknesses were estimated using manufacturer LCSR data with a Python optimization algorithm.

Based on the regulatory limit of 8 s at NOP/NOT, the pre-test criterion was calculated as 8.429 s using the simplified model. However, for conservatism, the acceptance limit was set to 8 s. If an RTD exceeds this value, it is considered unacceptable.

5. Application of the Simplified Model

The simplified cylindrical model can be applied to preventive maintenance. By calculating the degradation rate of equivalent thermal conductivity and assuming its continuation, the model predicts whether the response time in the next test will meet regulatory limits.

This maintenance approach can be summarized as follows.

1. RTD response time is periodically measured at the start of each outage.
2. Using the simplified model, equivalent thermal conductivity is calculated from the current and previous response times.
3. The degradation rate is determined, and the next cycle's response time is predicted.

4. If the prediction indicates non-compliance, preventive maintenance such as thermowell cleaning or RTD re-seating is performed.

Table 3: Process for Simplified RTD Modeling

Metric	Previous Test (s)	Current Test (s)	Predicted Next (s)	Action Required
Response Time(s)	4	6.5	**10.626**	**YES**
Equivalent Conductivity (W/m·K)	13.481	8.169	**4.950**	
Conductivity Change Rate	60.60 %			

Normally, if the LCSR test at the beginning of an outage shows that an RTD does not meet the response time criterion, the sensor is often replaced as a conservative measure, even if it is not defective. By applying the proposed preventive maintenance, issues such as thermowell contamination or poor RTD insertion can be resolved in advance through cleaning or re-seating. This approach helps avoid unnecessary RTD replacement and reduces maintenance costs.

6. Conclusion

This study proposes a pre-test method to minimize overhaul schedule delays caused by RTD response time failures during the second test in Korean standard nuclear plants. A simplified cylindrical model was developed to represent the RTD assembly, and layer thicknesses were optimized using manufacturer LCSR data. The model reproduced the average response time (≈4 s) and was applied to estimate response times under manufacturer, pre-test, and NOP/NOT conditions.

Based on the regulatory limit of 8 seconds at NOP/NOT, an acceptance criterion for the pre-test was derived as 8.429 seconds. For conservative application, the limit for pre-test was set to 8 seconds. This criterion enables abnormal RTDs to be detected before the formal LCSR test.

The model also supports predictive maintenance by tracking thermal conductivity degradation across cycles, predicting future response times, and allowing preventive actions such as thermowell cleaning or RTD re-seating. This approach improves maintenance efficiency and avoids unnecessary RTD replacements.

7. Limitations

Although the proposed method provides a practical way to predict RTD response, several limitations remain:

1. The complex RTD geometry was simplified as a homogeneous cylinder, reducing detailed accuracy.
2. The model relied on limited technical drawings and documents, leaving some uncertainty in layer properties.
3. A constant degradation rate of thermal conductivity was assumed, though it may vary in reality.
4. Field validation has not yet been performed under real plant conditions.

Despite these limitations, the model still offers a useful basis for RTD response prediction and maintenance planning.

ACNKOWLEDGMENTS

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