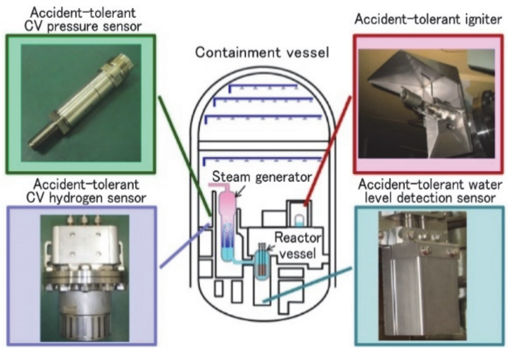
Development and Implementation of New Accident Tolerant Instruments Against Severe Accident Conditions - Enhancing Reliability of Measurements During Severe Accidents -



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Based on the lessons learned from the Fukushima Daiichi Accident, new regulatory requirements request enhancement of reliability for instrumentation and monitoring systems in severe accident management. Particularly it is essential for in-situ instrumentation, located in a containment vessel, to have function to withstand harsh environmental conditions during a severe accident. Therefore, Mitsubishi Heavy Industries, Ltd. designed and developed new accident-tolerant sensors such as pressure, water level and hydrogen monitoring system and a hydrogen igniter to withstand severe accident environmental conditions of high-temperature, high-pressure steam atmospheres with chemical spray and high radiation exposure through qualification testing. These new accident-tolerant sensors were installed and have been in operation in domestic PWRs.

1. Introduction

In March 2011, the Great East Japan Earthquake occurred. A tsunami after the earthquake led to loss of power supply and to be consequently failure of safety functions of multiple systems and components at the Fukushima Daiichi Nuclear Power Plant. The subsequent inability to maintain proper reactor cooling made core damaged, and caused a severe accident that resulted in a hydrogen leak and explosion. In instrumentation and monitoring system, the reliability of measurement in a harsh environment during a beyond-design-basis event became an issue, as especially represented by the fact that the reactor water level readings during the core degradation significantly differed from the actual water levels. Based on this lessons learned, as measures for further improvement of safety, in order to prevent the occurrence and propagation of severe accidents caused by large-scale natural disasters or acts of terrorism such as intentional large airplane crash and to take countermeasures, practical application of new sensors with improved reliability and durability of instrumentation functions was urgently required.

Especially when it comes to the plants with Pressurized Water Reactor (PWR), the equipment installed inside the containment vessel (hereinafter referred to as CV) is required to withstand distinct environmental conditions during an accident. These include the exposure to water from the CV spray system, the generation of high-temperature, high-pressure steam resulting in vapor infiltration, condensation etc., and the exposure to extremely high doses of radiation. The environmental conditions under a severe accident, which is in new regulatory requirements established after the Fukushima Daiichi Accident, are much more severe than those under original design-basis accidents (hereinafter referred to as DBAs) as shown in **Figure 1**(a). In such an environment of extremely high levels of thermal load and radiation, it is difficult to use electronic components and circuits containing organic materials and semiconductors. This indicates that conventional sensors for DBAs monitoring, with exceptions such as sheathed type thermocouples or resistive temperature detectors made of materials with less thermal and radiation degradation (e.g., metal and ceramics), are not applicable to

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sensors for severe accident monitoring. Therefore, Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) started developing accident-tolerant sensors for the measurement object shown in Figure 1(b), excluding the temperature sensors and structurally similar sensors, among the instrumentation functions newly required to be installed.

This report pertains to our newly developed products that function in severe accident environments. Specifically, these include sensors for in-situ measuring pressure, water level and hydrogen concentration in the CV, and the electric hydrogen burner (i.e., hydrogen igniter) in which the heater is used to heat and burn hydrogen. Their products' specifications and qualification test results are presented in this paper and current status of installation in domestic PWR plants and our standardization initiatives are also reported.

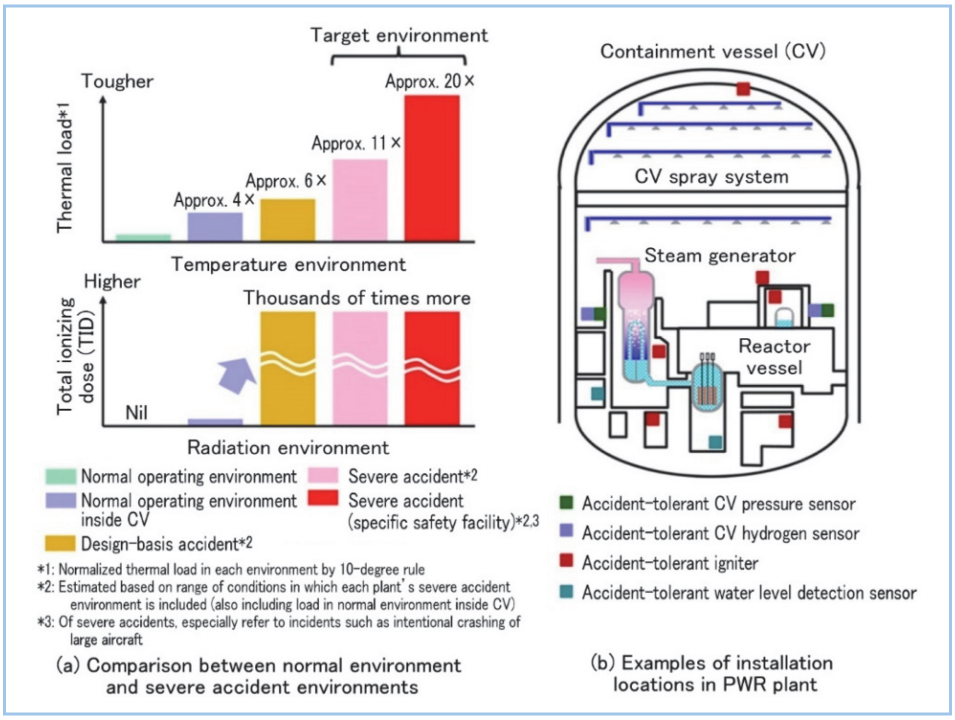


Figure 1 Severity of severe accident environment and sensor installation locations

2. Research and Development of accident-tolerant sensors

2.1 Intended Application

Intended application and objectives of newly developed accident-tolerant sensors are as follows:

(1) Containment pressure sensor

This sensor provides in-situ measurement of containment atmosphere pressure, and gives important information to operate filtered vent system which protects a CV against overpressure failure.

(2) Containment hydrogen sensor

This sensor provides in-situ measurement of containment atmosphere hydrogen concentration during a severe accident that results in serious core damage, and gives information necessary to identify hydrogen generation and the risk of hydrogen combustion, deflagration or detonation.

(3) Hydrogen igniter and temperature sensor for monitoring igniter operation

This equipment is used to control combustible gases such as hydrogen released at the early stage of a severe accident for preventing a hydrogen explosion that could damage the CV. The temperature sensor provides information for operators to understand if the equipment works to reduce hydrogen concentration.

(4) Containment level switch

This sensor detects that preflooding in the lower reactor cavity compartment has been completed for effective molten core cooling, and that a water level has been reached in order to control the upper limit for water injection from an external water source for the purpose of core cooling and preventing CV failure.

2.2 Specifications with improved design to withstand severe accident environments.

Followings are product specifications and brief design description of our newly developed accident-tolerant sensors, which summarize how to withstand severe accident environments. Due to weakness of electronic components and circuits under the harsh environments, the transducer, which converts sensor output into a preset signal, is installed outside the CV so that electronic components and circuits are isolated from harsh environments of high temperature, high pressure vapor atmosphere and high radiation exposure in the event of an accident.

(1) Accident-tolerant CV pressure sensor

Table 1 shows the product's specifications and exterior view. The measurement principle is given in **Figure 2**(1). As shown therein, the sensor operates on the principle of measuring the change in the resistance caused by the changes in the cross-sectional area and length of the strain gauge (which is a metal foil mesh bonded onto the insulator), when pressure is applied to the diaphragm.

The strain gauge is usually bonded onto a thin resin insulator with a lead wire attached to it. To achieve higher environmental performance, resin was replaced by an inorganic insulating material, and the strain gauge was directly adhered to the surface of a diaphragm. The screening of a sensor with better performance in high-temperature has resulted in high measurement accuracy even at temperatures as high as those in severe accidents.

Table 1 Specifications of accident-tolerant CV pressure sensor

Accident-tolerant pressure sensor	Item	Specification
	Measuring principle	Strain gauge
	Measuring range	0-1 MPa
	Ambient temperature	Normal temperature to 200°C
	Ambient pressure	Atmospheric pressure to 1.6 MPa
	Radiation	1 MGy
	Accuracy	±0.5%
	Temperature Effect	0.01 %RO*1/°C
	Signal output	4-20 mA*2

*1: RO: Rated Output (output at upper limit of measurement range)
*2: Output of transducer installed outside CV

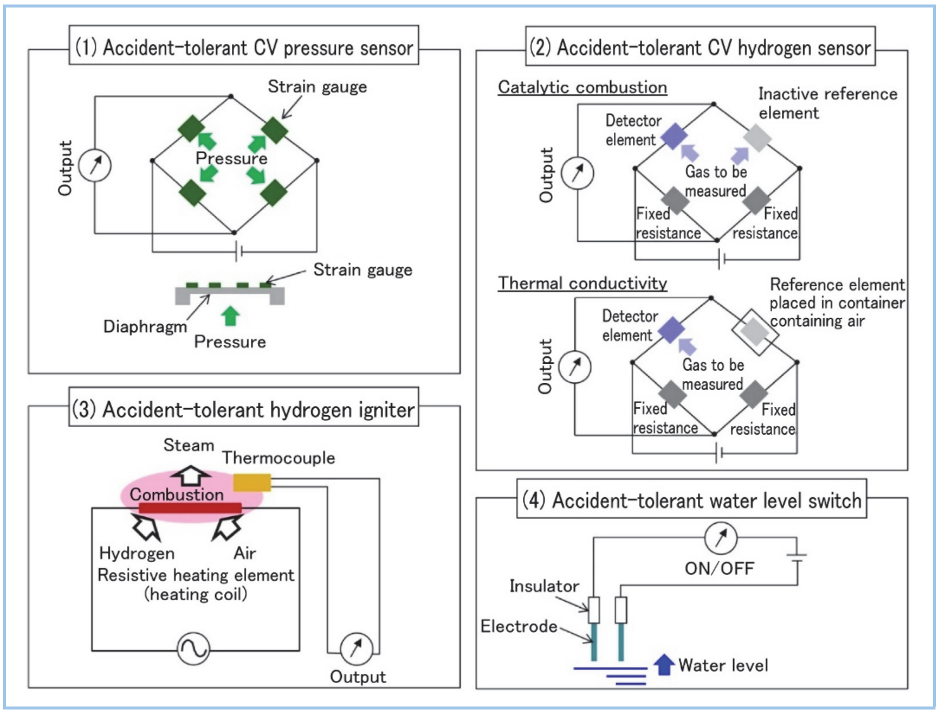
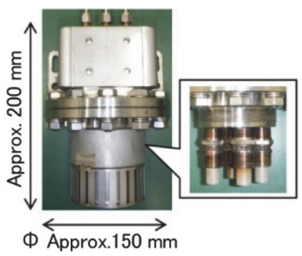


Figure 2 Measurement principles

(2) Accident-tolerant CV hydrogen sensor

Table 2 shows the product's specifications and exterior view. The measurement principle is given in Figure 2(2). As shown therein, two different principles of measurement are combined to handle the change in the atmosphere around the sensor, which ranges from the atmospheric environment to saturated steam conditions during severe accidents. Specifically, the two types of sensor detection principles are: catalytic combustion (using the heat released by the reaction between hydrogen and oxygen) and thermal conductivity (using the difference in the thermal conductivity of gases, i.e., hydrogen >> air). The former can take stable measurements in the presence of air including an environment with steam. The latter is measurable under the conditions in which the oxygen concentration is less after, for example, the operation of CV venting. To improve the environmental capability to perform reliably during a severe accident, the hydrogen sensor uses no organic materials and is protected with a waterproof cover, so that spray water and steam mist do not compromise the measurement performance.

Table 2 Specifications of accident-tolerant CV hydrogen sensor

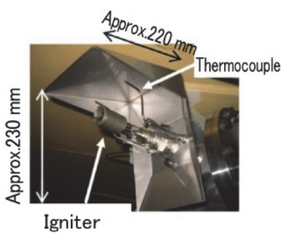
Exterior view	Item	Specification
	Measuring principle	Catalytic combustion / thermal conductivity
	Measuring range	0-20 vol%
	Ambient temperature	Normal temperature to 200°C
	Ambient pressure	Atmospheric pressure to 0.8 MPa
	Radiation	500 kGy
	Accuracy	±2-3 vol%
	Temperature effect	Included in an accuracy
	Signal output	4-20 mA*1

*1: Output of transducer installed outside CV

(3) Accident-tolerant hydrogen igniter and temperature sensor for monitoring igniter operation

Table 3 shows the product's specifications and exterior view. The operating principle is given in Figure 2(3). As shown therein, an electric heating coil, which is a resistive heating element of a coiled heater element, is used to raise the surrounding air temperature, thereby enabling hydrogen to burn near the lower limit of flammability even in air or steam atmospheres of severe accident environments. In order to monitor the temperature change resulting from hydrogen burning, the thermocouple is positioned where a marked increase in the temperature is caused by hydrogen burning and radiant heat transfer from the heater is low. The materials used for the igniter were selected considering the thermal impact of hydrogen burning on the igniter itself. The waterproof measures against spray water are also taken. Thus, the environmental capability to perform reliably during a severe accident has been enhanced.

Table 3 Specifications of accident-tolerant hydrogen igniter and temperature sensor for monitoring igniter operation

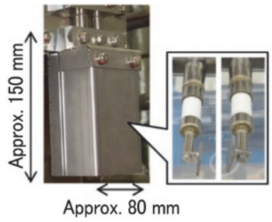
Exterior view	Item	Specification
	Operating principle	Heating coil
	Electric Energy	556 W (AC 120 V)
	Hydrogen concentration at lower limit of ignition	8 vol% or lower
	Ambient temperature	Normal temperature to 200°C
	Ambient pressure	Atmospheric pressure to 1.6 MPa
	Radiation	NA*1
	Monitoring sensor of igniter operation	Thermocouple

*1: Extremely low degradation due to equipment comprises of metal and inorganic materials (ceramics).

(4) Accident-tolerant water level switch

Table 4 shows the product's specifications and exterior view. The measurement principle is given in Figure 2(4). As shown therein, once two electrodes touch with or are immersed in water, it will conduct electricity and detect the signal. In the event of a severe accident, the ensuing atmosphere (with steam, spray water, etc.) degrades insulation. The effect of the insulation degradation (i.e., increase in the leakage current between the electrodes) is minimized by enhancing the detection sensitivity (optimization of the shape of the electrode plate attached to the tip of an electrode rod), preventing the insulator from getting wet with spray water (with the use of a waterproof cover), and optimizing the water level detection settings of current between the electrodes.

Table 4 Specifications of accident-tolerant water level switch

Exterior view	Item	Specification
	Measuring principle	Electrode
	Detection height	Within 60 mm
	Ambient temperature	Normal temperature to 200°C
	Ambient pressure	Atmospheric pressure to 1.6 MPa
	Radiation	NA*1
	Signal output	ON/OFF*2

*1: Extremely low degradation due to a sensor comprises of metal and inorganic materials (ceramics).
*2: Output of transducer installed outside CV

3. Qualification test results of accident-tolerant sensors

Typical qualification test results of newly developed accident-tolerant sensors are summarized below:

3.1 Accident-tolerant CV pressure sensor

The availability and survivability of the pressure sensor during severe accidents were quailed by testing the following: the performance in the normal environment, temperature effect up to high temperature conditions, and the survivability through the irradiation test and the steam test with chemical spray.

Figure 3 shows the results of sensor output under steam test with chemical spray (up to 200°C and 1.6 MPa), which envelope the environments during severe accidents. All the sensor outputs followed the change in the pressure inside the steam chamber, thereby verifying the survivability in severe accident environments. The availability and survivability in severe accident environments were demonstrated by testing temperature effect under high temperature conditions (up to 300°C) and radiation exposure (up to 1 MGy)[(1)(2)].

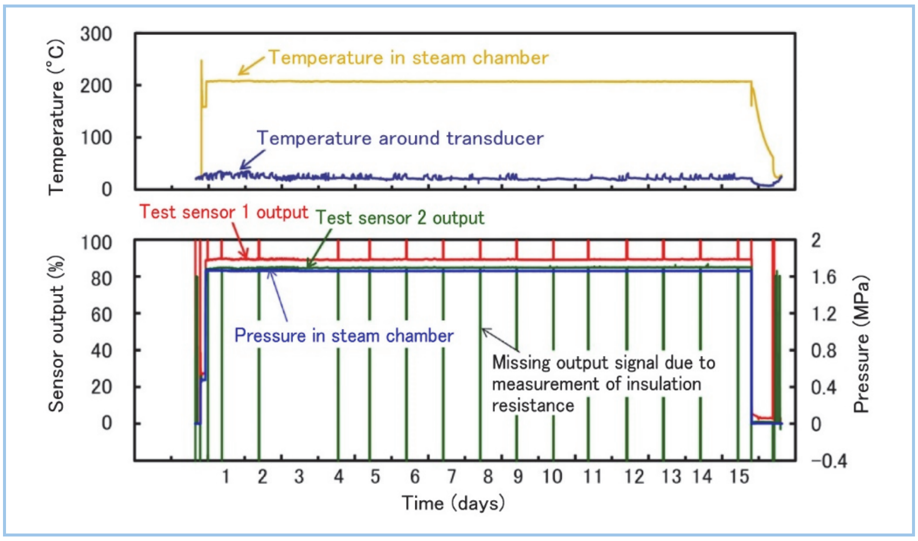


Figure 3 Accident-tolerant CV pressure sensor: steam spray test results

3.2 Accident-tolerant CV hydrogen sensor

The availability and survivability of the hydrogen sensor during severe accidents were qualified by testing the following: the performance in the normal environment, the accuracy in the steam (i.e., steam test), and the harsh environmental qualification through the irradiation test and the steam test with chemical spray.

Figure 4 shows the results of hydrogen concentration readings under the test conditions in which temperature, pressure and steam concentration were changed accordingly. In this test, two types of detecting sensor elements (i.e., catalytic combustion and thermal conductivity) are placed in a test chamber separately. The sensors with these elements were within a measurement accuracy of ±1.0 vol% and ±2.0 vol% over the measurement ranges respectively. The accident-tolerant CV hydrogen sensor is also qualified by an irradiation test (up to 500 kGy) and a steam test with chemical spray (under various conditions including saturated steam of 175°C and atmospheric pressure at 200°C) to verify the availability and survivability in severe accident environments[3][4].

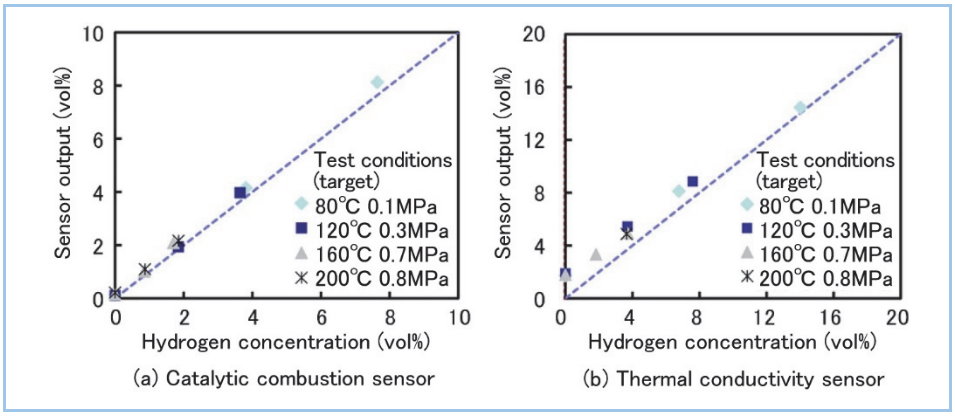
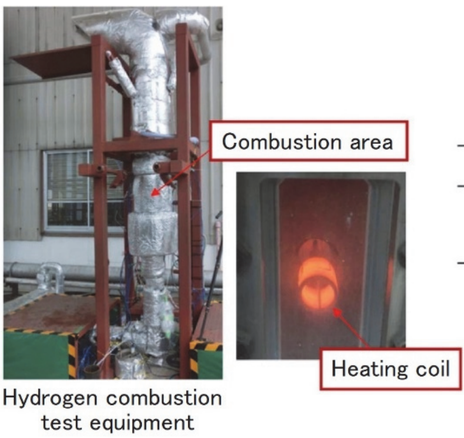


Figure 4 Accident-tolerant CV hydrogen sensor: steam test results

3.3 Accident-tolerant hydrogen igniter and temperature sensor for monitoring igniter operation

The operability in severe accident environments were qualified by evaluating the ignitability of hydrogen in the presence of steam (i.e., hydrogen combustion test) and conducting the steam test with chemical spray. The hydrogen igniter, which comprises of metal and inorganic materials (ceramics), sufficiently withstands a high level of radiation (500 kGy) during a severe accident. The temperature sensor for monitoring igniter operation is placed in such a way that the testing or analysis allows the temperature rise caused by hydrogen burning to be distinguished from that of radiant heat transfer from the heating coil.

Figure 5 shows the test results of the lower ignition limit of hydrogen concentration. In this test, the heating coil was installed in the hydrogen combustion test equipment, and hydrogen concentration was changed under the high steam concentration conditions (55 vol%). From the viewpoint of hydrogen ignition performance, unfavorable conditions are created by higher steam concentrations (the combustion reaction becomes inactive) and higher gas flow velocities (the surface temperature of the heating coil decreases). However, hydrogen was ignited under both conditions, when hydrogen concentration was 7.0 vol% or higher. This indicates that the requirements of ignitability (i.e., ignitable under conditions of a hydrogen concentration of 8 vol% or lower, steam concentration of up to 55 vol%, and flow velocity of 2.3 m/s or higher) have been satisfied.



Voltage	Steam concentration	Gas flow velocity	Hydrogen concentration	Test result
AC120V	55 vol%	5.0m/s	6.6vol%	Ignited
AC108V	55 vol%	3.7m/s	7.0vol%	Ignited

Figure 5 Accident-tolerant hydrogen igniter: hydrogen combustion test results

3.4 Accident-tolerant water level detection sensor

The availability and survivability of the water level detection sensor during severe accidents were qualified by conducting a steam test with chemical spray, in which the sensor is protected with a waterproof cover and along with the optimization of water level detection sensitivity. Furthermore, the water level detection sensor, which comprises of only metal and inorganic materials (ceramics), sufficiently withstands a high level of radiation (500 kGy) during a severe accident.

Figure 6 shows the results of sensor output under the steam test with chemical spray (up to 200°C and 1.6 MPa), which envelopes environmental conditions during severe accidents. The leak electric current is much lower than that threshold value of water level detection during spraying chemical spray, which is in the most conservative test condition (i.e., lower insulation resistance between the electrodes). This has demonstrated the availability and survivability in severe accident environments including the effectiveness of a waterproof cover.

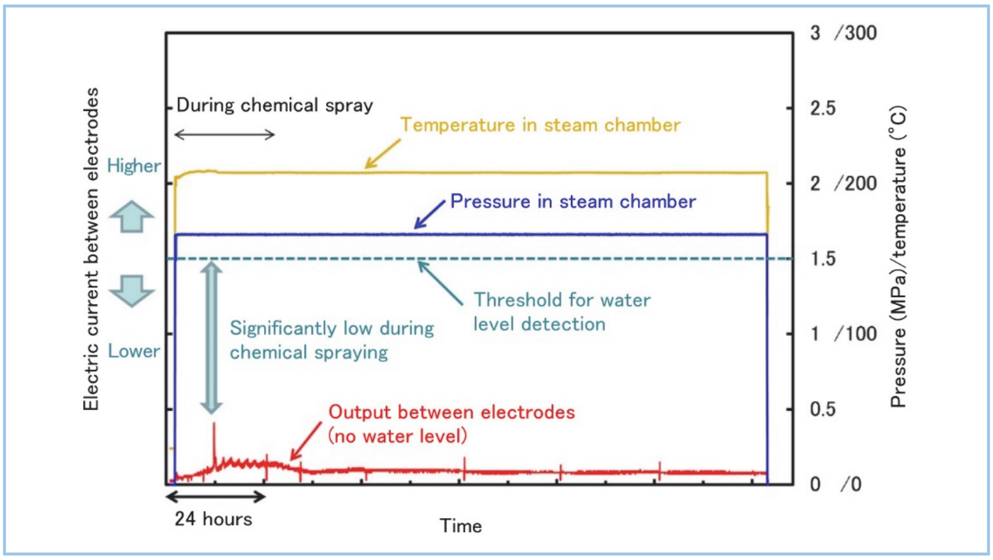


Figure 6 Accident-tolerant water level switch: steam test results with chemical spray

4. Application and our effort on standardization in PWR plants

MHI's newly developed accident-tolerant sensors application and our effort on standardization in the PWR are described below.

4.1 Application in PWR plants

Table 5 lists the number of our accident-tolerant sensors that have been installed in domestic PWR plants. These sensors meet new regulatory requirements and are in use among all restarted PWR plants in Japan. They have been in stable operation since 2015. MHI will continue to design and install these sensors in subsequent PWR plants currently under licensing in 2024.

Moreover, the development project to reduce the burden imposed on the plant staff during their operation to manage a severe accident is under way. Specifically, it pertains to enabling portable equipment to be permanently installed (e.g., realizing the practical application of accident-tolerant sensors that can be permanently installed and replace portable equipment). By providing instrumentation systems with higher environmental capability to perform reliably during a severe accident, MHI will continue to help enhance the reliability and safety of nuclear power plants.

Table 5 References in PWR plants

Sensor type	Number of sensors in operation*1	Start of operation*2
Accident-tolerant CV pressure sensor	24	From 2020
Accident-tolerant CV hydrogen sensor	24	From 2020
Accident-tolerant hydrogen igniter	160	From 2015
Accident-tolerant water level switch	48	From 2015

*1: Sensors installed in restarted plants
*2: Earliest year of restarted plants in which sensors were installed and in service

4.2 Standardization initiatives

Taking part in reviewing Standard Criteria for Accident Monitoring Instrumentation of the U.S. Institute of Electrical and Electronics Engineers (hereinafter referred to as IEEE), MHI shared its knowledge obtained from the development of accident-tolerant sensors for operation in severe accident environments, and contributed to setting the new recommendation in the revised 2016 version[5]. The qualification of our newly developed accident-tolerant sensors presented in this report was conducted to meet with the recommendation.

5. Conclusion

To achieve the enhanced reliability and safety of nuclear power plants, MHI developed accident-tolerant sensors for monitoring pressure, water level and hydrogen concentration and equipment for an hydrogen igniter, all of which function during severe accident environments. Their availability and survivability have been successfully demonstrated by qualification testing under normal and severe accident environmental conditions in CV. With the initiatives for installation in domestic PWR plants, accident-tolerant sensors have been in service since 2015, thus helping each plant achieve stable operation and higher safety. Our contribution to the revised IEEE Standard Criteria for Accident Monitoring Instrumentation is based on our experience in the development of these sensors. By offering instrumentation systems with higher environmental capability to perform reliably during a severe accident, MHI will continue to reduce the burden imposed on the plant staff during their operation to manage a severe accident, thereby enhancing the reliability and safety of nuclear power plants.

The development of an accident-tolerant CV pressure sensor is an achievement of the joint research and development (R&D) program between 11 electric power companies (Hokkaido Electric Power, Tohoku Electric Power, Tokyo Electric Power Company, Chubu Electric Power, Hokuriku Electric Power Company, Kansai Electric Power Company, Chugoku Electric Power Company, Shikoku Electric Power Company, Kyushu Electric Power Company, Japan Atomic Power Company, and Electric Power Development (J-Power)) and three plant manufacturers in Japan. The joint R&D program was conducted as part of a project funded by the Agency for Natural Resources and Energy of the Japanese Ministry of Economy, Trade and Industry, for the technological development of advanced safety measures for nuclear reactors for power generation.

References

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(3) S. Hasegawa et al., In-containment Hydrogen Sensor System against Harsh Environment during a Severe Accident, Proceedings of ICAPP2017 (2017)

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(5) INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, IEEE Standard Criteria for Accident Monitoring Instrumentation for Nuclear Power Generating Stations, IEEE 497 (2016)