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Improving nuclear power plant safety through independent water storage systems

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ABSTRACT

The safety of nuclear power plants (NPPs) depends on the actions taken to prevent nuclear accidents or to limit their consequences. This paper proposes improvement of pressurized water reactor safety by introducing of new system for water injection in the primary and secondary loops. The system is envisioned as a supplementary to the regular safety systems and to be operated independently. The proposed design consists of a water source, pipes, valves and a portable fossil-fuel driven pump, and implements the “Diverse and Flexible Coping Strategy” mitigation concept recommended by the US industry following the Fukushima accident. The potential of the supplementary water storage system to cope with two major initiating events, i.e. the station blackout and large loss of coolant accident, is investigated, and its broad impact on nuclear safety is quantified. The probabilistic safety assessment is employed in the analyses. In particular, a probabilistic safety assessment model of a pressurized water reactor is modified to consider the new independent water storage system. The core damage frequency of the plant is used as a risk measure. The results reveal that the core damage frequency of the analyzed NPP decreases significantly after the introduction of the proposed water storage system. Furthermore, the criticality of some of the most important basic events related to the provision of water flow during station blackout significantly decreases.

1. Introduction

The safety of nuclear power plants (NPPs) depends on the actions taken to prevent nuclear accidents or to limit their consequences. The probabilistic safety assessment (PSA) of NPPs indicates that station blackout (SBO) events, which occur due to complete loss of alternate current (AC) power, have a large impact on NPP safety (Volkanovski and Prošek, 2013). One of the main objectives upon the occurrence of SBO events is to ensure effective decay heat removal from the reactor core. A second safety-critical event in NPPs is the large loss of coolant accident (LOCA). The primary loop pressure and water are lost in few seconds in case of large LOCA event occurrence. Core damage is imminent after large LOCA if no coolant is injected in the reactor core and no decay heat removal is established on-time.

According to NUREG 4450 series (U.S.NRC, 1989–1990), prepared for the Nuclear Regulatory Commission (NRC), SBO and LOCA events are very often one of the largest contributors to NPP safety. Five light water reactors of generation-two are analyzed in the series. PSA models prepared for Surry NPP (Unit 1), Peach Bottom (Unit 2) and Gran Gulf NPP show that the SBO is the largest contributor to core damage frequency (CDF) (U.S.NRC, 1989–1990). Conversely, PSA results of Sequoyah NPP (Unit 1) and Zion NPP (Unit 1) show that LOCA events are the largest contributors (U.S.NRC, 1989–1990). Another PSA model made for the generation three plus UK AP1000 reactor (Westinghouse, 2007) show that the large LOCA is the second largest contributor to the CDF.

Several studies propose concepts for the improvement of NPP safety. In (Gjorgiev et al., 2014) the connection between NPP and accumulation-type hydro power plant is investigated. Furthermore, the study performs analyses where a pumped-storage hydro power plant is used instead. The hydro power plants in both cases are used as alternative AC power sources. The main objective of the additional power source is the mitigation of SBO events, i.e. to provide cooling of the reactor core using electricity from alternative power supply. The results show significant decrease of the station blackout CDF and significant decrease in total CDF. The US NRC order EA-12-049 (U.S.NRC, 2012a) urges that NPPs develop mitigation strategies for beyond-design-basis external initiating events. In response to this order, the US nuclear industry issued a general framework presented in the NEI FLEX Implementation Guide by the Nuclear Energy Institute (NEI) (NEI 12-06) (NEI, 2012).

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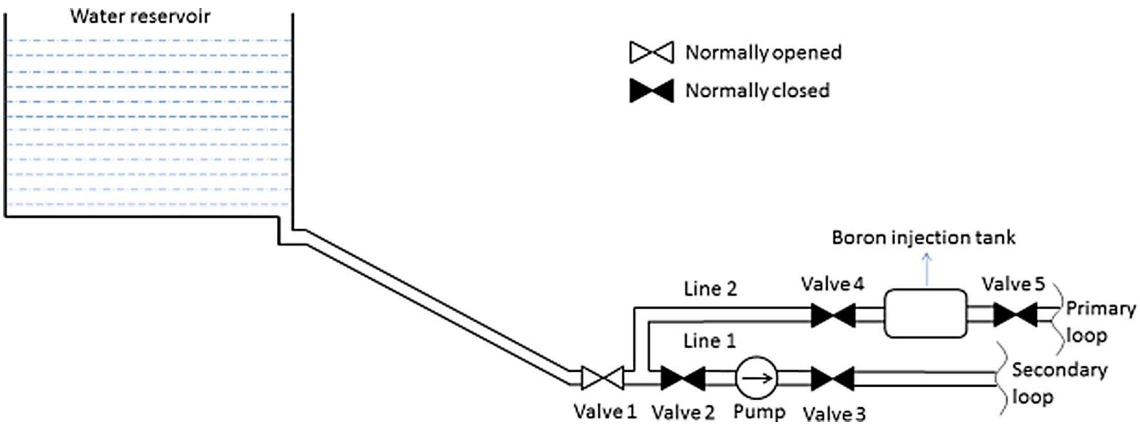

Fig. 1. Schematic of the proposed system and the connection with the NPP.

This mitigation strategy, known as FLEX, advocates for flexible and diverse strategies for increased defense-in-depth by providing multiple and diverse means of suppling electrical power and water, and thus supporting the main safety functions. Stress tests were conducted on the French nuclear fleet in 2011 by the Électricité de France (EDF), requested by the European Commission as post-Fukushima measure (ASN, 2011). The outcome of the tests pointed towards increasing the protection against extreme natural hazards by reinforcing parts of the installations and allocating complementary equipment which limits the releases in case of beyond design hazards. The overall goal is to devise an action plan that eliminates the unwanted effects of SBO, and the loss of the ultimate heat sink or a severe accident induced by extreme external events. The set of measures and equipment involved is named the "Hardened Safety Core" (HSC) (IRSN, 2012). Similarly, the Independent Core Cooling (ICC) for the Swedish NPPs has been proposed by the Swedish Radiation Safety Authority (Jelinek, 2014). The main objective of the ICC is to prevent reactor core meltdown during extreme external conditions. The system must be build independent from the existing core cooling systems with minimum operational length of 72 h.

Based on the previously elaborated concepts and motivated by FLEX, the objectives of this paper are (1) to propose an easily implementable design for providing a supplementary water source for cooling the primary and secondary loop of NPPs, and (2) to quantify the effects of the proposed design on the risk stemming from the two most hazardous initiating events, i.e. SBO and LOCA. To that aim, the paper is presenting a system supplementary to the regular safety systems for providing cooling water into the primary and secondary loop, with a goal to increase NPP safety. The system consists of an independent water source (off-site or on-site) and components for establishing connection with a pressurized water reactor (PWR) type of NPP. The connection between the NPP and the water source is provided by pressure pipes. The required pressure for water injection is established by both a portable gas-fired motor driven pump and gravity. Water reservoirs, wells, larger water bodies or water streams can be considered as water sources. In this paper, for demonstrative purposes, water reservoir is selected. The reservoir may be placed on-site or off-site as a part of on-river accumulation, i.e. hydro power plant reservoir or any other natural or manmade accumulation. The system can be considered partially passive because no active machinery is need to deliver the water coolant for certain scenarios. The supplementary water storage system can be activated in at least two events, i.e. the loss of all offsite and onsite AC power supply and the large LOCA. The latter employs the passive function of the proposed system.

The paper investigates the implications of the proposed water storage system on NPP safety. Probabilistic safety assessment for generation-two PWR plant is used as tool for risk assessment. The reference PSA model is modified in order to consider the coupled water storage system. The proposed system is modelled using the fault tree approach with the top event defined as failure to deliver water to the NPP. The decrease of the CDF is used as a measure for the safety implications of the proposed system. The changes of the NPP core damage frequency and the shares of the SBO and large LOCA events are quantified. The effects of the proposed system on NPP safety are analyzed and discussed. The results show that the introduction of the water storage decreases CDF and improves NPP safety.

The paper is structured as follows: in Section 2 a description of the independent water storage system is presented; Section 3 describes the PSA model of a PWR type of NPP and the modifications made with the implementation of the proposed system; Section 4 is dedicated on the performed analyses and obtained results; Section 5 provide conclusions.

2. Description of the proposed water storage system

2.1. System configuration and operations

The supplementary water storage system for water injection into the primary and secondary loop is presented in Fig. 1. The system consists of a water source, pipes, a portable diesel powered pump, valves, and a boron tank which satisfies the required conditions for safe operations. In this study, a water reservoir is considered as a water source. Valves 1, 2, 3, 4 and 5 in Fig. 1 are identical. Valve 1 is continuously open, valves 2 and 3 are opened when the pump is used for water injection in the steam generators (SGs), and valves 4 and 5 are opened when water is injected in the primary coolant loop. The system design allows for both pump or gravity to be used for driving water from the reservoir towards the NPP cooling systems. The portable diesel pump must have the design capability to inject water with the necessary pressure to the SGs. It is considered that the portable pump is protected from internal and external events, and thus it should be sheltered separately on-site or off-site site, where it can be easily reached and transported to the predetermined location in case of need.

Fig. 1 also shows that two connections (lines) to the NPP systems are provided. Line 1 connects to the secondary loop and it is used for the SBO event mitigation; Line 2 connects to the primary loop and it is used for the large LOCA mitigation.

After the SBO event occurs, the decay heat needs to be removed, and the cooling of the reactor core must continue. To this aim, the supplementary water storage system is joined to the secondary loop, i.e. the SGs, through the same pipelines utilized by the auxiliary feedwater (AFW) system. If the AFW system (e.g. AFW turbine-driven pump, check valves) fails after the occurrence of the SBO, the diesel pump is set for operation and valves 2 and 3 are opened. Subsequently, the system injects cold water to the secondary side of the SGs, where the water is vaporized and heat is dissipated through the secondary side safety valves. In this scenario, pressure in the range of 80 bars (Volkanovski and Prošek, 2013) is required. This is the main reason for

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