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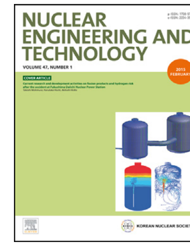

Invited Article

CURRENT RESEARCH AND DEVELOPMENT ACTIVITIES ON FISSION PRODUCTS AND HYDROGEN RISK AFTER THE ACCIDENT AT FUKUSHIMA DAIICHI NUCLEAR POWER STATION

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ABSTRACT

After the Fukushima Daiichi nuclear power plant (NPP) accident, new regulatory requirements were enforced in July 2013 and a backfit was required for all existing nuclear power plants. It is required to take measures to prevent severe accidents and mitigate their radiological consequences. The Regulatory Standard and Research Department, Secretariat of Nuclear Regulation Authority (S/NRA/R) has been conducting numerical studies and experimental studies on relevant severe accident phenomena and countermeasures. This article highlights fission product (FP) release and hydrogen risk as two major areas. Relevant activities in the S/NRA/R are briefly introduced, as follows: 1. For FP release: Identifying the source terms and leak mechanisms is a key issue from the viewpoint of understanding the progression of accident phenomena and planning effective countermeasures that take into account vulnerabilities of containment under severe accident conditions. To resolve these issues, the activities focus on wet well venting, pool scrubbing, iodine chemistry (in-vessel and ex-vessel), containment failure mode, and treatment of radioactive liquid effluent. 2. For hydrogen risk: because of three incidents of hydrogen explosion in reactor buildings, a comprehensive reinforcement of the hydrogen risk management has been a high priority topic. Therefore, the activities in evaluation methods focus on hydrogen generation, hydrogen distribution, and hydrogen combustion.

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1. Introduction

On March 11, 2011, off the Pacific Coast of Tohoku, an earthquake struck the Fukushima Daiichi Nuclear Power Station (NPS) operated by the Tokyo Electric Power Company (TEPCO). Units 1, 2, and 3 (among six units) were scrammed shortly after the earthquake [1]. Unit 4 was already under an outage for a periodic inspection, and all fuels were unloaded from the core and cooled in the spent fuel pool. Units 5 and 6 were under outage with all fuel loaded in the core and the pressure vessel heads in place. Lines of the offsite power were damaged because of the earthquake. All emergency diesel generators (EDGs) were automatically started to supply the onsite power.

After the arrival of the tsunami of historic scale, the site was flooded and all EDGs were shut down, except for those of Unit 6. It was later verified that offsite and onsite power supplying infrastructures such as metal clad switchgears were heavily damaged. It was judged that restoration of power would take a long time [1]. Under this situation, a long-term station blackout (SBO) from Units 1–5 was inevitable. A cold shutdown state was achieved in Units 5 and 6 by utilizing the power interchange line. There was no power interchange between Units 1–4 and Units 5–6. The direct current battery power of Unit 1 was lost because of the tsunami, but the DC power of Units 2 and 3 was exhausted within a certain period.

Loss of ultimate heat sinks and cooling systems designated for the SBO resulted in successive severe core damage in Units 1, 2 and 3, which led to failure of the last barrier, the primary containment vessel (PCV). A large amount of radioactive materials were released into the environment and they were dispersed in a wide area. In particular, a significant amount of fallout was observed in the northwest part of the Fukushima prefecture [2].

Another diverting event was a hydrogen explosion that significantly damaged the reactor buildings (R/Bs) in Units 1 and 3. Emergency workers were injured. Hoses and cables, which were still undergoing work, were broken. Scattered debris increased the space dose rate and hindered the smooth operation of accident management. An even more unpredictable event was an explosion that occurred in the R/B of Unit 4. Later site verifications revealed a portion of hydrogen generated in Unit 3 flew into Unit 4 *via* the standby gas treatment systems (SGTSs) that shared the same stack [1].

As described previously, the experiences of the Fukushima Daiichi NPS underline the importance of providing countermeasures against the risks of fission products (FPs) release and hydrogen explosion under severe accidents. Since the Fukushima NPS accident, intensive discussions of the Japanese regulation framework have continued to include the requirements of severe accident countermeasures. The new regulatory requirement was enforced in July 2013 [3]. New regulatory requirements are backfitted to all existing nuclear power plants (NPPs).

The regulatory requirement composed of a hierarchical system. The system allows timely maintenance so that constant improvement of safety is ensured. The Regulatory Standard and Research Department, Secretariat of Nuclear Regulation Authority (S/NRA/R) has been conducting research and development (R&D) programs to gain a knowledge base in important areas. This article highlights FP release and hydrogen risk as two major areas. Relevant activities in S/NRA/R are briefly introduced.

2. FPs release to the environment in the accident

In the Fukushima Daiichi accidents, the boundary of the PCVs was breached after severe core damage because of high temperature and high pressure in the drywell atmosphere. Numerous estimations have been published [1,4]; however, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimated that the total amount of radionuclides released to the environment was in the range of 100–500 petabecquerels (PBq) for iodine-131 (I^{131}) and 6–20 PBq for cesium-137 (Cs^{137}) [5]. A study of leak paths and/or failure mechanisms of the PCV boundary are essential to identify vulnerabilities of the PCV under severe accident conditions such as the durability of sealing at the top flange and electrical cable penetrations under high temperature, high pressure, and high humidity. To examine effective wet well (W/W) venting strategies, it is also important to quantify FPs released to the environment by venting through the W/W while taking into account degradation of pool scrubbing under severe accident conditions. Based on these goals, descriptions focused on wet well venting, pool scrubbing, iodine chemistry (in-vessel and ex-vessel), containment failure mode, and treatment of radioactive liquid effluent.

2.1. *Venting*

Based on TEPCO's records, hardened venting through the W/W was attempted for Units 1, 2, and 3 [1]. This indicated that PCVs were eventually depressurized by W/W venting in Units 1 and 3. On the other hand, operation of W/W venting was ready in Unit 2, but it is widely believed that W/W venting did not work because the rupture disc was not broken. An important lesson learned from Unit 2 is the importance of specifying an appropriate set point of W/W venting for securing the integrity of the PCV in a severe accident management guide/procedure.

Under severe accident conditions, it is predicted that the suppression pool (S/P) remains at a near-saturated condition because the PCV pressure is generally regulated at the vapor pressure of the S/P. If venting were conducted under such conditions, rapid vaporization or flashing would occur. It is likely that enhanced droplet entrainment and revolatilization of FPs would change the scrubbing processes and degrade decontamination in S/P. To reduce the uncertainty of the source term, it is necessary to improve the fidelity of physical models of pool scrubbing in the S/P. As discussed later, separate effect tests and integral effect tests are in progress.

The rule level requires that, in the event of severe core damage, containment failure shall be prevented by equipment and procedures for reducing the pressure and temperature in