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Original Article

Development of Highly Reliable Power and Communication System for Essential Instruments Under Severe Accidents in NPP

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ABSTRACT

This article proposes a highly reliable power and communication system that guarantees the protection of essential instruments in a nuclear power plant under a severe accident. Both power and communication lines are established with not only conventional wired channels, but also the proposed wireless channels for emergency reserve. An inductive power transfer system is selected due to its robust power transfer characteristics under high temperature, high pressure, and highly humid environments with a large amount of scattered debris after a severe accident. A thermal insulation box and a glass-fiber reinforced plastic box are proposed to protect the essential instruments, including vulnerable electronic circuits, from extremely high temperatures of up to 627°C and pressure of up to 5 bar. The proposed wireless power and communication system is experimentally verified by an inductive power transfer system prototype having a dipole coil structure and prototype Zigbee modules over a 7-m distance, where both the thermal insulation box and the glass-fiber reinforced plastic box are fabricated and tested using a high-temperature chamber. Moreover, an experiment on the effects of a high radiation environment on various electronic devices is conducted based on the radiation test having a maximum accumulated dose of 27 Mrad.

1. Introduction

The availability of emergency countermeasures after a severe accident is the most critical issue in nuclear power plant (NPP) safety [1–8]. Since the Fukushima accident, reliable and continuous measurements of the NPP during a severe accident are critical to support decision-making that is adaptable to rapidly varying accident environments. From several previous

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severe accidents, it was found that the loss of measurements is the major cause of delays in crucial decisions such as a seawater injection or public evacuation, and these delays consequently lead to uncontrollable public fears of NPPs.

A sequence of measurement loss after a severe accident can be determined as follows:

1. A beyond design basis accident involving significant core degradations occurs [1]
2. Major instruments and power/communication lines are exposed to extremely high temperature, pressure, and moisture, which are mainly due to both reactor failures and poor accident management
3. The instruments and connected cables are damaged and permanent instrument failure happens when repairs to the instruments are not available due to the high radiation environment of a severe accident [3,4].

To overcome the physical failure of currently installed instruments and cables, which are designed by following the equipment qualification based on design-based accidents, several methodological approaches for enhancing the reliability of equipment have been researched [5–8]. The previous methodologies can be classified into the following three categories, where a configuration of the collective results is depicted in Fig. 1:

1. Problem definition: intensified temperature and pressure profiles were suggested for reviewing and/or designing the protection of the NPP equipment against severe accident environments.
2. Increase in redundancy: additional instrument channels were applied as extra redundancies to deal with the malfunctions and degradations of the existing channels.
3. Physical reinforcement: instead of replacing all damageable equipment, physical protective remedies against extreme temperature and pressure conditions were introduced for existing instruments and cables.

To identify the design requirements of Categories 2 and 3, the peak temperature and pressure during a severe accident can be determined by various methods [8,9]. As shown in Fig. 2, a temperature profile during the 72 hours after an accident having a peak temperature of 627°C and a long-term ambient temperature of 187°C was evaluated based on simulations of various points in the containment building. In spite of that, lower temperature profiles can be expected in some regions, such as the upper parts of the containment building. The highest peak temperature of 627°C is selected as a design requirement in this paper to achieve a conservative design. A hydrogen explosion can be considered as the worst condition that puts maximum stress on the equipment. From equivalent experiments by the Electric Power Research Institute [10], the peak pressure value can be determined as 5 bar (or 72.5 psig).

To deal with the loss of conventional wired power and communication cables, reserved wireless channels have been suggested for both the power channel and the communication channels by adopting an inductive power transfer system (IPTS) and radio frequency (RF) communication, respectively [7,8,11,12].

Direct use of the temperature and pressure conditions in Category 1 as design requirements of the NPP equipment is impractical due to the extremely high cost. Therefore, a thermal insulation box and a glass-fiber reinforced plastic (GFRP) box were conceptually proposed to protect only some of the equipment, which is essential for evaluating the NPP integrity, from extremely high temperature and pressure [7,8].

In this paper, the design principles of “increasing redundancy” and “physical reinforcement” are proposed and experimentally verified with relevant prototypes. As the wireless power channel, 10-W level IPTS using a dipole coil resonance system is designed over a 7-m distance, where the target distance matches the length of the main route of the conventional power/communication cables from the inner wall to the outer wall of the containment building shown in Fig. 1. The wireless communication channel is composed of two Zigbee modules covering a 10–20 m range without any

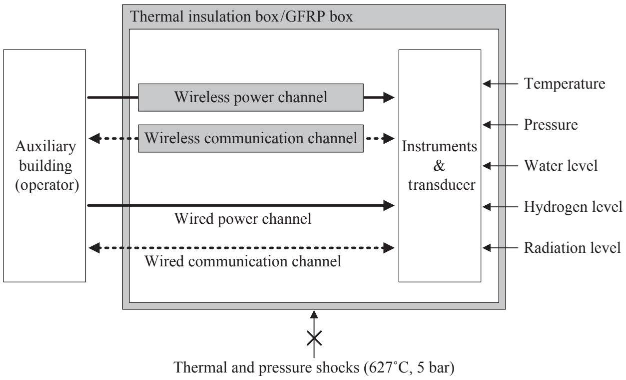

Fig. 1 – Configuration of the proposed highly reliable power and communication system for essential measurements in the nuclear power plant. GFRP, glass-fiber reinforced plastic.

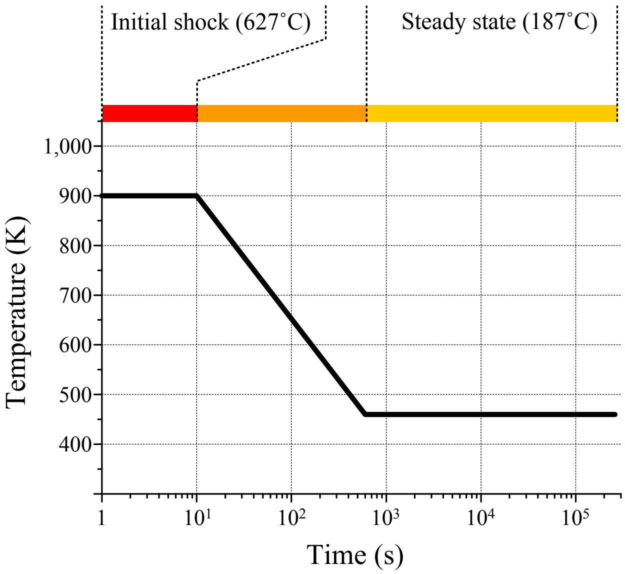

Fig. 2 – Dynamic temperature profile of the containment building during a severe accident lasting 72 hours.

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