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Features of modelling of processes in spent fuel pools using various system codes

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ABSTRACT

Severe accidents have not yet occurred in spent fuel pools, however, the consequences can be very severe and a big amount of radioactive material can be released to the environment. Thus, the modelling of possible accidents using computer codes and analysis of consequences is very important. This paper presents results of modelling of cooling water volume decrease events in the spent fuel pools using four different system codes RELAP5, RELAP/SCDAPSIM, ATHLET-CD and ASTEC. The work is aimed to identify possible unrealistic fuel storage pool parameter states, trends and values and to assess the possible errors caused as a result. The influence of the selected modelling assumptions, approximations and impact of the structure of the models on the substantial nuclear fuel storage pools parameters during the beyond design basis accident were investigated.

1. Introduction

After the irradiated fuel assemblies (spent fuel assemblies - SFA) at the nuclear power plant (NPP) are extracted from the reactor core, they are handled and stored in a system of compartments filled with water. Generally, each reactor has a spent fuel pool (SFP) for storing spent fuel, which is generated during 10–30 years of operation of the reactor.

The most challenging consequences for the SFP can occur in the case of loss of water. The loss of water accident in SFPs is a severe accident, which may occur due to water leakage or due to the loss of heat removal from them (loss of water due to evaporation). Because of the large amount of fuel in the SFPs there is a high potential of energy release. But, from the other hand, the probability of a loss of coolant from spent fuel storage pool is low – about 10^{-6} per pool per year, according USA Nuclear Regulatory Commission (U.S. Nuclear Regulatory Commission, 2001). During operation time in USA occurred two losses of spent fuel pool coolant inventory events, where the water level decreased in the spent fuel pools by ~1.5 m (U.S. Nuclear Regulatory Commission, 1997). During the Fukushima accident the mitigation measures (water injection into the SFP of Unit 4) allow to prevent the damage of fuel rods cladding. Furthermore, the accidents in the Japanese NPPs due to earthquakes and the loss of electricity supply for a long time (much longer than generally evaluated in safety justification for NPPs) provide with the safety justification to investigate the facilities for intermediate spent fuel assemblies storage. This is very important in order to evaluate the correct time of the general stages and possible consequences of such accidents.

The loss of water from SFP accidents leads to fuel heat up, the loss of cladding integrity due to ballooning and the release of volatile fission products. After the temperature rises above 1000 °C, the exothermic reaction of the air and steam mixture with fuel cladding starts, which causes large amounts of heat and hydrogen to be generated. Due to the aforementioned reaction the temperature of the fuel rods claddings reaches a melting point of stainless steel and zirconium niobium alloy. Such severe phenomena require special organizational measures. The results of such type of analysis are used for the development of spent fuel pool accident management guidelines, to allow a correct interpretation of the results avoiding improper management of severe accidents.

Search in the ScienceDirect scientific database of the words “Accidents in Spent Fuel Pools” provides links to more than 220 articles. Further examination reveals that only about 10% of the articles are related to the processes in spent fuel pools. In these articles real events were investigated (for example, accidents in Paks NPP), but it is obvious that the amount of articles with investigation of processes in SFP increased after the accident in Fukushima NPP. In number of articles heat transfer in spent fuel storage is investigated. The authors use a variety of computer codes – the

Abbreviations: ASTEC, accident source term evaluation code; ATHLET-CD, code for the analysis of thermal-hydraulics of leaks and transients with core degradation; NPP, nuclear power plant; RELAP5, code for the reactor excursion and leak analysis program; SFA, spent fuel assembly; SFP, spent fuel pool.

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employment of system thermal hydraulic computer code RELAP is very popular, CFD computer codes also are used. A good example of RELAP5 usage is the paper by Groudeva et al. (2013) investigated the thermo hydraulic behaviour of the spent fuel during the fuel transfer from the reactor vessel to the SFP in case of dry out for VVER440/V230 units 3 and 4 at Kozloduy NPP. They estimated the time for dry out of SFP, heat up of spent fuel and time for recovery actions from the operators. Ye et al. (2013) performed a CFD simulation to evaluate the cooling ability of a passive cooling system to remove the decay heat released by the spent fuel assemblies. The spent fuel pool of CAP1400 (a passive PWR developed in China) was selected as a reference pool. Aghoyeh and Khalafi (2010) provided the design of a make-up water system for the optimal water supply and its chemical properties in a storage pool of spent nuclear fuels. The Tehran research reactor (TRR) make-up water system was investigated in their work. Assuming the loss of cooling system for the SFP located at the Chinshan NPP in Taiwan, Wang et al. (2012) adopted the TRACE code coupled with the CFD method to study the safety issue related to the SFP. Their results showed that the fuel uncover may occur about 2.7 days after the loss of cooling system in the SFP.

There are not too many papers in which processes taking place in the SFP during severe accidents are investigated. For example in paper (Throm, 1991) steam – zirconium reaction phenomenon in SFPs is investigated.

The main processes that take place during severe accidents in SFP are the same as in the nuclear reactor core. However, the time intervals and the sequence of events in SFP are specific; also the nodalisation of SFPs is specific. The literature review shows that usage of the CFD codes allows to perform detail modelling of processes during the water heat-up phase in the spent fuel pools, because the heat transfer and fluid mixing is the strongest side of CFD computer codes. The system computer codes allowed to model the processes in wider scale. Thus, the modelling of spent fuel pools is a specific task. On the other hand, when high-volume systems, where heat and mass transfer phenomenon of various intensities may occur (such as natural convection, evaporation, boiling, and so on), are being modelled by system codes, there is a rather high probability to receive unrealistic long-term calculation results. The calculation results received by using different codes and different assumptions demonstrated the potential limits of such inaccuracies as well as the impact of nodalisation and solution methods to the results of calculation. During the modelling of severe accident in SFP, some specific parameters (temperature variation tendencies, heat generation ratio during oxidation, mass balance) may be calculated which contradict the reality and might lead to incorrect interpretation of results.

In this paper the RELAP5, RELAP/SCDAPSIM, ATHLET-CD and ASTEC codes were used for the analysis of various scenarios of loss of water from SFP accidents in Ignalina NPP. The main objective of this analysis is to show the results predicted from the calculations in order to identify possible unrealistic parameters' values and incorrect interpretations of them.

2. The design of spent fuel pools at Ignalina NPP

Each reactor unit of Ignalina NPP is equipped with a system of spent fuel pools. The whole complex of spent fuel storage and handling system is comprised of 12 pools (Fig. 1): two pools (Rooms 236/1 and 236/2) are used for non-cut SFAs after they are extracted from the reactor; five pools (Rooms 336, 337/1, 337/2, 339/1, and 339/2) are used for shipping casks with spent fuel bundles (one SFA consists of two spent fuel bundles connected in an axial direction) storage; all other are used for handling the spent fuel in SFPs. The design of spent fuel pools at Ignalina NPP in more detail is presented in paper (Kaliatka et al., 2008).

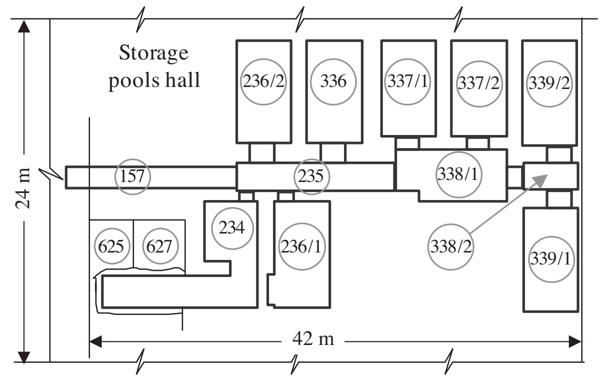

Fig. 1. Layout of buildings in storage pools hall of Ignalina NPP Unit 2.

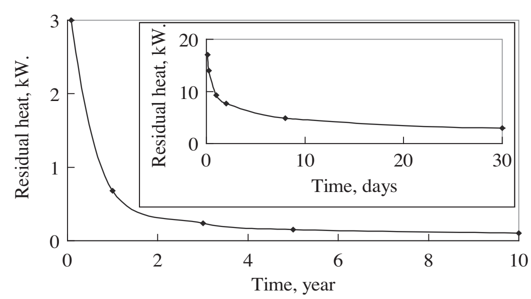

Fig. 2. Residual heat of SFA in SFP (Institute VNIPIET, 2003).

The residual heat in SFPs depends from the type of fuel initial enrichment and its burn up level. The highest initial enrichment of fuel used at the Ignalina NPP was 2.8%. The residual heat from the spent fuel assemblies with an initial enrichment of 2.8% and an average burn up of 27 MWd/(kgU) when the average generated power is 2.5 MW is presented in Fig. 2 (VNIPIET, 2003). For the analysis of the accident the maximum possible number of SFAs in the SFPs is used – 7901 spent fuel assemblies.

3. Modelling assumptions and models

During the modelling of loss of water from the spent fuel pools accidents three main assumptions in the models were used to evaluate possible consequences:

- the maximum amount of spent fuel assemblies is placed in the spent fuel pools (7901 SFAs – total mass of uranium in SFPs is equal to 752,400 kg);
- the residual heat of SFAs in SFPs is the maximum possible (maximal theoretically possible power is equal to 4253 kW);
- the water level is 16.9 m from the bottom of the SFP;
- the water temperature is 50 °C;
- for the water leakage accidents it is assumed that the water leakage through the rupture of the drainage pipe is the maximum possible (21.1 kg/s) and that the flow rate from the makeup system is maximum as well (27.8 kg/s).

The best-estimate system codes were used for the analysis: code RELAP5 (INEL, 1995) for thermal hydraulics and RELAP/SCDAPSIM (Allison and Wagner, 2001), ATHLET-CD (Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) mbH, 2006) and ASTEC (Van Dorsselaere et al., 2009) codes for the analysis of severe accidents. In all models the SFAs are grouped into 4 groups (ROD1, ROD2, ROD3, and ROD4). The ROD1 represents the smallest group