The Three-Dimensional Temperature Indication for the Reactor Core by Using Multiple Thermocouples

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***Abstract*— The premise of accident mitigation lies in the accurate diagnosis of the accident. The serious accident, in which the core of the nuclear reactor at the nuclear power plant (NPP) is melted, is a very serious problem. Examples of this kind of accident may be found in the Fukushima accident. Therefore, a rapid incident response and accurate diagnosis is more important than anything. The ultimate goal of severe accident mitigation at a nuclear reactor is to maintain the confidentiality of the containment building and the cooling of the core meltdown in the reactor. Confirming the progressive state of diagnosis and the cooling of the reactor core when the serious accident occurs is a very important factor in the development of response strategies after the accident. Japan has taken various measures to deal with accidents after the nuclear accident of Fukushima. Strengthening the reliability of the instrumentation system is also included in the counterstrategies. Therefore, this paper presents the expected effects and the temperature distribution display method of the core by using an in-core instrumentation (ICI) with multiple thermocouples. This research project is currently underway in Korea.**

Keywords- In-core instrumentation(ICI), severe accident(SA), thermocouple(TC), nuclear power plant(NPP) , core exit temperature (CET)

I. INTRODUCTION

Currently, the In-core Instrumentation (ICI) is installed in the reactor to detect the neutrons generated by the fission process in the reactor. It is also used to measure the burn-up and output distribution of the nuclear fuel in a domestic nuclear plant in Korea. Generally, the quantity of the ICI can be very different according to the number of fuel assemblies in the NPP. In the case of SKN 3 and 4 in domestic NPPs, they were designed to be 61 ICIs in order to provide information on the core cooling of the inadequate core cooling monitoring system (ICCMS). This measured temperature could also be used to check the entry condition of severe accidents. In other words, on the basis of the core exit temperature (650 ℃ standard) obtained from the K-Type thermocouple that exists on top of the In-core Instrumentation (ICI), the condition leading to the serious accident advances. Confirming the progress state for the reactor core when a serious accident occurs is a very important factor in the development of response strategies after the accident. If we could know the upper temperature as well as the temperature distribution (upper, middle, bottom) in the reactor core, it could considerably help us to address serious accidents. Therefore, this paper suggests the three-dimensional temperature indication of the full range for the reactor core without changing the shape of in-core instrumentation (ICI).

II. THE CHARACTERISTICS OF EXISTING IN-CORE INSTRUMENTATION (ICI)

A. The Structure of In-Core Instrumentation (ICI)

The ICI is a critical instrument with a total length of 35 meters. It can measure the amount of neutrons three-dimensionally in real time in the reactor core of a NPP. The configuration of ICI is made of five neutron detectors for detecting thermal neutron flux, one thermocouple for measuring the reactor core exit temperature (CET), one background detector for the correction of the detector signal, and eight filler cables for filling the remainder of the annulus, as shown in Figure 1.

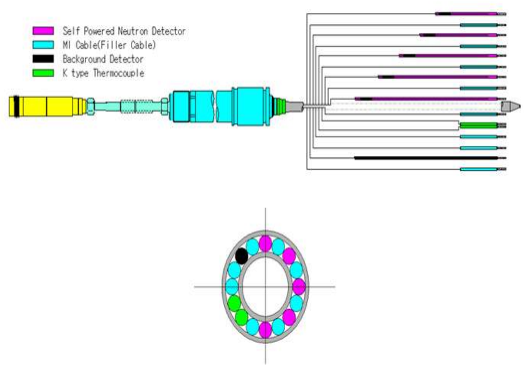

Figure 1. The configuration diagram of existing ICI

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The K-Type thermocouple made with 2 cables, a background detector and eight filler cables wrapped helically around an inner central member and encased by an outer sheath tube. The outer sheath tube protects the detectors and thermocouple from contacting the reactor coolant .The outer sheath tube is connected to the header/seal plug through an adaptor, which provides the sealing surface to the reactor core. The detector assemblies are capable of providing the means to monitor in-core neutron flux over the entire range.

The core exit thermocouple utilizes alumel and chromel wires with a grounded junction. Each alumel and chromel wire is mineral-insulated and sheathed separately with AL_2O_3 insulation and an Inconel 600 sheath. The materials of sheathe tube have been selected to withstand the effects of the reactor coolant system pressure, temperature and radiation.

The ICI assembly includes a central member assembly. The central member assembly is straight and joined to the seal plug header by brazing. The detector cables are connected in a metal flexible waterproof conduit which extends from the seal plug to the electrical connector. All detectors should extend the full length of the ICI assembly. All components and materials used in the assembly have been thoroughly proven to satisfy the design specification.

B. The Characteristics of the K-Type Thermocouple

The K-type thermocouple is widely used in nuclear power plants (NPP) and it provides reliable service. Generally, the thermocouple assembly is the finished product. Usually, only nondestructive tests are performed on the assembly, whereas destructive tests are confined to selected bulk cable specimens [1]. This K-type thermocouple has been used representatively in the In-Core Instrumentation (ICI) of nuclear power plants. It generates a low voltage output which is directly proportional temperature due to Peltier and Thomson effects.

Generally, in the event of a serious accident at a NPP, such as Fukushima, the temperature of the reactor will rise rapidly. It is difficult to monitor the inside situation of the reactor. Therefore, our goal was to confirm the behavioral characteristics of the K-type thermocouple when the reactor is exposed to high temperatures and create an environment by using a blast furnace at 1500℃. To confirm the behavioral characteristics of the thermocouple, we put the thermocouple slowly into a blast furnace and measured the reference data (temperature, voltage, resistance) using a recorder per 0.5 sec, as shown in Figure 2.

Figure 2. The recorder and blast furnace

The K-type thermocouple is usually capable of measuring temperatures up to 1260℃ degrees [4]. However, these tests show some different results that confirmed it to be possible to detect up to 1350℃ degrees before the cables melt. The temperature rapidly increases during insertion into the melting furnace. However, it is not possible to determine an accurate temperature when melting begins. Therefore, data on the voltage or resistance can only be used to confirm the approximate degree of melting rather than the exact temperature due to changes in the cable resistance caused by high temperature and noise, as shown in Figure 3.

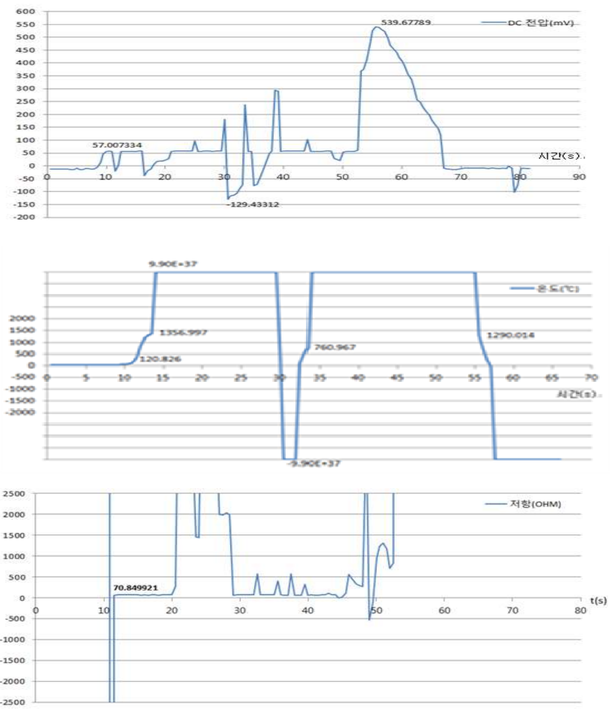

Figure 3. The test result (voltage, temperature, resistance) in the blast furnace

This test illustrates the estimation possibility for the status of molten core through the high-temperature characteristics test of the K-type thermocouple. It turns out that it is possible to measure the K-type thermocouple up to 1350℃ degrees before melting during insertion into the melting furnace [2].

III. THE DEVELOPMENT OF ICI WITH MULTIPLE THERMOCOUPLES

A. The Contents of Major Design Changes for ICI

This is a method of additionally building more than one K type thermocouple that is able to measure up to 1260 ℃ in an existing ICI. The thermocouple added is installed and a requested position is placed after removing the filler cables in the existing ICI. The filler cables are located in the ICI to fill the space for the existing components, which are neutron detectors, a thermocouple, and a background detector. As the filler cable was removed, it was replaced with a thermocouple in place. These thermocouples act as existing filler cables.

This design change makes it possible to take the temperature of the required position in the reactor core before it melts. After the temperature measuring junction, the rest of the cables is used as the existing filler cable. The temperature measuring junction was made to be in contact with the protective tube of the ICI to speed up the reaction time for the temperature measurement. The multiple thermocouples ICI is enlargedly applicable up to five from one without changing the appearance of the conventional ICI, as shown in Figure 4.

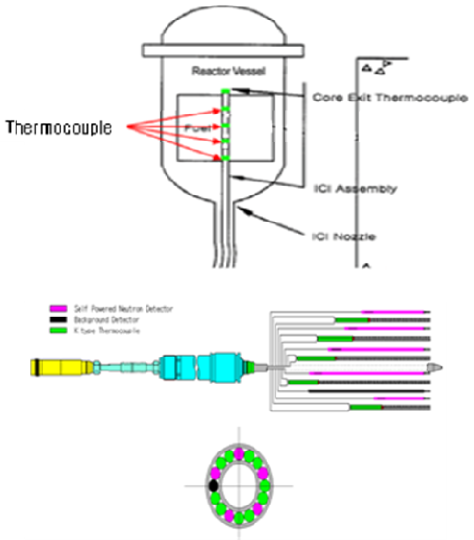

Figure 4. The schematic diagram for multiple thermocouples ICI

In the case of APR1400 (a reactor type in Korea), it is possible to indicate the three-dimensional temperature of the reactor core by placing up to maximum 305 TC(ICI 61 × TC 5) in the reactor core, including the entire bottom of the reactor. Generally, a thermocouple of ICI is provided for the measurement of the outlet temperature for the reactor core.

This temperature is used to confirm the entry condition of serious accidents. The using of a multiple thermocouple ICI enables us to measure the temperature for the reactor core that was not damaged during the normal operation and serious accidents. Further, it is possible to know the state of the reactor core by comparing the indication points where the temperature is indicated or not.

B. The Expected Benefits of Multiple Thermocouples ICI

The degree of core damage is very important information in determining the mitigation strategies for accidents. The accurate information about the degree of core damage is more important when determining a more effective injecting between the cooling water in the reactor and the reactor outside (reactor cavity) than during the accident. The temperature stereoscopic information provided by the multiple thermocouples is very important information to verify the validity of core cooling after injecting cooling water in the reactor, as shown in Fig 5.

This information is very useful to determine the extent of damage to the core and estimate the degree of oxidation of the nuclear fuel cladding material. The existence of more thermocouples in many places in the reactor core can be close to the actual estimate of the degree of oxidation for the coating material. Thus, the importance and necessity of multiple thermocouples is suggested in terms of diagnosis and the mitigation of accidents in NPPs.

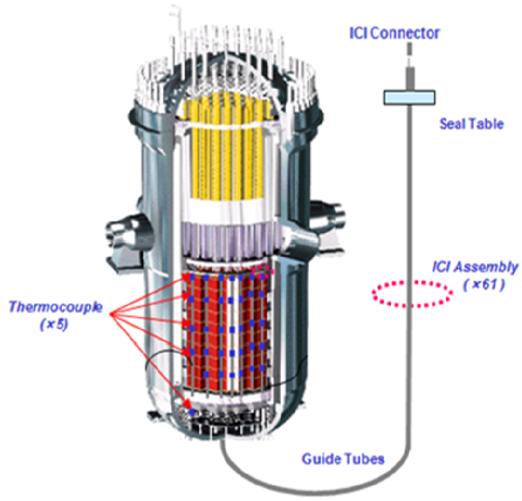

Figure 5. The schematic diagram of the installed multiple thermocouples ICI

A multiple thermocouples ICI provides information about the three-dimensional core state, which can be explained by the following effects:

1) *Core damage ratio and shape information:* Using a survival distribution and temperature distribution of the multiple thermocouples ICI can provide information about the realistic core damage rate and shaped core damage. Thus, the melting ratio of the reactor core and the cladding oxidation can be estimated during severe accidents.

2) *Provide accurate information about the geometric area for reacotr core:* This information provides the position and percentage of the area that is not damaged by the reactor core. This can become crucial information to determine the possibilities of the reactor core cooling and the basis for determining the cooling water injection.

3) *Provide information of position for core molten pool:* It is possible to estimate the formation position of the molten pool with respect to the non-survival region of multiple thermocouples ICIs at that time. This is important information for the cooling strategy to select more effective methods between the outside (reactor cavity) and inside of the reactor for cooling water.

4) *Provide information of cooling validity for reactor core*: When the cooling strategy of reactor was executed, it was to provide more reliable information about whether the cooling of the reactor core is being performed properly or if the cooling is not sufficient. The success or failure for cooling strategy in the melted reactor core considerably affects the implementation decisions of the outdoor cooling strategy for the reactor.

5) Secure the diversity for reactor core monitoring system: It is possible to obtain status information and to ensure the diversity associated with multiple thermocouples' ICI for the reactor core through many available thermocouples, even though the malfunction or failure of several thermocouples occurred [3].

IV. CONCLUSIONS

The In-Core Instrumentations (ICIs) were used to detect the Core Exit Temperature (CET) in a reactor. This measured temperature was also used to check the entry condition of severe accidents. However, if a serious accident occurs, the upper portion of the core is damaged. This instrument has not been available. If we could know the upper temperature, as well as the temperature distribution (upper, middle, bottom) in the reactor core, it could help us considerably to address the serious accident. Therefore, this paper suggests a three-dimensional temperature indication of the full range for the reactor core without changing the shape of the existing In-Core instrumentation (ICI).

The use of a multiple thermocouple ICI enables us to measure the temperature for the reactor core that was not damaged during the normal operation and serious accidents. The degree of core damage is very important information in determining the mitigation strategies for accidents. The temperature stereoscopic information provided by the multiple thermocouples is very important information to verify the validity of the core cooling after injecting cooling water in the reactor. In this study, the expected benefits of multiple thermocouples ICI were introduced to help the diagnosis and mitigation of accidents in NPPs.

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