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# Modification of Reference Temperature Program in Reactor Regulating System

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## Abstract

In Yonggwang nuclear units 3 and 4 currently under commercial operation, the cold leg temperature was very close to the technical specification limit of 298℃ during initial startup testing, which was caused by the higher-than-expected reactor coolant system flow. Accordingly, the reference temperature (Tref) program needed to be revised to allow more flexibility for plant operations. In this study, the method of a specific test performed at Yonggwang nuclear unit 4 to revise the Tref program was described and the test results were discussed. In addition, the modified Tref program was evaluated on its potential impacts on system performance and safety. The methods of changing the Tref program and the associated pressurizer level setpoint program were also explained. Finally, for Ulchin nuclear unit 3 and 4 currently under initial startup testing, the effects of reactor coolant system flow rate on the coolant temperature were evaluated from the thermal hydraulic standpoint and an optimum Tref program was recommended.

## 1. Introduction

During the initial startup testing of Yonggwang nuclear unit (YGN) 3 and 4, the higher-than-expected reactor coolant system (RCS) flow caused an increase of about 2℃ in the operating cold leg temperature (Tcold) at full power. The measured Tcold was very close to the technical specification limit of 298℃, which reduced the flexibility for plant operations. The relation between reactor coolant temperature and flow rate is straightforward as follows:

$$Q = \dot{m}\,\Delta h = \dot{m}\,C_p\,\Delta T \qquad (1)$$

where, Q, $\dot{m}$, $\Delta$h, $\Delta$T represent the reactor power, RCS flow rate, enthalpy rise and temperature rise, respectively.

The Tref program for reactor coolant average temperature (Tavg) is programmed as a function of turbine load to satisfy the main steam pressure requirements. The reactor regulating system (RRS), in conjunction with the control element drive mechanism control system (CEDMCS), forms a closed-loop control system which automatically maintains a programmed Tavg by adjusting reactivity through CEA position changes. Since the Tref program is made based on the nominal design flow rate of 100%, the higher flow rates reduce the temperature rise through the core, which decreases the hot leg temperatures (Thot) and increases the cold leg temperatures (Tcold) while the Tavg is maintained constant. Hence the actual Thot and Tcold become deviated from the nominal design values.

To resolve this problem, two approaches were originally proposed either to lower the Tcold or to increase the technical specification upper limit. The technical specification range for Tcold is between 294°C and 298°C at 100% power. It would be convenient therefore to increase the upper limit by 1°C or 2°C to either 299°C or 300°C. Unfortunately, this change would require a major revision to FSAR Chapter 15 safety analyses (most likely the steam line break accident) and to loss of coolant accident (LOCA) assumptions in FSAR Chapter 6. Also, the large mass of water contained in the cold legs along with increased maximum Tcold would increase the stored energy and the potential energy release to the containment during the LOCA. As a result, it was not practical to modify the technical specification limit for Tcold. Therefore, the first alternative, i.e. Tcold reduction, was chosen to resolve the Tcold problem.

It is obvious that a reduction in SG pressures follows Tcold reduction. However, the measured SG pressures were about 1095 psia, 25 psia margin against the warranted value of 1070 psia. The approximate margin between the actual SG exit pressure and the minimum design pressure could be determined by adjusting SG dome pressures. A plant trend group at that time indicated SG dome pressure at about 1095 psia at 99.7% plant power. The SG exit pressure was 1089 psia, about 6 psia less. Margin to minimum pressure was therefore about 19 psia. This means SG dome pressure must be higher than or equal to 1076 psia to ensure that SG exit pressure is higher than or equal to 1070 psia. During initial startup testing of YGN 4, a specific test was performed to establish a new Tref program for Tcold reduction. The revised Tref program based on the test results was evaluated with respect to the system performance and safety.

In this paper, the test methods for revising the Tref program were described and the test results were discussed. The modified Tref program was evaluated on its potential impacts on system performance and safety. In addition, the methods for changing the Tref program and the associated pressurizer level setpoint program were described. Finally, for Ulchin nuclear unit (UCN) 3 and 4 currently under initial startup testing, because it is expected to have high RCS flow rates similar to YGN 3 and 4, the effects of RCS flow rate on the coolant temperature were evaluated from the thermal hydraulic standpoint and an optimum Tref program for UCN 3 and 4 was recommended.

## 2. Overview of Related Systems

The RRS in conjunction with the CEDMCS maintains the Tavg within a desired, predetermined program. The Tref for Tavg is designed to be a function of turbine first stage pressure. This design is based on and takes advantage of the fact that the turbine first stage pressure increases almost linearly with turbine load. The higher Tavg is maintained, the higher steam generator temperature will be for any given load condition on the secondary. Since the steam generator is at saturated conditions, its pressure will be higher for higher temperature conditions. Since the turbine generator is designed for the most efficient operation at one particular steam pressure, it is desirable to maintain steam pressure as near the design value as possible.

The linear output signal from the turbine first stage pressure instrumentation is denoted as the turbine load index (TLI). The TLI signal is used by the RRS to produce a Tref signal. This signal corresponds to the designed Tavg vs. reactor power program for the optimum plant operating conditions. In order to assure accuracy of the RRS system calculations, the turbine first stage pressure transmitters that input to the RRS must be properly calibrated. The calibration range of the transmitters must be equivalent to 0-125% of turbine throttle flow and 0-65 $kg/cm^2$ of turbine first stage pressure for the 4–20 mA output of the pressure transmitter.

The RRS generates a programmed signal representing the RCS Tavg to the pressurizer level control system (PLCS) for control and display. The main purpose and function of the PLCS are to provide a mechanism for the automatic and manual control for pressurizer level by controlling chemical and volume control system (CVCS) charging flow and letdown flow rate. A pressurizer level setpoint is variable. With Tavg being below approximately 297.94°C (corresponding to 15% power), the pressurizer level setpoint is held constant at a minimum value of 33%. Above 297.94 °C and up to the normal full load Tavg of approximately 311.58 °C, the level setpoint is ramped linearly from the original 33% to a maximum of 52.6%.

## 3. Modification of T-ref Program

### 3.1 Test Method

During initial startup testing of YGN 4, a test was performed to modify RRS Tref program in order to lower the cold leg temperatures sufficiently below the technical specification upper limit. The main purpose of the test was to allow more flexibility for plant operations by increasing margin to the technical specification limit of 298 °C. Based on overall review of the plant conditions, the target for Tavg reduction at 100% power was set at 1°C. The boron exchange technique was used. The cold leg temperature was lowered by securing normal makeup to compensate for negative reactivity effect due to fuel depletion. The concept was to measure any change in electric output due to Tavg reduction by 1°C while SG dome pressure being ensured to be higher than or equal to 1076 psia. While Tavg being lowered, fine adjustments were made to the turbine control valves to maintain reactor power as constant as possible.

As the first step of the test, the base data were collected during maintaining the plant conditions steady for 2 hours. Then two sets of plant parameters were collected for two hours for each set following Tcold reduction by 0.5°C sequentially. While the reactor power was maintained as constant as possible by normal makeup to compensate for fuel depletion, data was collected to determine the optimum Tref program. Major plant trend group included Tcold, Thot, SG pressures, turbine first stage pressures, electrical output, departure from nucleate boiling ratios (DNBR), linear heat rate (LHR), reactor powers, etc.

### 3.2 Test Results and Discussions

The test results are summarized in Table 1. Fig. 1 shows the trends of major parameters during the test. Using a combination of gradual opening of turbine control valve no. 4 and securing the normal makeup, Tcold was successfully lowered by about 1.2°C to approximately 295.7°C with the secondary calorimetric power kept constant. At the same time, as Tcold was lowered, Tavg was also lowered by about 1.0°C to 310.1°C. Based on the test results, it was recommended that the RRS Tref program should be reset from its original full power value of 311.58°C to 310.28°C, a net decrease of 1.3°C. In order to maintain the new operating conditions for the recommended RRS Tref program, the Tref program and the associated pressurizer level setpoint program were revised.

The DNBR and LHR power operating limits (POL) were increased according to Tcold decrease as expected. This effect was sufficient to compensate for slight decrease of thermal efficiency in the aspects of the plant performance or the plant operational flexibility. The POL derivative depending on temperature is defined as $\partial POL/\partial T$ and its value was -0.4938 for YGN 3 and 4 cycle 1. The reduction in Tavg caused a reduction in SG pressures while the minimum SG pressure was still maintained with sufficient margin. The thermal efficiency was slightly decreased as expected. Although the enthalpy at SG exit was increased along with the decrease of SG pressure, the increase of enthalpy at turbine exit was greater than that at turbine inlet. The decrease of Thot at full power will provide better integrity of SG tube.

The effects on other systems and safety analyses of modification of RRS Tref program were also evaluated. It was concluded that new operating conditions did not affect other system design results if main steam pressure requirement was satisfied. In addition, the Tcold variation within the technical specification limit did not affect the safety analyses results. Thus the new Tref program could be applied to YGN 3 and 4 successfully without any additional documentation and any changes in other system designs.

### 3.3 Installation of New Tref Program

As mentioned in the previous section, the Tref program setpoint in RRS and the associated pressurizer level setpoint program should be revised in order to maintain the new operating conditions. At 100% power, TLI is about 8.0 VDC, which is equivalent to 52.0 kg/cm$^2$g of turbine first stage pressure. The turbine first stage pressure transmitters are calibrated in the range of 0-65 kg/cm$^2$g which is equivalent to 0-125% turbine power indicated by TLI. When TLI is at 100%, original Tref should be at its upper limit which is 311.58 °C. The original Tref has the following relation with TLI:

$$T_{ref} = 0.2 \times TLI + 0.4555 \qquad (2)$$

where Tref and TLI are the values in VDC normalized for Foxboro software. To change the Tref program, the gain needs to be adjusted to accommodate any temperatures in the range between 250°C and 350°C range which is equivalent to 0-10VDC for Tref. The gain in the relation between Tref and TLI was revised for the new Tref program while the bias was not changed. The revised gain was 0.1841. This change is shown in Fig. 2. With the revised gain, Tref was at its upper limit of 310.28°C when TLI was at 100%. The pressurizer level program needed to be revised as well with changing the Tref program. Accordingly, the related gain and bias were revised appropriately as shown in Fig. 3.

## 4. Recommendations on UCN 3 and 4

The RCS coolant flow rates of UCN 3 and 4, currently under initial startup testing, are expected to be similar to those of YGN 3 and 4. Thus, in this study, the effect of RCS flow rate on the coolant temperature was evaluated from the thermal hydraulic standpoint, and an optimum Tref program for UCN 3 and 4 was proposed. Investigated first were the best estimate coolant temperatures for the maximum allowable flow limit, 113.1% and the nominal design flow rate, 100%. Those are calculated based on the Tavg maintained at 311.58°C during the normal operation of 100% power, which are shown as the best estimate (BE) in Table 2. If the ± 1.1°C (2°F) dead band of RRS Tref control program is taken into consideration, the Thot and Tcold have the maximum and minimum expected bounds. The expected ranges of the temperatures is provided in Table 2. For other flow rates in between, the Thot and Tcold are interpolated from the end values and plotted in Fig. 4, where Thot is gradually decreasing and Tcold is increasing with flow rate.

The predicted maximum Tcold curve meets the technical specification limit of 298°C near at the flow rate of about 107.5% as shown in Fig. 4; Thus it is probable that Tcold at the actual flow rate exceeds the limit because the RCS flow rates of UCN 3 and 4 are expected to be between 108-110% of nominal design flow rate for the beginning phase of plant life. The associated measurement uncertainty is not included because this calculation is performed on a best estimate basis. Based on the data in Fig. 4, it is necessary to move Tref program in RRS downwards by some degrees to eliminate or reduce the possibility of exceeding the technical specification limit, which will reduce Tavg and Tcold by approximately the same amount.

The samples of Tcold reduction are investigated as shown in Fig. 4. The 0.4°C is the minimum required that makes the upper bound curve to just meet the technical specification upper limit of 298 °C at 110% of nominal design flow. The 1.3°C is what was actually selected for YGN 3 and 4 Tref adjustment; the lower bound curve was lowered to meet the technical specification limit 294°C at 104.5% design flow.

The 1.0°C is recommended for the optimum value for Tref reduction because it is not too much and not too less to ensure that the Tcold upper limit of technical specification, 298°C, will not be violated unless the RCS flow rate exceeds 113%. Since the Tref was reduced by 1.3°C for YGN 3 and 4 and the impacts on the plant performance have been successfully managed so far, the 1.0°C reduction is expected to be acceptable for UCN 3 and 4.

## 5. Conclusions

A specific test was successfully performed to modify the Tref program at YGN 3 and 4. Also, the modified Tref program and the associated pressurizer level control program were successfully installed into plant control systems. Consequent Tref program allows sufficient margin to the technical specification limit of cold leg temperature. Evaluations showed that it did not affect other system design and safety analyses. In addition, the operating margins in DNBR and LHR were increased sufficiently to compensate for the slight decrease of thermal efficiency. For UCN 3 and 4, the analyses showed that the 1.0°C would be the optimum value for Tref reduction, which assures that the Tcold upper limit of technical specification will not be probable to be violated unless the RCS flow rate exceeds 113% of nominal design flow.

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Table 1. Summarized Test Results

| Parameter | Base Data | 1st Data Set | 2nd Data Set |
|---|---|---|---|
| Tavg (°C)[1] | 311.12 | 310.53 | 310.08 |
| Tcold (°C)[2] | 296.92 | 296.26 | 295.74 |
| SG Pressure (psia($kg/cm^2g$))[3] | 1106.2(77.79) | 1094.1(76.94) | 1085.6(76.34) |
| TFSP ($kg/cm^2g$) | 53.53 | 53.64 | 53.72 |
| Turbine Control Valve No. 4 Opening Position (%) | 25.7 | 29 | 31.5 |
| COLSS LHR POL (%) | 110.67 | 111.20 | 111.21 |
| COLSS DNBR POL (%) | 113.68 | 114.68 | 115.25 |
| Reactor Power (BSCAL)(%) | 99.36 | 99.49 | 99.57 |
| Electrical Output (MWe) | 1039.23 | 1039.57 | 1040.73 |
| Efficiency(100*MWe/BSCAL)(%) | 37.15 | 37.12 | 37.13 |

Note:
1. Average of Thot and Tcold from safety channel
2. Tcold from safety channel
3. Average of SG 1 and 2 pressures

Table 2. Temperature Ranges over Design Flow Band

| Flow (%) | Temperature(°C) | BE-dead band | BE | BE+dead band |
|---|---|---|---|---|
| 100 | Hot Leg | 326.22 | 327.33 | 328.44 |
| | Average | 310.47 | 311.58 | 312.69 |
| | Cold Leg | 294.72 | 295.83 | 296.94 |
| 113.1 | Hot Leg | 324.39 | 325.50 | 326.61 |
| | Average | 310.47 | 311.58 | 312.69 |
| | Cold Leg | 296.56 | 297.67 | 298.78 |

Fig.1 Trends of Key Parameters during Testing

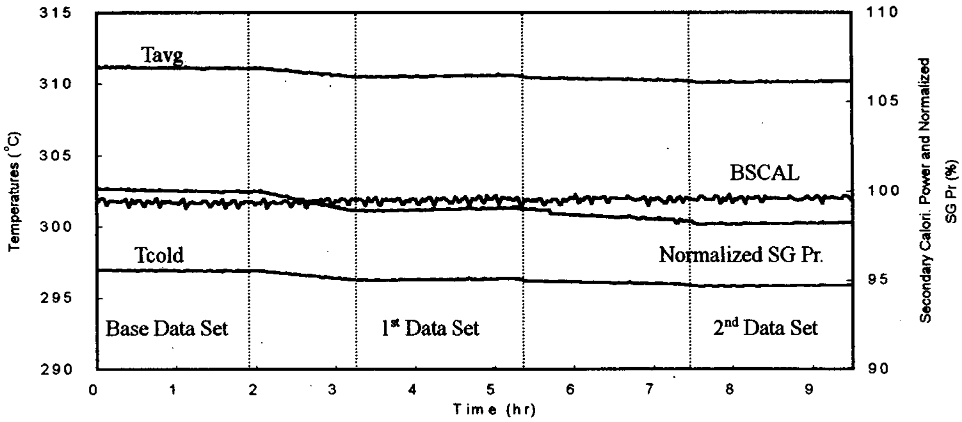


Fig.2 Tref vs. TLI for Original and Modified Tref Programs

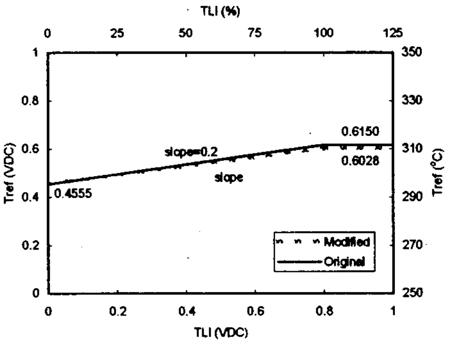


Fig.3 PZR Level Setpoint vs. Tavg for Original and Modified Tref Programs

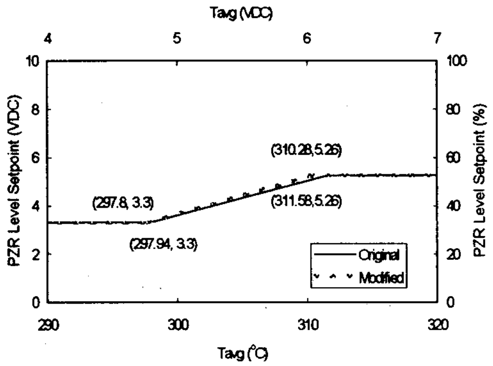


Fig.4 Maximum and Minimum Adjustments of Tcold for UCN 3 and 4