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Invited Article

Large Scale Experiments Simulating Hydrogen Distribution in a Spent Fuel Pool Building During a Hypothetical Fuel Uncovery Accident Scenario

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ABSTRACT

Following the Fukushima accident and its extended station blackout, attention was brought to the importance of the spent fuel pools' (SFPs) behavior in case of a prolonged loss of the cooling system. Since then, many analytical works have been performed to estimate the timing of hypothetical fuel uncovery for various SFP types. Experimentally, however, little was done to investigate issues related to the formation of a flammable gas mixture, distribution, and stratification in the SFP building itself and to some extent assess the capability for the code to correctly predict it.

This paper presents the main outcomes of the Experiments on Spent Fuel Pool (ESFP) project carried out under the auspices of Swissnuclear (Framework 2012–2013) in the PANDA facility at the Paul Scherrer Institut in Switzerland. It consists of an experimental investigation focused on hydrogen concentration build-up into a SFP building during a predefined scaled scenario for different venting positions. Tests follow a two-phase scenario. Initially steam is released to mimic the boiling of the pool followed by a helium/steam mixture release to simulate the deterioration of the oxidizing spent fuel. Results shows that while the SFP building would mainly be inerted by the presence of a high concentration of steam, the volume located below the level of the pool in adjacent rooms would maintain a high air content. The interface of the two-gas mixture presents the highest risk of flammability. Additionally, it was observed that the gas mixture could become stagnant leading locally to high hydrogen concentration while steam condenses. Overall, the experiments provide relevant information for the potentially hazardous gas distribution formed in the SFP building and hints on accident management and on eventual retrofitting measures to be implemented in the SFP building.

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1. Introduction

1.1. Background

The 2011 Fukushima accident has recalled attention to the importance of the behavior of spent fuel pools (SFP) in case of a loss of the cooling system associated with a station blackout. Spent fuel assemblies are commonly stored in pools located in buildings not designed to withstand over-pressure. In cases when the pool cooling capability is lost or heavily degraded for very long time, e.g., in a postulated long lasting station blackout with damage of the SFP building due to external events, the steam and later on the hydrogen release cannot be confined within the SFP building [1–3].

To avoid that combustible air/hydrogen mixtures, leading to deflagration and/or detonation that would form in the building, a possibility would be to implement mitigation devices, e.g., passive autocatalytic recombiners/igniters aiming at reducing the hydrogen concentration, or another possibility would be to dilute (inerting) hydrogen with steam and to vent the resulting mixture outside the SFP building. The physical phenomena associated with hydrogen distribution is complex and involves multi-phase, multi-components mixing and stratification, multi-compartment transport induced by density or pressure differences, condensation induced by the proximity of a cold wall or the activation of safety system, re-evaporation phenomena, etc. The usual approach in safety analysis is to identify, through simulations using advanced three-dimensional computational tools (e.g., GOTHIC, FLUENT, GASFLOW, etc.) the regions/compartments where combustible mixtures may form and elaborate a mitigation strategy accordingly. The validation of such computational tools against a suitable experimental database (e.g., in large-scale, multi-compartment facilities with conceptual flow diagram-grade instrumentation) is a continuous process undertaken by the scientific community and it is necessary to identify the computational needs (e.g., physical modeling, mesh features, time steps, etc.) to analyze similar scenarios in nuclear power plants.

At the expert meeting held by the International Atomic Energy Agency in Vienna [4], it was underlined that analysis of severe accidents related to SFPs had not been carried out as much as in other areas. The need for research and development on hydrogen flammability patterns to address the implementation of mitigation measures were identified and recommendations on expanding the existing projects on accident prevention and mitigation were given. Also, it was pointed out that that “continued detailed investigations of the accident sequence, including assessment of computer code applicability to observed severe accident phenomena” should be undertaken. Since then, numerous analyses have been carried out for specific plant designs involving various code comparisons (e.g., MELCOR, RELAP5, ATHLET CD, ASTEC, etc.) [5–7].

In the meantime, the OECD/NEA (Organization for Economic Co-operation and Development/Nuclear Energy Agency) SFP project by Sandia National Laboratory in the USA (2011–2013) was conducted to provide experimental data relevant for hydraulic and ignition phenomena of prototypical water reactor fuel assemblies. This project consisted of two phases: (1) the first phase focusing on axial heating and burn propagation; (2) the second phase addressing radial heating and burn propagation including the effects of fuel rod ballooning. The Paul Scherrer Institut was part of the project and the input deck used for MELCOR code in the SFP project was the base for the scoping calculation conducted to simulate an accident scenario in the SFP building [7].

1.2. Objectives and approach

The Swissnuclear Experiments on SFP (ESFP) project focused on the late phase of a postulated severe accident, involving the partial uncovery of the fuel assembly, hydrogen generation by fuel-cladding metal–water reaction, and release of hydrogen and steam to the gas space of the SFP building and from there to the environment.

The main objective of the PANDA ESFP project is to investigate hydrogen concentration build-up into the SFP building for different venting positions. Subsequently, the experiments should provide relevant information for severe accident management concerning the need of implementing a mitigation system in the SFP building itself.

A wide variety of SFPs exist, and it was not the objective of the project to focus on the SFP of a particular nuclear power plant. Therefore the PANDA tests are defined in a general way, i.e., the results do not apply to any specific SFP building. Nevertheless, the test conditions and the associated phenomenology are representative of the phenomenology in the SFP building gas space during a postulated severe accident. Moreover, the experimental database which was obtained is suitable for the assessment and validation of advanced computational tools to analyze hydrogen concentration build-up in the SFP building under various postulated conditions.

2. Test scenario and parameters

2.1. Preliminary analysis with MELCOR

Calculations using the advanced Lumped Parameter computational tool MELCOR were carried out at Paul Scherrer Institut within the ESFP project to obtain representative initial and boundary conditions for the experiments [7]. As reference, the geometry of a SFP of a typical Generation II pressurized water reactor (~400 MW) was considered. For the generic SFP building a total volume of about 5,700 m^3 was considered. The SFPs consisting of three pools (Storage Pool-A and B and the Transfer Pool-C; Fig. 1) have been analyzed with MELCOR. Calculations have been made for four different configurations, varying the pool water level, the fuel activity, and the number of fuel elements. Combining together these last two parameters the integral heat loads of 0.5 MW and 4.7 MW were considered in the MELCOR analysis. The parameters of the calculation are presented in Table 1.