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Possible accident scenarios related to the Spent Fuel Pool operating events

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ABSTRACT

After the accident in Fukushima Daiichi NPP, the Nuclear Energy Agency Committee on the Safety of Nuclear Installations (OECD/NEA CSNI) initiated activities to address some technical issues. As a one of results, the Status report on Spent Fuel Pools (SFPs) under Loss of Cooling Accident Conditions was created. To give a valuable contribution to the post-Fukushima accident decision making process, brief summaries were produced on:

- The status of SFP accident and mitigation strategies;
- Assessment of current experimental and analytical knowledge about loss of cooling accidents in SFPs and their associated mitigation strategies;
- The strengths and weaknesses of analytical methods used in codes to predict SFP accident evolution and assess the efficiency of different cooling mechanisms for mitigation of such accidents;
- Identification of additional research activities required to address gaps in the understanding of relevant phenomenological processes, where analytical tool deficiencies exist, and to reduce the uncertainties in this understanding.

The final report was approved by OECD/NEA CSNI in December 2014 with the reference NEA/CSNI/R(2015)2 and it is available for download on the OECD website http://www.oecd-nea.org/nsd/docs/2015/csni-r2015-2.pdf.

Joint Research Centre of European Commission took the leading role in creation of the chapter about possible accident scenarios, past accidents and precursor events. Evaluations of past events where SFP cooling has been lost show that malfunctions of the SFP cooling system are in most cases caused by inoperable cooling pumps. The other important causes are inadvertent diversion of coolant flow and Loss of ultimate heat sink.

This paper is providing short general report overview and more details about JRC contribution.

Keywords: *Nuclear Safety, Spent Fuel Pool, Accident scenarios*

1. INTRODUCTION

Spent fuel pools (SFPs) are large accident-hardened structures that are used to temporarily store irradiated nuclear fuel. Due to the robustness of the structures, SFP severe accidents have long been regarded as highly improbable events, where there would be more than adequate time for corrective operator action. The Fukushima Daiichi nuclear accident that followed after the Great East Japan Earthquake on 11 March, 2011, has renewed international interest in the safety of spent nuclear fuel stored in SFPs under prolonged loss of cooling conditions.

Following the 2011 accident at the Fukushima Daiichi NPP, the Nuclear Energy Agency Committee on the Safety of Nuclear Installations (NEA CSNI) decided to launch several high-priority activities to address certain technical issues. Among other things, it was decided to prepare a Status Report on Spent Fuel Pools (SFPs) under loss of cooling accident conditions [1]. This activity was proposed jointly by the CSNI Working Group on Analysis and Management of Accidents (WGAMA) and the Working Group on Fuel Safety (WGFS). The main objectives, as defined by these working groups, were to:

- Produce a brief summary of the status of SFP accident and mitigation strategies, to better contribute to the post-Fukushima accident decision making process;
- Provide a brief assessment of current experimental and analytical knowledge about loss of cooling accidents in SFPs and their associated mitigation strategies;
- Briefly describe the strengths and weaknesses of analytical methods used in codes to predict SFP accident evolution and assess the efficiency of different cooling mechanisms for mitigation of such accidents;
- Identify and list additional research activities required to address gaps in the understanding of relevant phenomenological processes, to identify where analytical tool deficiencies exist, and to reduce the uncertainties in this understanding.

The proposed activity was agreed and approved by CSNI in December 2012, and the first of four meetings of the appointed writing group was held in March 2013. The writing group consisted of members of the WGAMA and the WGFS, representing the European Commission and the following countries: Belgium, Canada, Czech Republic, France, Germany, Hungary, Italy, Japan, Korea, Spain, Sweden, Switzerland and the USA. Status Report on SFP mostly covers the information provided by these countries.

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Joint Research Centre of European Commission took the leading role in creation of the chapter about possible accident scenarios, past accidents and precursor events. Evaluations of past events where SFP cooling has been lost show that malfunctions of the SFP cooling system are in most cases caused by inoperable cooling pumps. The other important causes are inadvertent diversion of coolant flow and Loss of ultimate heat sink.

Special attention is given to three fuel events that happen outside the reactor. Events from Paks NPP and Bruce-A NPP resulted in fuel damage were also outside SFP at the time of event, but those events are interesting because of similarity with conditions in SFP. Third event is about the most serious SFP scenario from Fukushima Daiichi nuclear accident.

2. STATUS REPORT ON SFP UNDER LOSS OF COOLING AND LOSS OF COOLANT ACCIDENT CONDITIONS

Status Report on SFP is intended to summarize current understanding of the behaviour of SFPs in loss of cooling and loss of coolant accident conditions. Past accidents and precursor events are reviewed, in particular the behaviour of the spent fuel facilities during the Fukushima Daiichi accident. Important aspects of the accidents and involved phenomena are addressed, such as the thermal-hydraulic behaviour of the pool, the issue of criticality, the accident progression under partial or complete loss of coolant, the hydrogen risk, the fission product release, etc. The report provides a brief assessment of current experimental knowledge about loss of cooling and loss of coolant accidents. It also presents state-of-the-art computer codes used for analyses of SFP accidents, and discusses strengths and weaknesses of models and methods used in these codes. The probability of SFP accidents and assessments of off-site health effects and contamination consequences of SFP accidents are, however, beyond the scope of this document.

The fuel residing in At-Reactor (AR) SFPs is usually characterized by higher decay power than fuel stored in Away-From-Reactor (AFR) pools. Since the progression rate and severity of a loss of cooling/coolant accident correlates with the power of the stored fuel assemblies (FAs), the most challenging accident scenarios are expected in AR storage pools. For this reason, the report focuses on AR SFPs in light-water reactor (LWR) and Canada Deuterium Uranium (CANDU) reactor nuclear power plants.

The report is also aimed to identify areas that need additional knowledge and to identify potential improvements in computational models and tools for better predictions of SFP accident progression and time margins to significant radiological releases. Better understanding of the SFP accidents phenomenology and coolability mechanisms is needed for reliable estimation of accident progression and radiological consequence.

3. SPENT FUEL POOLS DESIGN

A typical design of the SFP in pressurized water reactors (PWRs) is shown in Figure 1, whereas Figure 2 shows a typical pool design for boiling water reactors (BWRs). The pools are constructed of reinforced concrete with a stainless steel liner to prevent leakage and maintain water quality. The pools are envisaged to withstand design-basis seismic events.

Each plant has a source of high purity water to fill the SFP, referred to in nuclear power plants as make-up. The preferred sources are usually the refuelling water storage tank for PWRs and the condensate storage tank for BWRs. The normal make-up is through a connection from the water source to the suction of the SFP cooling system pumps, and local valve operations are needed to initiate SFP make-up. The make-up rates among plants have a wide range. Plants also have alternate methods to provide make-up, if normal make-up is unavailable, and may include the service water system and the fire water system.

For BWRs, the SFP is generally located within the reactor building, but outside of the primary containment. Also for PWRs, the SFP is usually located outside the containment, but adjacent to it in a separate fuel handling building or within the auxiliary building. Exceptions are the Russian VVER-1000 design, the German Kraftwerk Union (KWU) KONVOI or pre-KONVOI PWR design, and the AREVA EPR design, where the SFP is located inside the containment.

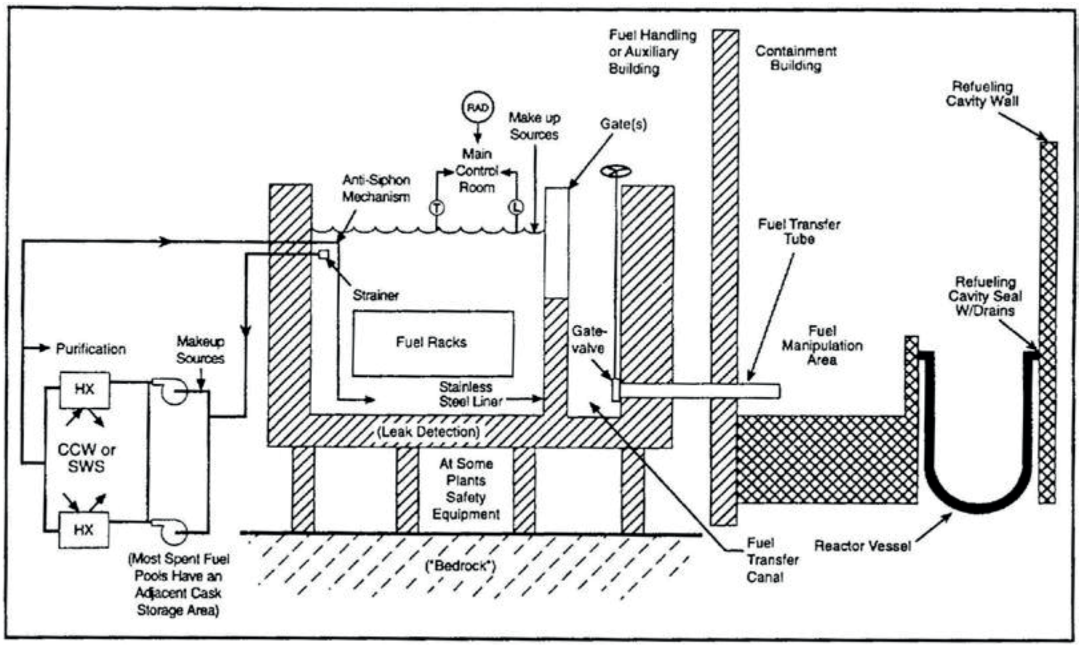

Figure 1: Generic SFP design for PWRs

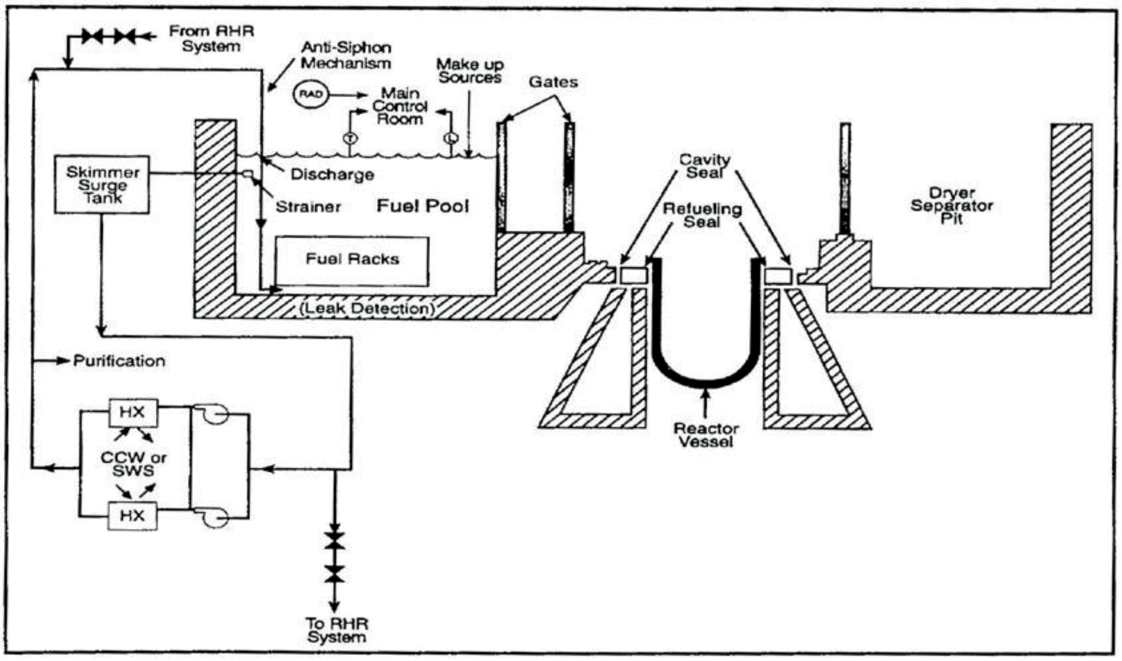

Figure 2: Generic SFP design for BWRs

Typically, SFPs in light water reactors are about 12 m deep and vary in width and length. The fuel is stored in stainless steel (SS) racks that are submerged with approximately 7 m of water above the top of the stored fuel. The water in the SFP of a BWR is demineralized water, whereas PWRs and VVERs use borated water. In addition to cooling, the SFP water inventory provides radiological shielding for personnel in the fuel pool area and adjacent areas. Shielding is also provided by the thick concrete walls of the SFP. Each plant generally has technical specification requirements for water temperature and level, and for the margin to criticality for the fuel stored in the SFP.

4. SPENT FUEL POOL OPERATING EVENTS

Status Report on SFP describes selected events where the cooling of pools or part of their water inventory is lost are described. We can say that no major events occurred, i.e., events with significant consequences related to SFP loss-of-cooling have not happened. However, the described events illustrate different scenarios in which SFP cooling or water level was affected, and in escalated scenarios, it could result in fuel damage. Therefore, the described events are selected such that difference in their nature is emphasized rather than level of significance.

4.1. Fuel related events

In 2009, the European Clearinghouse on NPP Operational Experience Feedback performed a study on events reported in the IAEA International Reporting System for Operating Experience [2] related to nuclear fuel. The SFP related events causes relate to human errors and, to a lesser extent, design deficiencies. Some of these deficiencies originated from the initial design of the SFP, but in some occasions, the design deficiencies derived from a change in the characteristics of the stored fuel (e.g. higher enrichment and burn-up, re-racking).

In the study [2], 28 events have been identified to be related to fuel integrity in storage facilities, mainly in the SFP. According to their nature, they have been classified in events related to Loss of cooling; Loss of margin to criticality; Fuel integrity, and Radiological impact.

Events with loss of cooling (including SFP water level drops) (Table 1) are relatively the most frequent ones, and are caused or related to configuration control of the SFP cooling system (interconnections and manual operation), leakages in the liner, and the lack of monitoring systems, so detection of the problem could be delayed. This group of events includes all the events that have originated from any kind of loss of cooling capacity, either cooling system equipment malfunction or loss of coolant (significant drop of the fuel pool water level). It should be remarked that these events are slow, and there is usually enough time to restore the cooling function.

Table 1: Some past events related to loss of SFP cooling

NPP, type	Event	Cause	Consequences
Kori 1, Korea, PWR	Loss of shutdown cooling due to station blackout during refuelling outage	Loss of off-site power resulted in loss of SFP cooling.	SFP temperature increased slightly.
Catawba 1, USA PWR	Dual unit loss of off-site power resulting from inadequate relay modification	Loss of off-site power resulted in loss of SFP cooling.	Short loss of SFP cooling capability.
Forsmark 3, Sweden, BWR	Emergency diesel generators failed to start after undetected loss of two phases on 400 kV incoming off-site supply	Loss of two phases on 400 kV off-site power resulted in loss of SFP cooling.	Loss of SFP cooling capability with no increase in SFP temperature.
Almaraz-2, Spain, PWR	Irradiated fuel, both in the vessel and the SFP, without forced cooling during refuelling outage	Loss of component cooling water system capability.	SFP cooling was lost for 7 hours and temperature increased by 12 K.
Belleville 2, France, PWR	Disruption of the SFP cooling	Fire in the pump room of one of the two SFP cooling system trains, while the other was out of order.	Simultaneous failure of SFP cooling trains, for 6 hours and then for 15 hours.
SONGS 2, USA,	Inoperable SFP cooling pumps results in loss of safety function	One SFP cooling pump out of service and the other	SFP temperature increased slightly.

NPP, type	Event	Cause	Consequences
PWR		tripped on overcurrent signal.	
SONGS 2, USA, PWR	Both trains of SFP cooling inoperable results in a loss of safety function	Salt water cooling system low flow affected component cooling water system.	SFP temperature increased slightly.
Khmelnitski 1, Ukraine, VVER-1000	Drop in the level of the wet refuelling pool and flooding of reactor building areas	Inappropriate valve maintenance activities caused leak through open joint on one SFP valve.	Significant drop in the level of the wet refuelling pool (1.9 m).
Borssele, The Netherlands, PWR	Insufficient testing of functionality of siphon breaker valve at spent fuel basin	Lack in inspection program.	None*.
Cattenom 2 and 3, France, PWR	"Siphon breaker" missing on SFP cooling systems pipes	Injection pipe could extract the water from the pool through a siphon effect.	None*

* Design/Inspections changes implemented later to prevent potential uncontrolled drainage of SFP.

Events with radiological impact are also relatively frequent, due to the numerous activities and circumstances that could lead to radiological exposure of the workers. It should be noted that radiological exposure in this context does not mean fuel overheating and radioactive release from damaged fuel. The main cause of these events is activities in the SFP building, not carefully planned and analysed to identify all possible sources of radiological exposure (risk analysis).

Events with a reduction in the margin to criticality and events with fuel integrity concerns are rare, and their specific causes are erroneous concentrations of boron, incidents with inadequate neutron absorbers in structures, errors in the calculation of the margin to criticality, or failure in the control and monitoring of the SFP water chemistry. Restoring the boron concentration, repairing the neutron absorber in the structures, and correcting the calculations are sufficient to recover the criticality margin.

4.2. Fukushima Daiichi accident

The Great East Japan Earthquake took place on 11 March 2011, and the resulting tsunami caused loss of emergency diesel powered AC generators and produced conditions known as station blackout (SBO) at the Fukushima Daiichi Nuclear Power Station (NPS). As results of the SBO, the emergency cooling systems and water supply systems failed and the three Units 1 to 3 subsequently suffered severe core damage.

Following the loss of all AC power at Units 1 to 5, the SFP cooling flow was lost in the Unit 1 to Unit 4 SFPs, while the Unit 6 air-cooled emergency diesel generator survived the tsunami and was used to maintain cooling and water supply for the Unit 5 and Unit 6 SFPs [3]. With no pool cooling to remove decay heat at the Unit 1 to Unit 4 SFPs, emergency water injection was conducted by using a helicopter, a concrete pump truck, a fire truck, and the make-up water condensate or SFP cooling and cleanup system line. Eventually, pool water cooling by the alternative cooling system was started at Unit 1 to Unit 6 SFPs, and the water temperature has then been maintained below 40 °C, which is a typical SFP temperature. Video inspections reveal that the fuel racks appear to be intact, and water analyses indicate that fuel damage in the pools is unlikely. Hence, there is no evidence that the fuel in the pools was damaged.

The most serious scenario happened in unit 4 SFP. Around 15:35 on 11 March, the SFP 4 lost all AC power when EDGs stopped functioning as the seawater pumps and power panels were flooded by the tsunami. The cooling and water supply for the SFP likewise failed. Around 6:00 on 15 March, the reactor building was damaged by a hydrogen explosion, and a large amount of debris dropped into the pool. On 16 March, a helicopter flew close to the operating floor of Unit 4, at which time the water surface of the pool could be seen, but no exposed fuel was observed.

According to the original schedule, the drain of the reactor vessel and reactor well should have been completed by 7 March 2011, but the operations were delayed and the reactor well was still filled with water on March 11 [4] [5]. This situation played an important role during the course of the accident and significantly slowed the decrease of the SFP 4 water level: the water-tightness of the pool gate was lost due to the pressure from the reactor well side as the SFP water level became low. It induced a water inflow from the reactor well to the pool.

At first, the water inflow from the reactor well was not considered and it was estimated that the fuel would be uncovered by late March. Therefore, from 20 March, water was added via helicopter, fire truck, and concrete pump truck. Eventually, the water level reduced to 1.5 m above the top of the fuel racks as the amount of evaporation was larger than the water injection, including water inflow from the reactor well, until around 20 April, as shown in Figure 3[3].

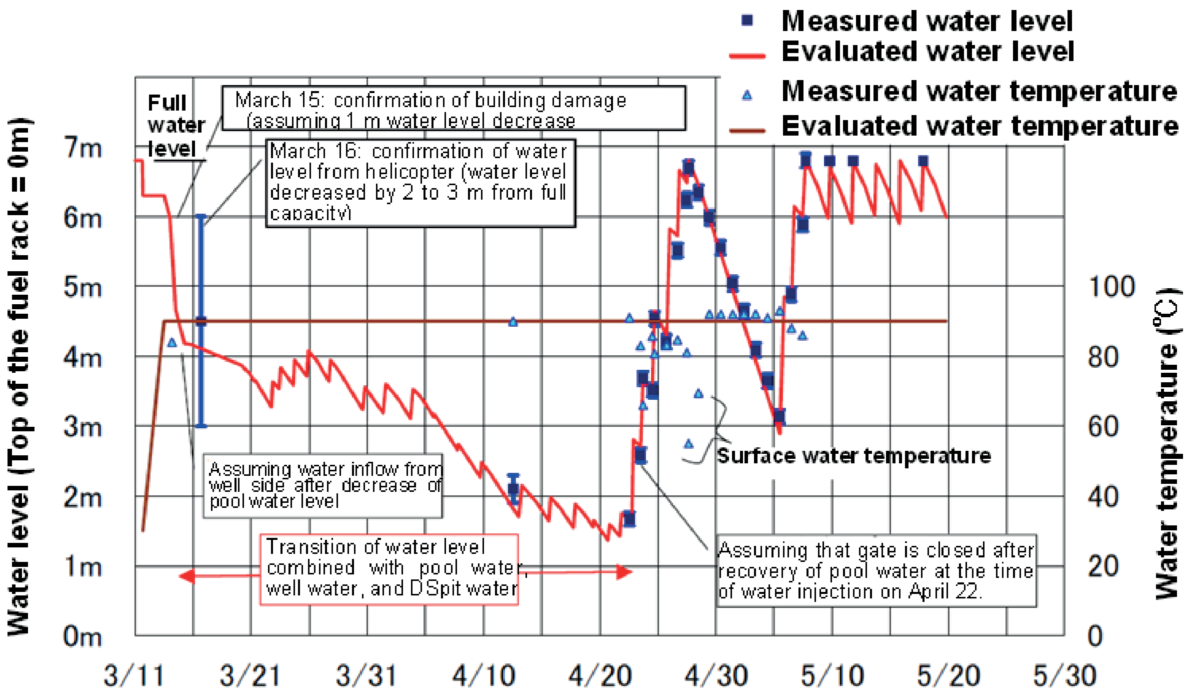

Figure 3. Evaluated water level and water temperature in the SFP 4 by TEPCO

The assumptions made in the estimation are as follows:

- The water level is assumed to have been reduced by 1.5 m as a result of sloshing by the earthquake and the explosion.

- Inflow from the reactor well occurred before 22 April. The water level was calculated by considering the water in the pool and the reactor well and dryer and separator pit collectively. After 22 April, the pool gate was closed, and no inflow from the reactor well was considered.

Later, intensive water injection conducted between 22 and 27 April succeeded in recovering the water level to the full capacity. The water injection was then suspended until 5 May to study the trend of the reducing water level. Subsequently, the water level recovered again to full capacity by intensive water injection, and then the water level is considered to be maintained at near full capacity by repeated reduction and recover due to evaporation and water injection.

On 31 July, pool water cooling by the alternative cooling system was started. The pool water temperature was around 75 °C when the cooling was started and reached a steady condition on 3 August when the water temperature stabilized at about 40 °C.

4.3. The Bruce-A Unit 4 fuel transfer incident

On 1983 November, a CANDU 37-element fuel bundle was overheated in steam-air environment in the fuel transfer mechanism of Bruce-A Unit 4 reactor, Canada [6]. This event differs from the case of loss of coolant in CANDU SFP because there were no neighbouring fuel bundles, and the decay heat was higher than expected for a bundle in a CANDU SFP. Also, the temperatures at the end-plates were lower than the temperatures in the rest of the bundle.

Bundle G70551W was a standard 37-element Bruce Nuclear Generating Station bundle irradiated to an average burnup of 5.9 MWd/kgU at an average outer element power of 41 kW/m. It was discharged from the reactor as part of normal scheduled fuelling. The bundle was kept in the fuelling machine under heavy water cooling for about 2 hours before discharge to the fuel transfer chamber. Because of problems with other equipment, the bundle was left on the cradle in the flooded fuel transfer chamber for many hours. The vent valve was left closed, so injection of air from the instrumentation bubbler formed an air space in the top of the chamber, which slowly uncovered the bundle. After the bundle was uncovered, local boiling would also have occurred, which could have displaced further water from the chamber. The bundle was probably partly uncovered for a total of 5 hours; the vent valve was opened once during the incident, which would have re-flooded the bundle. The incident was terminated when the fuel port seal was opened, submerging the bundle and releasing airborne activity from the chamber.

Sheath oxidation was more rapid at the bearing pad braze heat affected zones. At the central bearing pad plane of the bundle, the sheaths of 22 of the 37 elements (in the upper and central parts of the bundle) were severely oxidized, and in many cases were ballooned and distorted. Hydriding was found in the unoxidized part of some sheaths. The inner elements had degraded into rubble. None of the sheath oxides had a columnar structure, so the bundle temperatures probably did not exceed 1050°C. Melting of a few of the beryllium brazes indicated temperatures above 970°C. Oxidation of the sheath inner walls and of the UO_2 was minimal, so the air was probably rapidly deoxygenated by the Zircaloy oxidation. Also, fuel-sheath interaction was not observed.

4.4. The Paks cleaning tank incident

On April 10, 2003, during refuelling outage in the Paks unit 2, Hungary, 30 spent fuel assemblies were being cleaned in a special container in the fuel manipulation pit of the SFP. After completing the cleaning process, the fuel was left in the container with reduced cooling, which resulted later in severe cladding oxidation and fuel damage [7][8].

The cleaning system consisted of a container installed in a pit for fuel manipulations connected via a lock to the SFP, interconnecting lines, heat exchangers and filter equipment (Figure 4). This technical system formed an internal closed circuit almost completely submerged into water, except for the heat exchangers and filters that were located on the reactor desk or beside it. The container received 30 assemblies for cleaning at a time, and the cleaning process was performed by circulation for about 35-40 hours. During the annual outage of Paks unit 2, altogether 210 FAs, i.e. assemblies for 7 containers, were scheduled to be cleaned.

The cleaning programme for the sixth batch of FAs loaded into the cleaning tank was completed by 16:55 on April 10. The fuel was not removed from the cleaning tank immediately, since the crane was busy with other tasks. The coolant was circulated by a submergible pump with much lower mass flow rate than used in the cleaning process (Figure 4). Contracted specialists continuously maintained the cooling of the cleaning tank at 37 °C. At 21:53, activity was detected by the krypton measurement system installed in the cleaning circuit, and at the same time, the 'alarm' level was reached by the noble gas activity concentration monitors in the reactor hall, and then the operational dosimetry systems installed in the ventilation stack indicated abrupt increase of noble gas activity (max. 0.2×10^{13} Bq/10 min). The plant supervisor ordered to terminate the work carried out in the reactor building and to leave the area. An extraordinary maintenance committee was called, in order to evaluate the event and to take necessary actions. As highest priority, it was decided to open the cleaning tank, to carry out visual inspection, and if possible, to separate the nonhermetic FA and also to analyse the water quality.

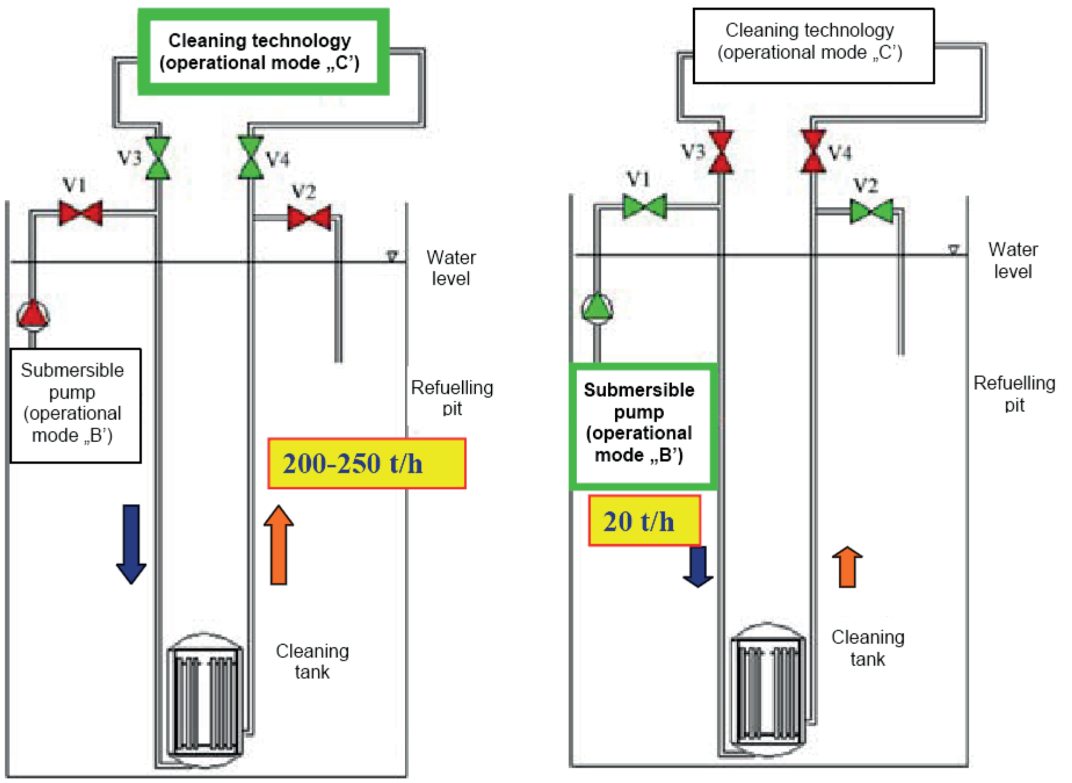

Figure 4: Arrangement of the cleaning tank cooling during cleaning (left) and post-cleaning (right) [7].

The cleaning tank head was unlocked by a contractor at 02:15, April 11. Immediately after this, an activity increase was observed in the dosimetry control and monitoring system) and, at the same time, the water level in the SFP lowered by approximately 7 cm. The first results of water chemistry analysis identified the fission products ^{134}Cs, ^{137}Cs, ^{131}I, ^{132}I, ^{133}Xe and ^{85}Kr in the samples at activity level of 10^4-10^7 Bq/kg. Activity of less volatile species was also detected in the water samples [9]. During the cleaning tank head removal operation, one of the three cables of the lifting tackle broke, thus the head removal failed. The head was lifted on April 16, 2003, and the inspection was performed with video camera. The damage of the fuel assemblies was seen to be more severe than assumed before.

Later inspection has revealed that, due to the special design of the cleaning tank and the characteristics of the fuel assemblies, the cooling by the submersible pump of lower mass flow was insufficient. The low flow rate pump was not capable of removing the decay heat (241 kW) due to a by-pass effect. The temperature stratification blocked the flow, and therefore, the coolant temperature reached saturation temperature in the upper part of the cleaning tank. Then, the steam-formation pushed the main volume of the coolant out of the cleaning tank vessel. This way, the FAs were left without proper cooling for hours and heated up to above 1000 °C, which resulted in severe damage and oxidation of the FAs. Oxidation in high temperature steam and hydrogen uptake resulted in embrittlement of the fuel assembly shrouds and the fuel rod cladding. When opening the cleaning tank, the injection of cold coolant caused the breaking up of the embrittled shrouds and fuel rod cladding.

Video examination indicated that most of the fuel assemblies suffered damage. Brittle failure and fragmentation of FAs were observed. Above the upper plate, several assembly heads were broken, standing in inclined position. One assembly header was found far from its original place. Many FAs were broken and fragmented also below the upper plate, and some assemblies were fractured in their entirety. Fuel rod fragments and shroud pieces accumulated on the lower plate between the FAs. Many fuel rod pieces and fragments of assembly shroud were dispersed within the tank. Some fuel pellets fell out of fuel rods, their form remained mainly intact. Heavy oxidation of the zirconium components was identified. Less oxidation was found in the periphery than in the centre, and the bottom part of the fuel remain intact. The radioactive noble gases that escaped from the damaged FAs were released into the environment through the reactor hall stack with negligible impact on the environment. Most of the non-gaseous fission products were trapped by the large water mass of the pool, and removed by the water purification system [9].

The OECD-IAEA Paks Fuel Project was performed to support the understanding of fuel behaviour in accident conditions on the basis of analyses of the Paks incident. Computer simulations of the most relevant aspects of the event and comparisons of the calculated results with the available information were carried out between 2006 and 2007. The numerical analyses improved the understanding of the Paks incident and helped to make more precise some parameters of the incident, such as:

- the by-pass flow at low flow rate amounted to 75-90 % of the inlet flow rate, which led to the formation of a steam volume;

- the maximum temperature in the tank was between 1200 and 1400 ºC;

- the degree of zirconium oxidation reached 4-12 %;

- the mass of produced hydrogen was between 3 and 13 kg.

The OECD-IAEA Paks Fuel Project improved the current knowledge on fuel behaviour under accident conditions, and led to recommendations for some further actions for research in this area.

5. CONCLUSIONS

Adequate cooling of the spent fuel in the SFP can principally be lost either by malfunction of the pool cooling system or by loss of the pool water inventory. In the Status report on SFPs under Loss of Cooling Accident Conditions examples are given for both types of events. The chosen events are not the most significant ones, but they present different possible scenarios that lead or could lead to loss of spent fuel cooling.

Losing the cooling of the SFP in a nuclear power plant is an event mostly connected with inability of SFP cooling pumps to operate. This is often caused by loss of electrical supply to pumps. Usually, if the loss of off-site power occurs, manual action is needed to connect back-up electrical supply. If back-up electrical supply is unavailable, the pumps cannot operate and the temperature of the pool will consequentially start to increase. In evaluated recent events, electrical supply became available and cooling continued well before the SFP water reached the maximum allowed temperature.

The most serious SFP scenario from Fukushima Daiichi nuclear accident studies showed several latent weaknesses that could result in fuel uncovery in SFP 4 and damage. This was the main reason why interest in the safety of spent nuclear fuel stored in SFPs under prolonged loss of cooling conditions increased.

Although Paks and Bruce incidents cannot be considered as a typical SFP accident, they gave insights that can be useful for understanding phenomena related to SFP loss of cooling/coolant accidents. They also prompted research about such accidents.

An improved understanding of the phenomenology of SFP accidents and coolability mechanisms, along with a consensual view of the extent of remaining uncertainties, are indispensable for reliable estimation of accident progression and radiological consequence.

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