New Intrinsically Smart Severe Accident Instrumentation Saves Costs and Enhances Severe Accident Management

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ABSTRACT

The Severe Accidents (SA) at Fukushima in 2011, identified the need for enhanced I&C to follow the progress of SA. Since SA environments are significantly Beyond DBA conditions, some new advanced Inherently Smart sensors had to be developed and tested. Nuclear plant designers and operators have helped focus the I&C enhancement based upon lessons learned from the Fukushima accidents. The result has been the addition of I&C for direct measurement of SA conditions hydrogen concentration, oxygen concentration, temperature, and pressure that provide unambiguous information for management of Severe Accident scenarios. The benefits are immediate from three important aspects. First, they deliver on the nuclear promise for enhanced safety at reduced costs. These Inherently Smart sensors have no maintenance and replace equipment that has high maintenance costs. Secondly, these sensors provide multiple benefits, such as condition monitoring information all the time and direct measurement of SA conditions if they are needed. Thirdly, and most importantly, simplify operator actions and training for SA. SA scenarios and SA Management can now rely on direct measurements to know such things as, the extent of fuel damage, integrity of the reactor pressure vessel, when corium is on the floor of containment, and conditions upon which to activate the hardened vent.

Key Words: Severe Accident, Hydrogen

1 INTRODUCTION

The environments in the Fukushima Severe Accidents (SA) significantly exceeded the Design Basis Event (DBE) Accident conditions. SA temperature was 192% of the DBE temperature and the SA Pressure was 194% of the DBE pressure. Additionally, SA studies are now predicting SA temperatures between 250°C and 640°C. These excessive environmental conditions exceed the capability of existing instrumentation.

Typical safety related I&C in Light Water Reactors s qualified to Design Basis Accident temperatures of 174 °C and peak pressures of about 60 Psig.

These new SA conditions require more temperature and pressure resistant I&C to perform in SA conditions.

Fukushima was a game changer and showed the deficiency of SA I&C because it was the first time that a nuclear plant had blown up because of hydrogen and carbon monoxide during the SA. The hydrogen explosions occurred because of lack of adequate I&C to measure or detect the concentration of Hydrogen and no way to assess its location or risk of explosion.

There were at least 4 hydrogen explosions in 3 nuclear plants and this shows that SA environments can cause a common mode failure mechanism.

This paper discusses the development of new advanced Intrinsically Smart Severe Accident Instrumentation and how it saves costs and enhances SA management.

1.1 Intrinsically Smart Severe Accident Instrumentation

SA are events with nuclear fuel damage. The SA events at Fukushima exceeded that capability of I&C. Therefore, new I&C had to be specifically designed to unambiguously measure and track the progress of SA conditions. Nuclear plant designers and operators have helped focus this I&C enhancement to concentrate on parameters important to them to manage a SA, such as direct measurement of critical parameters including SA temperature, pressure, hydrogen and oxygen.

The challenge in development was operating in the combined environments of temperature of greater than 640 °C, pressure over 120 Psig, and radiation over 5 MGy, while providing operators with unambiguous information so that they can manage an SA.

Since the environmental conditions exceed the capabilities of electronic instruments, a line of instruments had to be developed that are intrinsically smart and utilize physical or chemi-resistive changes in materials to detect and measure environmental conditions. The characteristics of these instruments are to convert an environmental condition directly to an electrical signal and thus provide a continuous measurement, utilizing no electronics in containment of a nuclear power plant.

Intrinsically smart instruments are unique because they are designed for SA conditions that include very high temperatures, very high pressures and exceedingly high radiation levels. They utilize very little common I&C components and avoid materials that would be problematic at these high conditions, like common insulated cable and plastic components. Instead the insulation materials are high temperature ceramics, which work well in high radiation conditions.

During development many tests were performed to evaluate the capability and performance of these new I&C instruments. These included short term and long term high temperature, high pressure and high radiation tests. Radiation tests included both dose rate tests and total integrated dose tests and included gamma and neutron radiation.

Critically important information, such as hydrogen concentration levels, oxygen concentration levels temperature, pressure and carbon monoxide were tested to insure detection of SA progress.

1.2 50.44 Combustible Gas Control Problems

Existing Hydrogen and Oxygen systems are covered under 50.44 Combustible gas control for nuclear power reactors. The regulation has some sections that are now dated because of the new information from Fukushima. Some examples of post-Fukushima discovered problems are found in Table 1.

Table 1. Fukushima discovered problems with 50.44 Combustible gas control for nuclear power reactors

50.44	Fukushima discovered problems
(1) Inerted atmosphere means a containment atmosphere with less than 4 percent oxygen by volume	Inerted containment does not prevent hydrogen explosions since at least 4 explosions occurred at Fukushima
(2) Combustible gas control. (i) All boiling water reactors with Mark I or Mark II type containments must have an inerted atmosphere. (3) (ii) Equipment must be provided for monitoring hydrogen in the containment. Equipment for monitoring hydrogen must	Atmosphere outside containment is not inerted There was no hydrogen monitoring outside of containment or at Spent Fuel pool and at least three explosions at Fukushima occurred in these areas.

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be functional, reliable, and capable of continuously measuring the concentration of hydrogen in the containment atmosphere following a significant beyond design basis accident for accident management, including emergency planning.	Fukushima and SA analyses show hydrogen equipment was not capable of SA Temperature, SA Pressure or SA radiation dose Existing Hydrogen /Oxygen sensors use gas sampling with these problems: Requires AC power for heat tracing and there is no safety related AC power. Sample mixes gases and gives false low readings. Takes almost an hour to measure thus not giving the instantaneous value for accident management SA pressure exceeds design pressure, thus cannot get sample back into containment; breaches containment. Designed for DBA or less and not BDBA Sample lines clog due to steam and poisons from fuel damage Unreliable isolation valves, pumps, motors, heat tracing and flow meters CO is generated during MCCI and there is no monitoring requirement for CO

2 EXISTING HYDROGEN AND OXYGEN SENSOR INSTRUMENTATION

The existing instrumentation for measurement of Hydrogen in combustible gas control systems is typically done by bulk sampling gases from containment. The process of bulk sampling dilutes and mixes the hydrogen with other gases so that a true Hydrogen concentration is not known and worse the true hydrogen concentration by definition has to be higher that the hydrogen concentration reported. Additionally, bulk gas sampling does not provide any information on the location of excessive hydrogen concentrations. Bulk gas sampling systems from containment tend to be complicated systems consisting of many moving parts such as solenoid valves, flow meters, pumps, motors and gas analyzers. These bulk sampling type of combustible gas monitoring systems are difficult and costly to maintain.

3 NEW ADVANCED HYDROGEN AND OXYGEN SENSOR INSTRUMENTATION

The new Advanced Hydrogen and Oxygen Monitoring System (HOMS) actually contains intelligent sensors for hydrogen, oxygen, temperature and pressure. HOMS sensors utilize a unique chemi-resistive sensors that is intrinsically smart and tuned to hydrogen, and oxygen as its core elements. The unique electro-chemical composition of the hydrogen sensor reacts with hydrogen, which allows the hydrogen concentration to be measured directly at any location in containment in a nuclear power plant. Similarly, the oxygen sensors reacts with oxygen to measure its concentration. Temperature and pressure sensors are comprised of unique radiation resistant and environmentally resistant materials.

The sensors are located in a Hydrogen Monitoring Unit (HMU), Figure 1, which can be placed in areas of containment that are likely to contain hydrogen in the event of a Severe Accident. Additionally, the HMU can detect CO and can be placed in locations to detect Molten Core Concrete Interaction (MCCI). HMUs are also located outside of containment in the operating floors and in the Spent Fuel Pool area.

4 ENHANCEMENTS FOR SA MANAGEMENT

HOMS is a valuable new tool to assist in SA management by providing key parameters from sensors designed to operate in SA conditions of hydrogen concentration, oxygen concentration, temperature and pressure and adds integrated SA mitigation features.

The need to measure SA parameters was discussed by BWR and PWR operators which listed the PWROG SAMG Key Parameters including:

- Containment Hydrogen Concentration
- Containment Pressure

The operators concluded that special consideration for containment flammable gases was needed because of uncertainty in the availability and accuracy of existing measurement devices, since hydrogen monitoring systems required AC power for heat tracing and operation and required opening of containment isolation valves at the precise time that containment should be sealed.

The development of the Advanced I&C not only met the considerations identified by the operators, it provided significant additional benefits only possible with direct measurement of SA conditions. These benefits include confirmation of hydrogen occurrence, identification of locations of hydrogen concentration in primary containment vessel, confirmation of core damage, confirmation of reactor pressure vessel damage, condition of core cooling, condition of debris cooling, identification to plant operators the detonation and deflagration risk by plant location, primary containment spray verification and success, primary containment vent verification and success, performance of hydrogen recombiners, verification that hydrogen is not leaking from primary containment into reactor building and confirmation of success of hydrogen mitigation actions.

The deployment of these advanced SA hydrogen and oxygen I&C sensors includes dedicated SA qualified glass-to-metal seal electrical penetration assemblies, connectors, and cables. The locations are typically been above the reactor to detect the onset of an SA, below the reactor or in suppression features to detect fuel exiting the reactor and MCCI, and in the spent fuel pool area to ensure the detection of combustible gases in this area, which in many plants is outside of containment.

5 COST SAVINGS

These advanced SA hydrogen and oxygen I&C sensors are very easy to maintain and operate. Since they directly measure combustible gases inside of containment at the locations in which they are mounted, there are no gas sampling lines needed from and to containment. Measurement of hydrogen is performed and converted to an electrical signal at the location in which it is being measured inside of containment. They eliminate gas sampling lines from containment and four containment isolation valves. Also eliminated are solenoid valves, flow controllers, gas analyzers, heat tracing, pumps and motors. The cost savings from not having to maintain all of this equipment more than pays for the Advanced Hydrogen and Oxygen Monitoring System.

Figure 1. GLS Hydrogen Monitoring Unit

6 SEVERE ACCIDENT TESTING

These advanced SA hydrogen and oxygen I&C sensors have been tested to worst case SA predicted conditions. These conditions include very high temperatures, pressure conditions exceeding the design capabilities of containments, radiation levels that are 250% of previously considered worst case radiation conditions, fissional materials exposure, and Seismic qualification. The conditions for testing were purposely very high.

The initial testing consisted of verifying the performance of the hydrogen sensor to measure hydrogen concentration for basic temperature dependency, stability at temperature, and performance under varying oxygen levels. The need for temperature dependency determinations and stability under temperature conditions was required because of the extremely high SA temperature exceeding of 1292 °F (700 °C). Prior to testing of these sensors, no nuclear plant hydrogen sensors had been tested to this high temperature level and few nuclear plant instruments were designed for these high temperatures.

Testing was performed for pressure. They have been tested to over 120 psig and the EPAs with glass-to-metal seals have been tested even higher. It was decided to ensure that the EPAs are not a weak link in the containment pressure boundary. Therefore, the EPAs were purposely tested to 300 psig because they form part of the containment pressure boundary. The Hydrogen sensors were tested to 150 psig.

The testing also consisted of high ionizing radiation total integrated dose (TID) tests and dose rate tests. The TID tests were in excess of 450 MRads. The TID tests are over 200% of TID tests performed for DBA conditions. The dose rate tests were performed in a nuclear reactor and hydrogen concentration was measured by the sensors under radiation dose rate conditions including dose rates of 1 MRad/hr.

They were was additionally tested for performance to SA fission products of Iodine (I2), Cesium Iodide (CsI), and Methyl iodide (CH3I) in order to ensure that these fission products do not poison the hydrogen sensors.

Seismic testing has been performed to IEEE STD 344 (Reference 3) in which the components were tested to severe seismic tests exceeding any know nuclear power plant application.

Testing for harsh environments was also performed.

7 CONCLUSIONS

The Severe Accidents (SA) at Fukushima in 2011, identified the need for enhanced I&C to follow the progress of SA. Advanced I&C for direct measurement of SA conditions hydrogen concentration, oxygen concentration, temperature, and pressure provide unambiguous information for management of Severe Accident scenarios. They deliver on the nuclear promise for enhanced safety at reduced costs. These Inherently Smart sensors have no maintenance and replace equipment that has high maintenance costs.

Most importantly SA scenarios and SA Management can now rely on direct measurements to know such things as, the extent of fuel damage, integrity of the reactor pressure vessel, when corium is on the floor of containment, and conditions upon which to activate the hardened vent.

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