Lappeenranta University of Technology
LUT School of Energy Systems
Energy Technology

Hanna Tynys

SAFETY ASSESSMENT OF INTERIM SPENT NUCLEAR FUEL STORAGE

Examiner:	Professor, D.Sc. Juhani Hyvärinen
Supervisors:	M.Sc. (Tech) Jukka Hautojärvi
	M.Sc. (Tech) Lauri Peltokorpi

ABSTRACT

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Safety Assessment of Interim Spent Nuclear Fuel Storage

Master’s thesis

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94 pages, 32 figures, 14 tables and 3 appendices

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Keywords: spent nuclear fuel, Apros, deterministic safety analyses

This master's thesis focuses on safety of interim spent nuclear fuel storages and presents thermal hydraulic safety analyses which are performed for a wet pool storage. Advantages and challenges of two storage types, a wet pool storage and a dry cask storage, are studied. The safety issues are considered during normal operation and also in accident scenarios. The storage types are specially considered in the point of view of Hanhikivi 1 spent fuel storage, which is currently in a design phase. Safety features of the storage of Hanhikivi 1 are also discussed in different accident scenarios.

Interim spent fuel storages are commonly considered safe due to the low decay heat of fuel. Historically no accidents with serious consequences have occurred. The key design objective is that severe fuel damages in storages shall be practically eliminated by design.

Dryout of a fuel pool and uncovering of the fuel in a wet storage is recognized to be the most serious accident scenario, especially in considering possible intense oxidation and the ignition of the zirconium cladding of the fuel. However such fuel uncovering and a zirconium fire are highly unlikely, due to the low decay heat of the fuel and the long time delays in question. Mechanisms of oxidation and zirconium fire are studied by using reference material from literature.

In this thesis thermal hydraulic safety analyses for Hanhikivi 1 wet storage concept are performed by using Apros simulation tool. The natural safety features, especially the long time frame needed for heating of the large water mass and the safety functions were sufficient to keep the fuel uncovered and intact in the analysed initiating events. The analyses will be used as a part of licensing material of spent fuel storage of Hanhikivi 1.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
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Hanna Tynys

Käytetyn ydinpolttoaineen välivarastoinnin turvallisuuskartoitus

Diplomityö

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Tässä diplomityössä tutkitaan käytetyn ydinpolttoaineen väliaikaisvarastoinnin turvallisuutta sekä tehdään turvallisuusanalyysejä vesiallasvarastolle. Työssä tutustutaan käytetyn polttoaineen kuiva- ja märkävarastoihin ja tyyppien etuihin ja haittoihin. Välivarastojen turvallisuutta kartoitetaan sekä pitkäaikaisturvallisuuden että onnettomuusskenaarioiden osalta. Varastointiin tutustutaan erityisesti suunnitteilla olevan Hanhikivi 1:n käytetyn polttoaineen varaston näkökulmasta. Hanhikivi 1:n varaston luontaisia turvallisuusominaisuuksia on tarkasteltu myös onnettomuusskenaarioiden yhteydessä.

Polttoaineen välivarastointia pidetään yleisesti ottaen turvallisena polttoaineen matalan jälkilämpötehon vuoksi. Historiallisesti vakavia onnettomuuksia ei ole tapahtunut. Tärkein suunnittelutavoite on suunnittelutoimenpitein käytännössä eliminoida polttoaineen merkittävät vauriot.

Märkävarastojen altaiden kuivuminen ja polttoaineen paljastuminen tunnistetaan merkittävimmäksi onnettomuusmekanismiksi erityisesti siksi, että se voi johtaa polttoaineen zirkonium-suojakuoren voimakkaaseen hapettumiseen ilmassa, zirkonium-tulipaloon. Käytetyn polttoaineen pidempiaikaisten varastojen osalta zirkonium-palo on epätodennäköinen polttoaineen alhaisen jälkilämpötehon vuoksi. Oksidoitumista ja zirkonium-palon mahdollisuutta ja mekanismeja on tarkasteltu lähdemateriaalin perusteella.

Työssä tehdään myös turvallisuusanalyysejä vesiallasvarastolle Apros-ohjelmalla. Analyysien tuloksena todettiin aikaviiveet altaiden suuren vesimassan seurauksena pitkiksi sekä turvallisuusjärjestelmät riittäviksi polttoaineen jäähdytyksen turvaamiseksi tarkasteltujen alkutapahtumien yhteydessä. Analyysejä käytetään osana Hanhikivi 1:n käytetyn polttoaineen välivaraston lisensiointiaineistoa.

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Finishing this thesis is the summit of six years of hard work and great experiences in Lappeenranta University of Technology. During the last few years I have not only gained knowledge via the interesting courses and lectures but also by participating many activities of student community in Skinnarila. Times in Armatuuri and LTKY gave me once in a lifetime experiences, organizing skills and most of all many amazing friends. These past years and late nights at the university would have been a lot harder without fantastic people in the guild room with their clever advice and awful jokes. So thanks to my dear friends!

I wouldn't be here without the support of my family, so thank you for all that you have done for me. Thanks also to my dearest Tomi for being there for me.

Towards new challenges! Thank you LUT and Skinnarila!

Espoo, 17.5.2017

Hanna Tynys

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LIST OF SYMBOLS AND ABBREVIATIONS

Roman symbols

A	Area	[m^2]
h	Enthalpy	[kJ/kg]
ΔH_{rxn}	Reaction Energy	[kJ/mol]
k_{eff}	Effective multiplication factor	[-]
p	Pressure	[Pa, bar]
t	Time	[s]
v	Velocity	[m/s]

Greek symbols

ρ	Density	[kg/m^3]

Abbreviations

BWR	Boiling Water Reactor
DBC	Design Basis Condition
DEC	Design Extension Condition
DiD	Defense in Depth
FH1	Hanhikivi 1 Nuclear Power Plant
HVAC	Heating, ventilation and air conditioning
IAEA	International Atomic Energy Agency
I&C	Instrumentation and control
LOCA	Loss-of-cooling Accident
MAM	Fuel Pool Manual Accident Management task category
MAMBU	Fuel Pool Manual Accident Management Back-Up task category
NPC	Fuel Pool Normal Process Control task category

NPP	Nuclear Power Plant
NRC	United States Nuclear Regulatory Commission
PREV	Fuel Pool Prevention, task category
PWR	Pressurized Water Reactor
SFP	Spent Fuel Pool
STUK	Säteilyturvakeskus, Finnish Radiation and Nuclear Safety Authority
UFC	Spent Fuel Storage of Hanhikivi 1
YVL	Safety requirements concerning the use of nuclear energy by Radiation and Nuclear Safety Authority STUK

1 INTRODUCTION

Nuclear power users all over the world are developing solutions for final disposal of the spent nuclear fuel. An operating repository is still some years away, even though some countries, like Sweden, Finland and France have the plans of disposal facilities almost finished, and Finland has already started construction of a final disposal facility in Eurajoki. Used nuclear fuel elements need to be stored for decades or even centuries while waiting for final disposal. Even when the disposal facilities are finished, fuel from reactors shall be stored years before the decay heat is low enough for final disposal. That is why interim spent fuel storages are an interesting and an important part of nuclear energy production, and still need to be researched and developed further.

Safety of interim storages has been under consideration already in the 1980's and the subject has been topical again after Fukushima Daiichi accident 2011. Spent fuel storages have been generally considered inherently low-risk due to low decay heat, and therefore severe accidents have not been studied systematically. However consequences of loss of coolant accidents in spent fuel pools could be serious and radioactive release large, especially because storages are not always placed inside a leaktight containment.

1.1 Background

Spent fuel storages are intended to ensure safe storing of nuclear fuel and to prevent fuel damages and radioactive releases during the storage period. After the fuel is removed from a reactor, heat removal must be ensured, because nuclear fuel produces still decay heat. Other safety requirements concern e.g. subcriticality, radiation protection and keeping fuel intact. Fuel retrievability after interim storage must also be ensured, to enable the final disposal.

There are two main types of interim spent nuclear fuel storages: a dry storage and a wet storage. Dry storages are used by most countries, especially the ones that do not have a solution for the final disposal problem yet (OECD/NEA 2016.) Wet storages are present in every light water reactor plant, for storing fuel before it is transferred into dry cask storage. Centralized wet storages, not located in reactor building, are used in countries planning on final disposal in near future, but also countries reprocessing nuclear fuel, like Russia and France.

Fennovoima ltd is in an early phase of constructing a new nuclear plant Hanhikivi 1 (FH1). During this phase of the project they need to prove feasibility of their concept of spent fuel interim storage to the authorities. A storage for spent fuel will be built soon after commissioning of the nuclear plant, and the spent fuel storage must be preliminarily designed at the same time with the actual power plant.

This thesis is a joint assignment for Fennovoima and Fortum Power and Heat ltd, which is a Finnish energy company, who operates Loviisa Nuclear Power Plant (NPP) and owns significant shares of other nuclear plants. Fortum has major competence in engineering and design of nuclear facilities, which is why Fennovoima has chosen Fortum to perform conceptual design and licensing documents for Hanhikivi 1 spent fuel storage.

1.2 Objectives and limitations

The aim of this thesis is to examine safety features of different interim spent fuel storage types and produce preliminary safety analyses for a wet storage. Safety of wet and dry storages is discussed both in normal conditions and in case of extraordinary events. Accident mechanisms and consequent phenomena in spent fuel storages will be studied in this thesis. Also severe accident conditions, which need to be proven to be practically eliminated in spent fuel storages, are considered.

One of the main focuses of this thesis is to produce thermal hydraulic safety analysis for spent fuel storage of FH1 (Hanhikivi 1) spent fuel storage. Analysis shall prove that the fuel integrity is maintained in assumed initiating events.

Thesis focuses on spent fuel of light water reactors. The storage options discussed in this thesis are mainly located outside the reactor building, however most of the information is suitable for in-containment-pools also. Similar storages are also used for reprocessing waste, but this thesis focuses on fuel removed from nuclear reactors. These limitations are chosen because the FH1 nuclear power plant is also light water reactor, and the interim spent fuel storage shall be built at the plant site, but not inside the containment.

1.3 Structure of thesis

Chapter 2 includes general information about interim spent fuel storing. Chapter 2 also describes different storage types, a dry and a wet storage and their features. Advantages and challenges of the storage options are described, and safety in long term is considered for both storage types. Comparison between the storage types is done in general, and also in case of the storage of FH1.

Chapter 3 considers accident scenarios mainly in wet storages of spent fuel. Internal and external hazards and initiating events are described as well as the possible consequential phenomena. In this chapter also some earlier analysis concerning accident scenarios are described. Some earlier operational experience and accidents, including Fukushima accident are described.

Chapters 4 and 5 present the thermal hydraulic analyses carried out in this thesis. Some modelling methods and tools for spent fuel storages are generally listed in chapter 4, and simulation tool Apros is introduced. Model of FH1 wet storage is briefly described. Produced thermal hydraulics safety analyses and their main results are presented in chapter 5.

Chapter 6 presents the conclusions made in this thesis based on the research and the analyses. Ideas for further research are also discussed in this chapter. Chapter 7 summarizes the main results of this thesis.

2 INTERIM SPENT FUEL STORAGES

Interim storages can be divided into two types: a wet storage and a dry storage. Both of them are used widely all over the world. Each type has its advantages and weaknesses. Wet storage consist of pools filled with water that can be borated or demineralized water. Storage pools are cooled via a cooling system by pumps or using natural circulation. Dry storage concept is based on air cooled containers. They are passively cooled by natural circulation of air. The containers are located either inside of a building (mainly in Europe) or outside (mainly in the USA). There are two types of containers: ones that are used only for storage, and others used also for transport, so called dual-purpose-casks. Nowadays most countries use dual purpose casks. (OECD/NEA. 2016.)

There are some fundamental requirements for nuclear fuel storage. Decay heat removal from the fuel must be secured. Subcritical conditions need to be maintained during normal operation, during fuel loading and in accident scenarios. Exposure for radiation is minimized by shielding and radioactive releases are prevented.

Prevention of releases is based on Defense in Depth (DiD) -principle. Fuel is kept intact using many layers of different barriers. One barrier may fail, but the others still protect the fuel. Finnish regulations demand five layers, in which two are designed to prevent accidents and the rest to protect the plant and the environment against effects of accidents. (YVL B.1 2013) DiD levels 4 and 5 are not applied for Spent fuel storages (YVL D.3 2013, §410). Defense in depth levels (YVL B.1. 2013, §421) are presented below.

1. **Prevention.** The first level is to ensure that the plant operates reliably and deviations from normal operation are rare. To achieve this, the design, manufacture, installation, commissioning, inspection, testing and maintenance of systems, structures and components, and the operation of the plant shall comply with high standards of quality and reliability with adequate safety margins. In case of a pool the first level includes natural and structural features which prevent accidents, for example locating the storage pools to solid ground, so that there is no leak path.
2. **Control of anticipated operational occurrences.** At the second level, in addition to the careful design and operation of the plant, provisions shall be made for deviations from normal operation; the plant shall be equipped with systems designed to detect

any anticipated operational occurrences and limit their escalation into accidents and, where necessary, to bring the plant to the controlled state. For example the inertia of large water mass in the pool would belong to this level.

3. **Control of accidents.** At the third level, provisions shall be made for accidents by means of reliable systems that are automatically actuated in the event of an accident; protect the barriers for confinement of radioactive substances; prevent the occurrence of severe fuel failure in postulated accidents and design extension conditions; and prevent the accident from escalating into a severe accident. The actual safety functions and systems belong to this level.
4. **Containment of release in a severe accident.** Level 4 is not generally used for spent fuel storages, because severe accidents, when fuel is severely damaged and this DiD level would be needed, are practically eliminated by design features.
5. **Mitigation of consequences.** Level 5 is not applied for spent fuel storages, because severe accidents, when fuel is severely damaged and this DiD level would be needed, are practically eliminated by design features.

Regulations require that severe accidents in spent fuel storages are practically eliminated using the first three DiD-levels. Practical elimination of fuel damages need to be proved using methods based on deterministic analyses, probabilistic reliability analyses, and expert assessments. Elimination cannot be solely based on probabilistic considerations. All additional reasonably practicable features that reduce the risk shall be implemented to design. (YVL D.3 2013, §412; YVL B.1 2013, §424).

Structural safety of spent fuel storages is based on physical barriers. Barriers are designed to maintain integrity under normal occurrences and in anticipated operational occurrences. In an accident at least one barrier should maintain its integrity.

1. **Fuel matrix** – retains solid fission products in fuel pellets and limits gaseous fission products release to gas space inside fuel element cladding;
2. **Fuel element cladding** – eliminates gaseous fission product release to cask or fuel pool coolant and in pool prevents direct contact between coolant and fuel;
3. **Fuel pool / dry storage cask**– retains fission products leaked from fuel elements to fuel pool or storage cask and enables capture of leaked fission products.

4. **Storage building** (if applicable) - air filters of building prevent the possible leaks to environment, but the building is not generally designed to withstand significant overpressure.

Besides structural safety, functional safety plays an important role on overall safety of the storage, especially in wet storage. Important safety principles for spent fuel storages as well as the whole plant, are redundancy, separation and diversity principles.

Diversity principle refers to components or systems having different operating principles. All systems/components should be able to implement a function separately. Redundancy principle refers to use of several parallel subsystems, so that required functions are performed even if one subsystem fails. Redundancy principle is for example in wet storage applied to functions which bring the pools to a controlled state, which in spent fuel storage refers to a state where fuel integrity is maintained but normal cooling functions are disabled. In controlled state the heat removal is done by warming of the pool water (before it starts to boil) or boiling, and the system is kept in controlled state by adding cold water to the pools. Separation principle refers to physical separation and functional isolation of important systems; separation prevents failure propagation from one subsystem to another.

Interim storages were originally designed for storing used nuclear fuel for short time periods. The intention was to reprocess or dispose nuclear fuel in a few decades. Only a part of fuel is nowadays reprocessed, in which case it is stored only for a relatively short time period. However a great amount of fuel, as well as vitrified reprocessing waste, is waiting for disposal. Fuel from first reactors has now waited disposal for 50 years, and will possibly be stored for another 50 years or even 300 years, since the plans for final disposal are delayed in some countries. Also it is economically feasible to store fuel in interim storage before it is placed in disposal facilities. The lower decay heat after longer cooling time in interim storage enables denser packing in the final disposal facility, conserving underground space.

Storing facilities and dry casks are originally designed and licensed only for a few decades, for example for 50 years (OECD/NEA. 2016). Storing fuel longer times, even 100 years, can cause several issues in interim storages. These issues are discussed in the chapters on long term safety for both storage options.

2.1 Wet Storage

Over 80 % of the spent nuclear fuel in the world is currently stored in wet storages (IAEA 2015). Storage pools are necessary in every nuclear plant in the world. In most light water reactor plants there are pools in reactor buildings or in an adjacent fuel building for storing fuel after removal from reactor. Fuel with high decay heat is placed at pools inside a containment and moved away-from-reactor pools after a few years cooling time when decay heat is lower. It can then be moved to a longer-term storage or reprocessing. Pools in a reactor building are not designed for storing the fuel of whole lifetime of the plant so their capacity is limited typically to 8-10 years.

Centralized wet storages are mainly used in countries that are reprocessing nuclear fuel. In France and Russia the fuel is moved to centralized wet storage after few years of cooling in nuclear plant. There is also a centralized wet storage called Clab in Sweden. (OECD/NEA 2016.) In Finland existing interim spent fuel storages are wet storages at the sites of operating plants. In Finland there is no centralized storage.

2.1.1 Cooling system of wet storage

In wet storages decay heat removal from used fuel is secured via cooling systems. Spent fuel is placed in pools filled with water. Water cooling is very effective and even fuel with high decay heat can be stored in pools. The ultimate heat sink can be the sea water or a cooling tower. Water temperature is kept low during normal operation, typically below 40–50 °C. Water flows through storage racks by natural convection and pools are cooled by external cooling system that normally is driven by pumps. External cooling system can also be passive and use natural circulation, for example in Gösgen Switzerland (IAEA 2015, 16).

Water in the pools is either demineralized of borated. Use of borated water decreases multiplication factor, but then decreasing of water level / amount of boron will have an increasing effect on multiplication factor. Borated water requires also more complicated water treatment systems.

Pools are typically constructed of concrete and lined with stainless steel liner. Pools are often build to withstand seismic events, whereas cooling systems may not. (Barto et al. 2014) Example of pool design is presented in Figure 1.

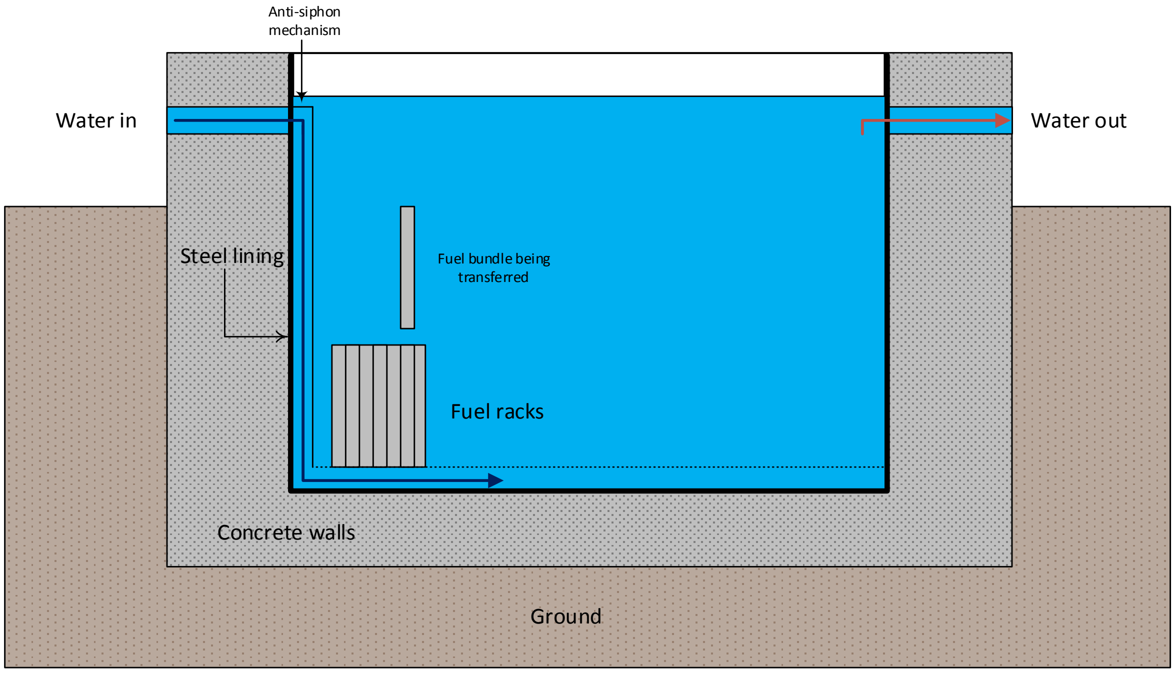

Figure 1. An example of a typical pool design.

As said earlier, severe fuel degradation shall be practically eliminated in spent fuel pools. This means ensuring a sufficient amount of water covering the fuel in all cases. According to Finish regulations the pool cooling must be secured with two redundant cooling lines, allowing cooling to be maintained even if any single component fails. (IAEA 2016, 50; YVL D.3 2013, §417, §422).

The cooling system to ultimate heat sink usually consists of several consecutive cooling circuits, and the heat is transferred from one circuit to another via heat exchangers. Mass flows in these circuits and temperature differences in heat exchangers depend on the decay heat of the elements and temperature of the ultimate heat sink.

Besides the normal cooling system, elimination of fuel uncovering accidents must be ensured with reliable pool water level monitoring instrumentation. Besides actual cooling system, wet storage includes many other important systems, e.g. water condition monitoring, decontamination system and demineralized water injecting system. Example of a wet storage is presented in Figure 2.

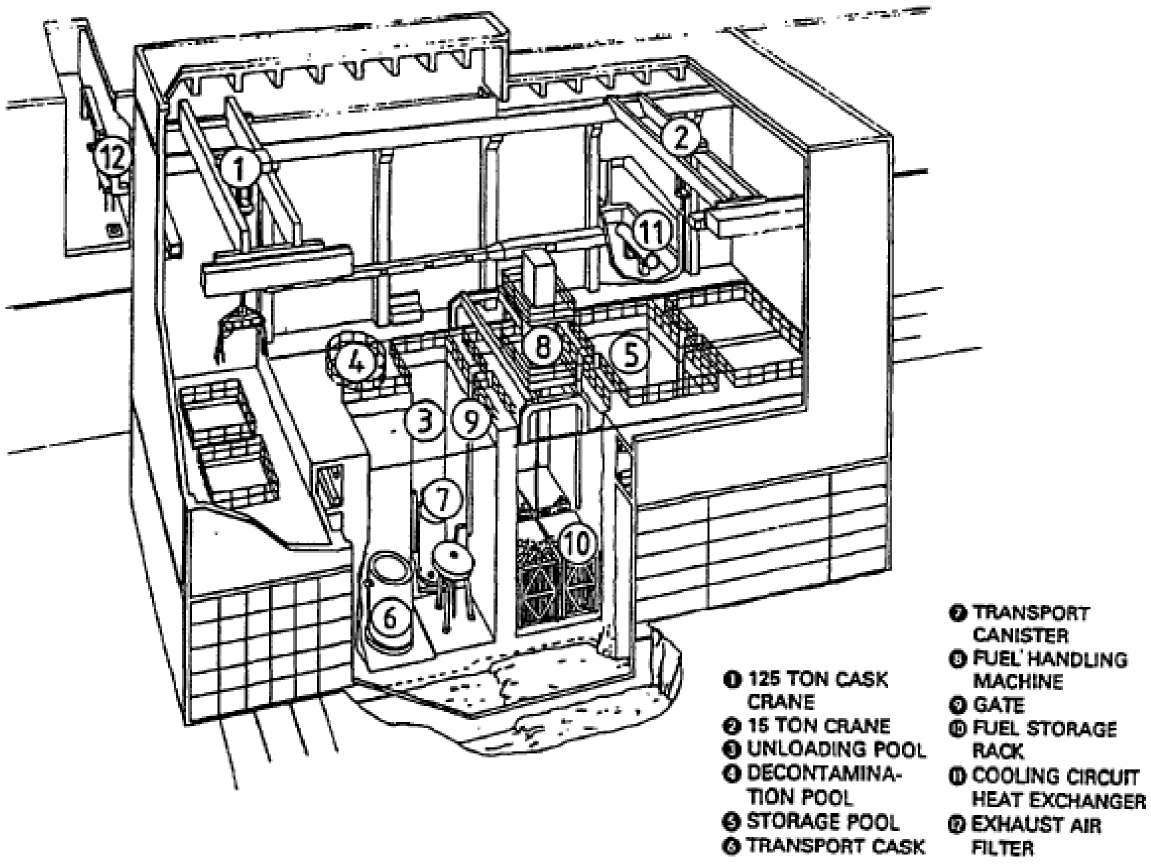

Figure 2. Loviisa pool storage. (IAEA 1999, 16)

2.1.2 Advantages of wet storages

Water has great heat removal abilities which makes removal of residual heat effective in wet storages. In storage pools fuel temperatures are well below 100 °C, in order of 50–80 °C at most (IAEA 1999) and this is relatively low for used nuclear fuel. Many rupture mechanisms are proportional to temperature, and lower temperature consequently results a better fuel condition and retrievability after storage. Mixing of different aged fuels is also possible in wet storage, and so local high temperatures can be avoided.

One big advantage of wet storage is accessibility of the fuel. Fuel condition is required to be monitored by measurements and also by visual inspections. Monitoring of the fuel condition is easy in wet storages, where visual inspections can easily be done under water. Each fuel element is accessible and can be separately inspected and moved. Fuel handling in pools is relatively fast and easy. Fuel transfer to pool can be done with a wet transfer cask and does not require hot cell or any other specific equipment or protected space, as may be required in a dry storage.

Water is also an effective and inexpensive radiation shielding, and placing fuel elements in a pool below large water mass keeps dose rates of workers in an adequate level without any other shielding materials.

Finnish regulations for interim spent fuel storages consider mainly wet storages, as in Finland there are yet no dry storages. Technology for fuel pools and licensing procedure of wet storages in Finland are well known.

Finnish regulations set a requirement for fuel evacuation from one storage unit, like a pool or a cask in case of a leak or another failure. Meeting the evacuation requirement is manageable with storage design containing evacuation pool. Moving fuel from one pool to another is quite simple if the pools are adjacent. There is no need to open any sealed lids or the like, as would be the case in dry storage cask.

Wet storage enables quite straightforward optimization of final repository. Fuel elements with different decay times can be easily mixed in a way that content of transport casks match optimal fuel element positioning in repository capsules. Moving fuel to repository can be done in casks with capacity matching the repository capsules. This however is highly dependent on final repository concept.

2.1.3 **Challenges of wet storages**

Cooling of wet storage is based on active systems and thus requires cooling systems. Cooling systems include a lot of components and interdependencies between process systems, power supply, I&C, and buildings (layout, HVAC) and therefore include some vulnerabilities due to large amount of components and systems that can affect cooling and each other. Wet storages also require some operational support and maintenance. Amount of operative waste is also relatively large, due to resins used in water treatment.

Wet storage building itself shall protect pools from hazards and threats. Airplane protection of the pools may be needed depending on regulatory framework. In Finland airplane protection is needed and the structures for that are expensive.

Cooling systems need electricity, and power loss can eventually lead to a loss of coolant inventory. Without coolant fuel overheats eventually and releases of radioactive particles or gases to environment are possible. In wet storages large amount of fuel is placed in one location, and that increases the risk of large radioactive release in worst accident scenarios. Consequences of accident scenarios in wet storages can be serious. They are described in more detail in chapter 3.

2.1.4 **Long term safety of wet storages**

Spent fuel has so far been kept in wet storage for decades, so effects of long term interim storage are quite well known. Experience of wet storages is available from more than 40 years. In this chapter fuel condition during interim storage period of few decades is discussed.

In wet storages fuel is kept the whole time under water and in low temperature. Fuel cladding integrity is in right conditions maintained even after 50 years of storage. (IAEA 1999, 8.) Based on data of wet storages during last few decades the corrosion of cladding is very low, and therefore corrosion effect is not the limiting factor for extended wet storage period. (IAEA 2015, 13.)

Water chemistry however plays an important role on preventing cladding degradation. Adverse water chemistry can cause fuel cladding degradation. (IAEA 2015.) Fuel leaks and damages could make the transport more difficult, as the damaged fuel elements may need to be stored in a special kind of containers. Damaged fuel may also create challenges in final disposal.

Aging may have an effect on cooling system components. Many of those however can be replaced with new ones. Metal liner of the pool is also more vulnerable for failures during a long time period. Leaking liner can however be quite easily fixed, if the fuel is moved to evacuation pool. Leaks are discussed further in chapter 3.2.2. Eventually deterioration of the pool structures is inevitable, which may be the limiting factor in lifetime of a wet storage. (IAEA 2015, 13.)

2.2 Dry Storage

Dry storages were developed as an alternative to wet storages in the late 1970's, when storage pools in reactor buildings started to fill up with fuel. Dry storages are nowadays used in most countries, except in Sweden and Finland. Generally fuel is transferred to dry casks after it has been cooled down at least a few years in pools.

There are three categories of dry storage casks: casks for storage only, dual-purpose casks for transportation and storage and multi-purpose casks licensed also for final repository in the USA. Casks can be stored in buildings (Europe) or placed outside (USA).

Casks which are used also for transportation are required to withstand 9 m dropping and 1 m dropping to a bar without severe fuel damages. Cask shall also tolerate 30 minutes conditions equivalent to burning, with minimum average temperature of 800 °C. Cask is required also to stay intact while being immersed 15 meters under water for 8 hours, and 200 meters for 1 hour. (IAEA 2012a, 115–117.)

Cask loading can be done either as wet or dry loading. Wet loading is proceeded under water and fuel is dried afterwards. Dry cask loading is performed in a hot cell, which is a specific space including necessary equipment for drying and helium filling. (IAEA 1999, 3.)

2.2.1 Cask design and cooling methodology

Dry storages usually consist of cylindrical casks which are placed in a storage room. The casks provide a physical barrier around the fuel. The casks secure a confinement and work also as a radiation shielding. The casks can be made of steel only, or they may be covered with a concrete shielding. Alternatively dry storages may consist of steel lined vaults or silos. Fuel elements are located inside the vaults or silos either horizontally or vertically.

Typically the height of dry storage casks is 5–7 meters and their weight is over 100 t. Storage capacity of one cask can vary from 10 to over 30 elements. Heat transfer capacity of a dry storage cask is the limiting factor for the maximum power of fuel placed in a cask. This means limitations to fuel burnup, enrichment and cooling time before placement to a dry cask is possible.

An example of a cask design by Rosatom is presented in Figure 3.

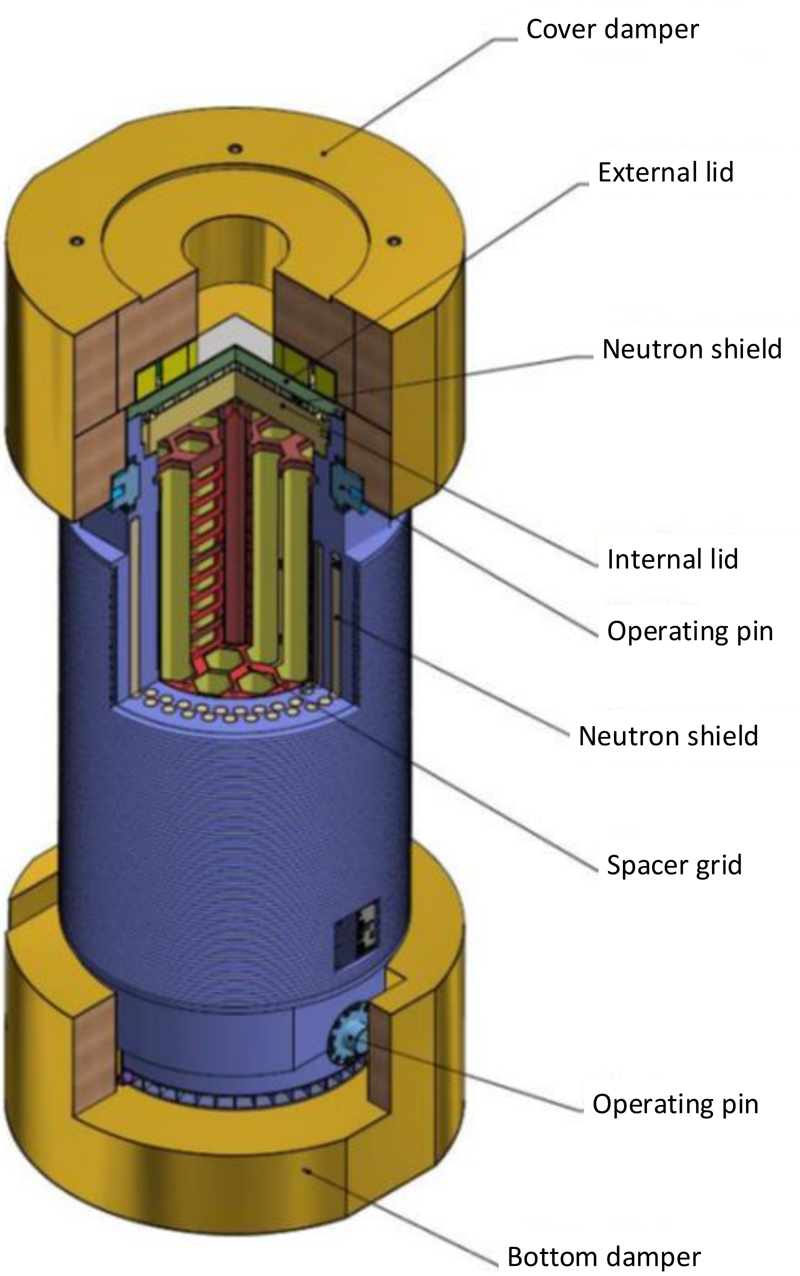

Figure 3. Example of dry cask design TUK-141 (Makarchuk & Afonyutin 2015).

As we can see from an exemplary design in Figure 3, dry casks are typically closed with double covers. Leaks between internal and external lids are measured. Typically the space between the lids is filled with helium and pressurized approximately to 6 bars (IAEA 1999, 44). Pressure between the lids is measured, and pressure changes indicate a leak in one of the lids. (Funke & Heinig 2008.)

Other measurements needed in a dry storage are measurements for cask's temperatures. After the fuel is loaded into a cask, the cask is filled with inert gas and sealed. Cask lids can be either bolted or welded, depending on the design. Bolted casks are easier to open, but welding is less vulnerable for rupture mechanisms. (Hanson et al. 2012, 115–147.)

Figure 4 presents a cask design with a concrete overpack and a steel container inside it. The steel container can be moved separately during loading and unloading.

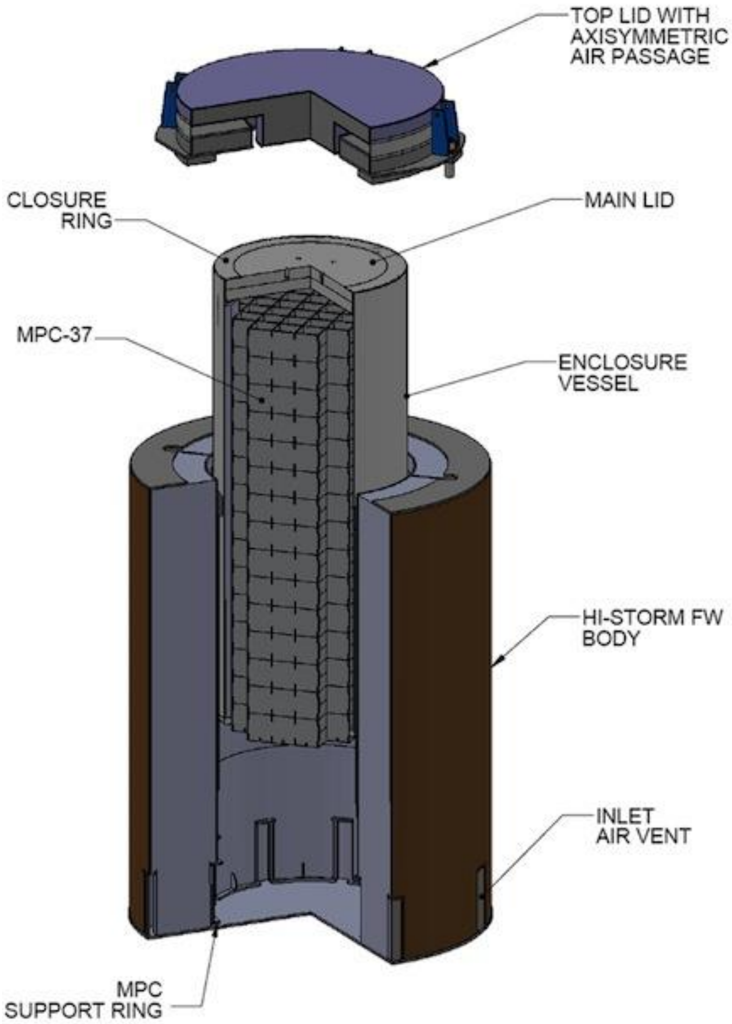

Figure 4. HI-STORM canister design by Holtec International. Canister is placed inside a concrete overpack (Holtec International 2016).

Cooling of dry cask is based on natural convection. Heat from fuel elements is transferred to the outer surface of cask, and natural air circulation is cooling the surface.

2.2.2 **Advantages of dry storages**

A dry storage does not need any operational activities besides monitoring after the fuel is placed in a cask. Dry cask cooling is passive, so there is no need for electricity for cooling of casks, but conventional ventilation of possible storage building may require electricity. Power breaks are unlikely to cause any problems in dry storages. Demand of power in accident conditions is small, (only temperature and radiation measurements and emergency lighting) and therefore it is easily backed up with batteries.

Passive cooling and a simple storage design ensure that managing a dry storage is easy. Need of operational activities and maintenance is low. A storage building for dry canisters can be simple and so it is inexpensive to construct. A building is not necessarily needed in dry cask storage, but it is required in Europe.

Amount of used fuel in one storage canister is small. Due to this the radioactive release in a situation where one canister is damaged is small compared to a situation where large amount used fuel is uncovered.

In a dry cask the fuel is stored in an inert atmosphere, where corrosion is not affected. Usually the casks are filled with helium, nitrogen or argon. Hydrogen pickup reaction does not occur in absence of water (Patterson & Garzarolli 2015, 2–1).

2.2.3 Challenges of dry storages

In a dry cask the fuel is stored in gas atmosphere, so the heat transfer is not as effective as in water. Compared to wet storage the fuel temperature is hence higher in dry storage, typically 200–350 °C in the beginning of the storage period (IAEA 1999) which makes some failure mechanisms, such as oxidation, more effective. Temperatures are however still quite low compared to fuel temperatures in reactor conditions. After drying and a storage period in dry cask conditions, retrievability of fuel needs to be considered. This is discussed in chapter 2.2.4.

Fuel drying is a time consuming operation that is done at the point when the fuel is moved to dry casks. There is no universal process for fuel drying, each cask or canister design has its own features. The fuel is generally dried to be as dry as possible, because the leftover water participates in many degradation mechanisms. Normally water removal is done by vacuum drying system and some water always remains in the cask. Water minimum can be approximated but the real amount of water can only be studied if a cask is opened. Water, steam or water compounds left in the cask can have effect on cladding, fuel and cask hardware condition. (Hanson et al. 2012, 51, 167.) Dry fuel cannot be easily submerged again in water without risks. In dry cask the fuel is in high temperature, and rewetting the fuel rods will cause large temperature gradients as the water vaporizes in the surface. Thermal stress can rupture the fuel, especially if it has already brittled in reactor and during storage.

Finnish requirements do not consider a dry storage option explicitly. Since there have not been any dry storage facilities in Finland, it is natural that detailed regulations for such systems are lacking. Some of the current requirements are hard to apply when dry casks are used. Finnish regulations set requirements for monitoring of the fuel condition. Monitoring of fuel conditions is difficult in a dry cask storage, because visual inspections of fuel can only be done when the canister is open. Casks are either welded or bolted, and opening of a cask can be complicated and time consuming. The intent of the fuel condition monitoring is to ensure integrity of fuel cladding, which in pools is the main barrier against activity release; in case of dry casks, the main barrier is the cask itself, and it might be possible to fulfil the intent of the regulations by cask integrity monitoring.

Packing fuel to dry casks requires special equipment that is expensive and need to be considered during construction phase. Loading fuel to dry casks is a time consuming operation and loading one cask can take several days due to fuel drying, filling of the cask with inert gas and temperature stabilization. Fuel needs to be carefully dried to avoid water residues in the cask. Residual water can react with fuel cladding and generate hydrogen inside a cask.

Dry casks have a limited maximum decay heat capacity. This means that the fuel needs to be cooled in a pool for several years, before it can be transferred into a dry cask storage. Sufficient cooling time depends on the fuel enrichment and burnup. Fuel with high enrichment and burnup requires a longer cooling time in a pool. This means that plant site need to have enough storage pool capacity for the fuel waiting for moving to a dry storage, so significant pool storage would be needed in any case. The other option for packing fuel with high decay heat, is to pack the casks only partially full, which may not be economically feasible.

2.2.4 Long term safety of dry storages

First dry casks were filled in 1980's so there is circa 30 years of experience of dry storages. Casks are licensed only for a period of few decades, typically 40–50 years. The dry storages seem to be safe and fuel condition kept quite good during the current licensing period. Extending storage time and storing higher burnup fuel are issues requiring more consideration in future. (Hanson 2012, 1–9.)

Oxidation of zirconium cladding cannot normally occur in a dry cask, due to the inert gas filling. However, if some water is left in the cask, then cladding oxidation might occur. Oxidation might also occur in the fuel side of the cladding, when zirconium reacts with oxygen in the UO_2. Oxidation of the cladding makes it weaker and more fragile. It might have an effect on heat transfer and increase the fuel temperature. The thickness of the formed oxide layer depends on for example the material composition of the alloy (Hanson et al. 2012, 100–101.)

Oxidation reaction also produces hydrogen. For every one zirconium atom oxidizing, four hydrogen atoms are produced and approximately 20 % of the released hydrogen is absorbed in the cladding, forming zirconium hydride, which makes the cladding brittle and reduces ductility. Cladding failure might occur when fuel is cooled for example during the drying operation. Cladding can also fail mechanically due to handling or transportation. (Hanson et al. 2012, 89; Siegmann 2000, 30.)

Delayed hydride cracking may occur during dry storage and fuel transporting. In this phenomenon, hydrides slowly form a crack through the metal and may cause a rod failure. Phenomenon is caused by the cladding stress and can be result of internal pressure of the rod.

Based on former research, fuel failures are however assumed to be quite small for current relatively small burnup fuels (maximum burnup 50 MWd/kgU). Fuel with higher burnup produces higher internal pressures and higher strains inside the rods in dry storage conditions. Internal pressures with high burnup fuel may be close, or even above the reactor system pressure (Siegmann 2000, 29). Basically, this means that many of these failure mechanisms are more likely, when the fuel burnup is higher.

Cask inner components, like basket where the fuel is kept and neutron shields are also facing different aging problems. Corrosion depends on the amount of water in the cask.

Neutron shielding is provided either by a concrete overpack or in case of dual purpose casks by a specific shields. These shields are usually made of polymer based materials composed of an effective neutron moderator and a neutron poison. The moderator (usually hydrogen or carbon) slows down the neutrons and then neutrons are absorbed by the poison such as boron. There are several failure mechanisms effecting the shields. Radiation causes embrittlement, corrosion is possible if water residues are present. Effects are dependent on the material of the shields. Cracking and thermal embrittlement of shields are likely during a long time period, but the effect of this rupture on radiation levels is probably low. Radiation levels caused by the fuel decrease during the long storage period. It is also possible to remediate the shields. (Hanson et al. 2012, 130–135.)

Outer components of the container, like metallic body, bolts or welds and seals are exposed to atmospheric effects, like the air humidity. This can lead to corrosion in the canister body and the sealing system. Newer canisters are usually more immune for the corrosion effects and the older ones have thick walls, so the consequences are likely to be minimal.

Sealing system is normally covered with special weather cover. Corrosion is likely to occur in the seals of the weather covers, but these seals are easily replaceable. The inner cask seals under the weather cover however may cause loss of confinement if they are not intact. It is also complicated to change the inner seals, and the operation must be done in a hot cell. The likelihood of the seals and bolts to break is however unknown. It depends on the stress in which the seals are kept and the thermal gradients they are facing. (Hanson et al. 2012, 115–147.)

Concrete overpackings of casks also face several thermal, chemical, radiation and mechanical phenomena impacting on their properties. Those mechanisms are basically well-known, but further development on overpackings is still needed in long-term dry storages.

Confinement of the dry storage casks, as well as retrievability of fuel in long-term storage needs more research. Especially dry storage of high burn-up fuel may create additional challenges in long-term storage.

2.3 Comparison of the storage options

Both storage options have their advantages and challenges. Comparison of the storage options, taking into account Finnish conditions and fuel which is used in FH1, is given in Table 1, which summarizes the main differences of wet and dry storages.

Table 1. Comparison of wet and dry storages.

	WET	DRY
COOLING	Active cooling system.	Passive cooling system.
LONG TERM INTEGRITY	Low temperature, some rupture mechanisms are smaller.	High temperature, but inert environment reduces corrosion.
FUEL	Suitable for all kinds of fuel.	Suitable for only relatively low decay heat. With high burnup fuel a long cooling time in wet storage is needed before dry storage.
LICENSABILITY	Well known.	Not earlier experience in Finland, may need regulatory revision of requirements.
BUILDING	Need to be airplane crash protected. More complex.	Not necessarily need to be airplane protected, building can be simpler.
INTERFACES	Might require more interfaces with NPP.	Can easily be separate from NPP.
PACKING	Relatively simple with a wet transfer cask, faster packing procedure (1–2 days/cask).	May require a hot cell, drying of fuel is time consuming, so longer packing procedure (4–5 days/cask)
OPERATION AND MAINTENANCE	Takes more effort.	Maintenance is easy, amount of operational waste is low.
MONITORING OF FUEL CONDITION	Easy, visual inspections can be done under water.	Visual inspections require opening of a cask
EVACUATION	Requires extra pool.	Requires opening of a cask, which requires a hot cell.
TRANSPORT	Requires transport casks.	Dual-purpose casks can be used for transport also.
FINAL DISPOSAL	Optimization of fuel element arrangements to final disposal is possible.	Depending on final disposal concept, might require more effort and equipment at the repository facility.

Overall the passive cooling system is the greatest benefit of dry storage option. It makes dry storage less vulnerable in internal and external hazards and exceptional conditions. Due to passive system, maintenance is also easier and amount of operational waste lower.

One of the greatest benefits of the wet storage option is the suitability for high burnup fuel, which can be stored in dry casks only after a long cooling period in a pool. In FH1 spent fuel storage the fuel burnup is relatively high and so the decay heat is also high. None of the currently licensed cask designs on the market seems to meet the requirement for decay heat removal capacity without a long cooling period in a pool. (Hautojärvi et al. 2016.) For example, based on an analysis performed for a certain suitable widely used reference cask, the required cooling time in a pool would about double compared to what is achieved in FH1 NPP. The achieved cooling period is relatively short in FH1 NPP for example due to the evacuation requirement set by YVL guides (YVL D.3 2013, §438) which needs to be taken into account. After the cooling period which is achieved in FH1 NPP, the analyzed reference cask could be filled only ~50–60 % full. (Sorjonen 2016.)

If a dry storage option were chosen in FH1, there would be two options: either to build more wet pool storage capacity away from the reactor or to fill up the dry casks only partly full. Filling the casks partly full does not seem to be economically feasible. One option would be also to design and license a new dry cask with greater heat removal capacity. Testing and licensing of a new cask would however be a long process, and it seems to be challenging taking into account the current timetable. (Hautojärvi et al. 2016.)

Other benefits of wet storage option are accessibility of the fuel and in Finland the earlier experience in licensing wet storages. Handling the fuel is more difficult and time consuming in dry storages, where fuel is dried and casks are sealed. Wet storage option is also more suitable for Finnish final disposal concept. Disposal concept consists of capsules that are to be filled with fuel elements of different ages. When using a wet storage, the suitable elements for one capsule can be packed to transfer cask in the storage, whereas with a dry cask storage the elements need to be taken from many different casks at the final disposal facility.

Wet storage pools in Finland need to be covered with an air-plane proof building. Whether or not this concerns dry storage casks also is unclear. The airplane protection is a great factor in the costs of the storage building. Construction of a wet storage requires more time and money than a dry storage, if procurement of dry casks is not taken into account.

Traditionally, if procurement of dry casks is taken into account, dry cask storages have been much more expensive than wet pool storages (per stored fuel element), but under current regulatory framework the difference in economic feasibility between a wet and a dry storage is less significant. (Hautojärvi et al. 2016.)

3 ACCIDENT SCENARIOS

Faults in systems, human errors and natural disasters could cause serious damage in spent fuel storages. Chapter 3.1 describes possible accident scenarios in wet storages. Possible consequences are described in chapter 3.2 and past accidents in 3.3. Accidents in dry storages are discussed in chapter 3.4.

3.1 Internal and external hazards

Possibility of serious accidents in spent fuel pools has been under consideration since the Fukushima Daiichi nuclear accident in 2011, even though the regulations define them practically eliminated (IAEA 2016, 64). Spent fuel storages are usually considered safe because of the low decay heat, so serious accidents in spent fuel storages have not been systematically studied. However consequences of accidents in spent fuel storages could still be severe. Fuel damages, hydrogen explosions, zirconium fire and radioactivity releases could occur in case of natural disasters, terrorism, airplane crashes or other hazards.

More systematic approach to internal and external hazards may be required by IAEA in future storage designs, as the IAEA guidance is updated. Also consideration of reasonable and logical combinations of different hazards may be required . Examples of these combinations are for example earthquake and tsunami, and collapse and fire. Also combinations with low likelihood but high potential consequences should be considered. (IAEA 2017, 22.)

Results of natural disasters are hard to predict and can be sudden and severe, as seen in Fukushima. Events as wide as earthquake and tsunami in Fukushima are highly unlikely, especially in Finland. In addition to natural disasters, internal events, like human errors or component failures might cause disturbance in pool cooling.

Event groups are divided to event categories based on their consequences and assumed frequency. Categories are design basis conditions (DBC), design exception conditions (DEC) and severe accidents (SA) (YVL B.1 2013). Severe accidents are not included in spent fuel storage design, since they are practically eliminated. Some events and hazards and their event categories and assumed frequencies are presented in Table 2.

Table 2. Main internal and external hazards and initiating events for spent fuel storages (Rein 2016.)

Initiating event group	Event category	Frequency
Fuel mishandling	DBC 2	$f > 10^{-2}$ 1/a
Disturbance in fuel pool cooling	DBC 2	$f > 10^{-2}$ 1/a
Loss of off-site power, short	DBC 2	$f > 10^{-2}$ 1/a
Break in the cooling circuit	DBC 3	10^{-2} 1/a > f > 10^{-3} 1/a
Dropping of container containing fuel bundles	DBC 4	10^{-3} 1/a > f > 10^{-6} 1/a
Fire	DBC 4	10^{-3} 1/a > f > 10^{-6} 1/a
Earthquake	DBC 4	10^{-3} 1/a > f > 10^{-6} 1/a
Light airplane crash	DBC 4	10^{-3} 1/a > f > 10^{-6} 1/a
Loss of ultimate heat sink	DEC A	$f < 10^{-4}$ 1/a
Loss of off-site power, long	DEC A	$f < 10^{-4}$ 1/a
Airplane crash	DEC C	10^{-5} 1/a > f > 10^{-7} 1/a
Large earthquake	DEC C	10^{-5} 1/a > f > 10^{-7} 1/a

3.1.1 Fire

A fire can be ignited in a storage building as a result of for example an electrical fault or a lighting strike. Fire could damage process or electrical systems, and lead to a loss of power. Also the structures could be damaged. To minimize the fire damage, buildings are usually divided to fire compartments, which will prevent spreading of fire.

In FH1 used fuel storage design the most important systems in spent fuel cooling are redundant and also divided to different fire compartments. Therefore local fire damages are not likely to cause serious problems in cooling of the pools.

3.1.2 Earthquake

Finland is seismically one of the quietest places in the world. Yearly in Finland is measured from ten to hundred earthquakes, whose magnitudes are typically 0–3 on Richter scale (a logarithmic scale for earthquake magnitude). The most powerful earthquake in the history of Finland happened in the Gulf of Bothnia in 1882, and its magnitude was 5. Earthquakes on such small scale as in Finland are highly unlikely to cause significant damage to buildings or systems. (Institute of Seismology 2016.) Earthquakes with magnitude over 5 may damage poorly structured buildings, and over 6 may damage well-build, but not earthquake protected structures.

Design basis earthquake is assumed to happen once in 1000–1 000 000 reactor years and design extension earthquake once in 100 000–10 000 000 reactor years. Vital systems and structures, like the pool structures and fire water connections are designed to withstand design extension condition earthquakes.

According to Barto et al. (2014, 29) spent fuel pools are likely to stand several earthquakes without structural failure. Possibility of a release due to an earthquake is estimated to be lower than once in a ten million reactor years.

As seen in Fukushima, the plant might survive an earthquake, but problems occurred due to the other phenomenon caused by the earthquake. The issue was no flooding as such, but the ensuing loss of all redundant safety process systems and their power supply.

However tsunamis are practically impossible in Finland, due to the shallow sea. Meteotsunamis, tsunamis caused by meteorological phenomenon, are possible in Finland and the small ones are even quite common. Highest measured meteotsunamis in Baltic sea are approximately 1,5 meters high, so they are unlikely to cause damage to NPP:s or spent fuel storages. (Jylhä, Kämäräinen, Pellikka et al. 2015.) Power supply in FH1 is secured by placing components 4 meters above the sea level. Process building as well as the emergency diesel generators of the plant are also placed several meters above the sea level.

3.1.3 **Airplane crash**

Airplane crashes to nuclear plants have not been recorded. Designing an airplane crash protection is nevertheless required, as the possibility of an intentional airplane crash terror attack cannot be completely excluded. There is also a threat of intentional or unintentional aircraft crash, and it must be considered in design of spent fuel storage. (IAEA 2003, 34–35.)

Effects of an airplane crash can be divided to global and local. Global effects include structural deformations, collapse and overturning, and can lead to functional failure of systems or components. Local damage includes penetration, scabbing and spalling. Also possibility of a fire and an explosion caused by the fuel of the airplane should be considered. (IAEA 2003, 34–35.)

Frequency of a light airplane crash in FH1 spent fuel storage is assumed to be 1/1000 – 1/1 000 000 and a large airplane crash 1/100 000 – 1/10 000 000. (Rein 2016). Airplane crash is considered in FH1 storage design to minimize the consequences. Structures will be designed to protect the fuel in case of accidents. It would be harder and more expensive to protect the whole cooling system of a wet storage from airplane crash, than only pools and emergency feed water systems, which are placed in a relatively small area.

3.1.4 Terrorism

Actions preventing damages in case of a terrorist attack, are similar to airplane crash prevention actions. Airplane crash is in IAEA documents assumed to be the enveloping scenario. (IAEA 2003, 35.) Subjects linked to intentional malevolence in nuclear plants are however classified.

Nuclear plants are protected with security arrangements, and when spent fuel is stored in the plant site, the storage is also covered with security actions of the plant. Plant site has safeguards and structural means to prevent external threats.

3.1.5 Fuel mishandling and dropping of loads

Fuel handling situations are usually considered as one of the most risky operations in normal operating of spent fuel storages. Operational experience has shown that there is a chance of damaging the fuel elements, even though the consequences are not likely to be serious.

Dropping a fuel element could in theory lead to many different accident scenarios. The fuel cladding could be damaged and cause leaking of radioactive substances to the pool. Fuel deformations could also occur, causing problems to the fuel handling and storing. One consequence could be an increase of the possibility of a criticality accident. Radiation exposure of workers is possible in case fission products are released. Load dropping may also result in damages on pool structures, which may lead to leak of the pool water. (IAEA 2012b, 45, 75.)

Dropping accidents shall be prevented by design features. This means preventing transfers of heavy loads over other equipment and pools, and minimizing the lifting height. Safety features must be considered also in design of cranes and fuel handling machines. Number of operator failures should also be minimized for example by applying "four eyes principle" (at least two persons working on a same task). (IAEA 2012b, 72.) Other factors which reduce the risk of dropping of loads are clear guidance, educated and experienced workers and suitable working conditions.

3.1.6 Loss of power

Wet storage cooling is highly depending on electricity, and so the loss-of-power disturbs the functioning of the cooling system. Short power breaks are quite likely (1 in 100 reactor years) to occur during the lifetime of the storage, but due to large water mass on pool, effects on pool temperature and fuel are slow. Problems occur when the duration of the power break exceed several days. More discussion about the phenomenology of loss-of-cooling accident and results is in chapter 3.2.1.

Hazards and natural phenomena can lead to loss of external power. External power loss can also occur in case of a disturbance in power grid.

3.1.7 Break in the cooling circuit

A break in the cooling circuit can cause a loss of cooling accident, by causing a damage to the cooling system. How serious the damages are depends on the design of the cooling system. For example if the system consist of two redundancies, in case of a leak in one redundancy, the other could be used. It is however possible that the pool water level decreases due to the leak and this might disturb the cooling function.

There is also a contamination risk in case of a leak in cooling system. Normally the activity levels in pool water are however relatively small. This depend on fuel condition, a leaking fuel rod could increase the activity of water. Leaking elements are not always stored in fuel pool, or they are placed inside special casks (Hozer, Szabom, Somfai & Cherubini 2014, 35, 109–111)

In case a heat exchanger between cooling circuits leaks, the contamination of intermediate circuit or sea water is possible if the pressure levels are such that the pool water leaks to the intermediate circuit. In FH1 interim spent fuel storage facility design the pressure of intermediate circuit is higher than pool water circuit's, which prevents such leak.

3.1.8 Loss of ultimate heat sink

Loss of the ultimate heat sink, which is typically either a sea or a cooling tower, will disturb the pool cooling system. In some cases, there is an alternative heat sink available, such as an auxiliary cooling tower. In these cases there is no danger, and cooling can be maintained by using the alternative form. In a situation when there is no alternative heat sink, pool temperatures start slowly rise and eventually water inventory will be lost. Results of loss-of-coolant are described in chapter 3.2.1.

Loss of the ultimate heat sink can be a result of for an oil accident or other chemicals in the sea or caused by weather conditions, like frazil or packed ice. Sea water flow can be also disturbed by sand, mud or clay or even algae or other organisms. In Sweden even jellyfish have caused disturbance in sea water cooling by clogging the water intake pipes (O'Rourke 2013).

The risk of loss of ultimate heat sink should be taken into account when choosing the plant site. The features of the seabed shall be studied. Water inlet structures shall also be designed so, that the clogging of the pipes is very unlikely. This can be done for example with different filter solutions, with heating of the water and the structures, or with an alternative water inlet. The condition of the sea water shall also be observed, and for removing possible dross shall be suitable cleaning systems or methods. (YVL B.7 2013; YVL B.7 Justification memorandum 2013.)

Spent fuel storage of FH1 has its own cooling system, that is not connected to the cooling system of the plant. Sea water system has two redundancies, that are physically separated to different fire compartments of pumping station. Sea water is taken in through an intake screen and a net filter to an intake chamber from where it is pumped to a heat exchanger. There are also two different water intake branches: the branch, which is normally used, goes directly out to sea and the other, which is used in case of sea water intake freezing, goes to the specific intake chamber. (Teräsvirta 2017b.)

3.2 Possible consequences of accidents

Natural disaster, terrorism, human errors and other events discussed in chapter 3.1 can have severe consequences in spent fuel pool. They can induce loss of cooling system and/or loss of coolant, which can lead to a fuel damage. This, or a fuel damage by any reason, can cause radioactive releases and danger to the surrounding environment. One issue to be considered in exceptional conditions is criticality that could also have severe results in a spent fuel pool. In this chapter the phenomena may occurring in accidents are discussed.

3.2.1 Loss of cooling

LOCA (loss of cooling accident) can be a result of loss of the cooling system and heat removal by boiling, or a leak in the pool. Fuel damages are possible if the fuel is uncovered, but under water damages are unlikely. shows the accident phenomenology in case the fuel pool cooling is lost.

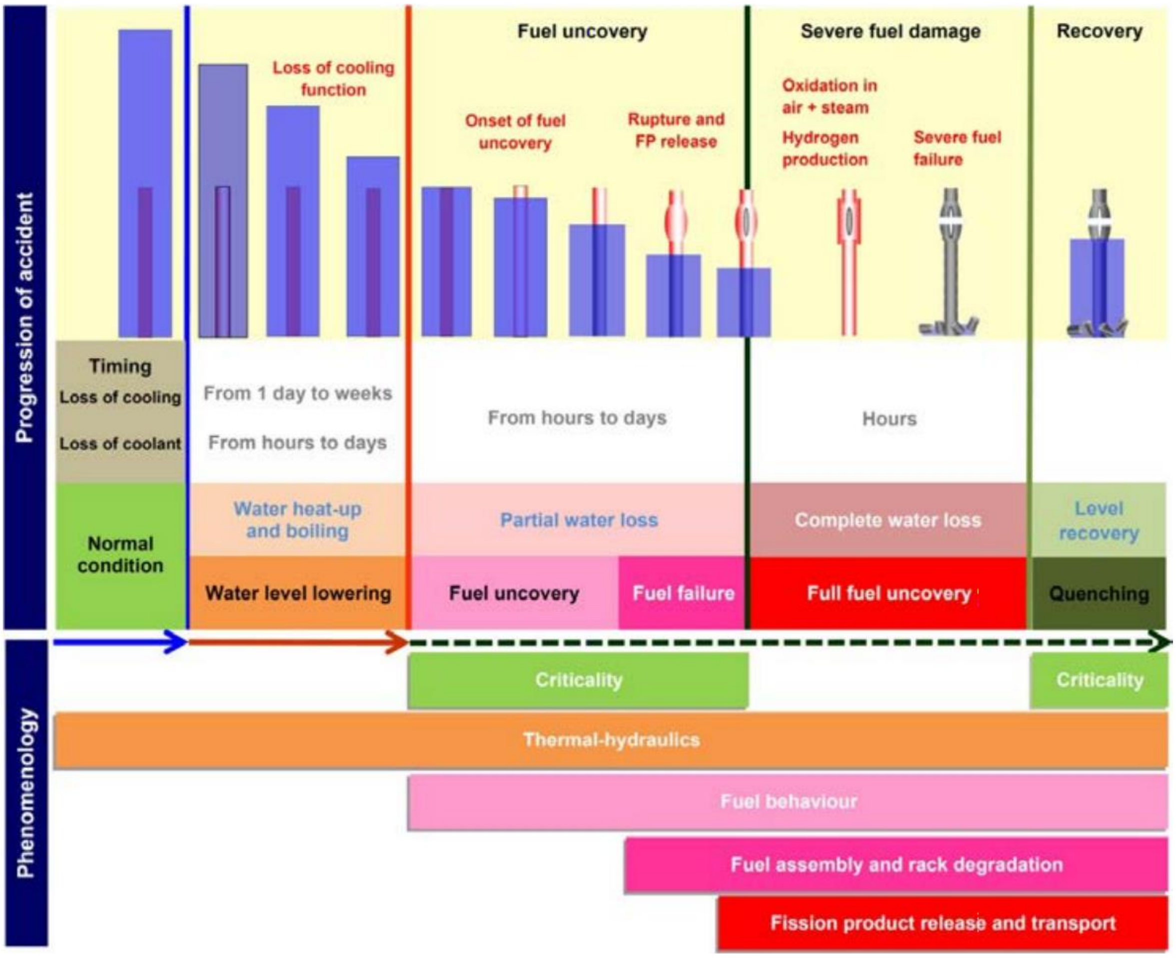

Figure 5. Accident phenomenology in spent fuel pools (Adorni, Esmaili, Grant, Hollands, Hozer et al. 2014, 87).

Loss of cooling system in a spent fuel pool leads to water heat-up. Due to the large water mass in the fuel pool the process is slow, and the pool reaches the boiling temperature in a few days, depending on the decay heat of the fuel. Decreasing of the pool surface is slow, and fuel uncovering will be an issue after several days, or usually in weeks. Boiling will eventually lead to uncovering of the fuel, unless the cooling system is restored or sufficient amount of water is injected to the pool regularly.

After the loss of cooling the fuel temperatures start to rise. Partly uncovered elements may be cooled enough by steam flow, if water surface is high enough. The more the water level drops, the less steam is produced in the bottom to cool down the upper part. Partly uncovered fuel may be cooled only by upward steam flow, if the geometry of the fuel elements or the fuel racks in the pool prevents horizontal flow between the elements as often is the case. Figure 6 shows cooling flows when fuel is covered, partly uncovered and totally uncovered.

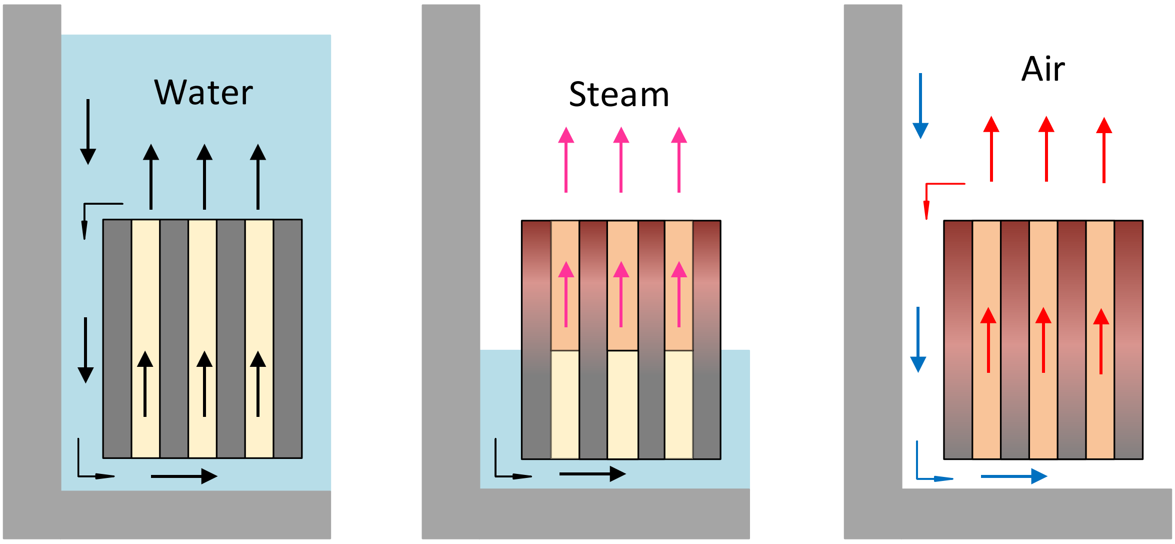

Figure 6. Partly uncovered fuel is cooled by steam produced in the covered part. Totally uncovered fuel is cooled with natural air circulation.

Totally uncovered fuel is cooled by natural circulation of air. Effectivity of this cooling depends mainly on decay heat of the fuel and the configuration of the storage rack.

Boiling will release steam to the pool room and make working conditions in the room more severe. This basically means that it shall be possible to perform the pool cooling actions outside the pool room. As the pool level decreases, the radiation levels in the room increase and eventually prevent access to the room. Room might also contain air contamination, if the pool water included radioactive particles due to for example a leaking fuel element.

High temperatures damage the fuel elements. Uncovering of the elements and temperature rise can cause ballooning on the fuel elements. When temperatures increase, the internal pressure of the rods rises and cladding expands in radial direction. This can eventually lead to cladding rupture. The deformations of cladding tubes are basically controlled by stress, temperature and creep strength. Creep depends on e.g. oxidation and material properties. In high temperatures (above 800 K) creep may cause significant deformation even in few minutes. (Adorni et al. 2015, 103–104.) During LOCA the fuel racks are also heated and may be damaged, which may create new paths for water flow between the elements.

Rewetting of fuel after the dryout can cause even more damage to the elements, when temperatures decrease quickly.

3.2.2 Leaks in fuel pools

Consequences of uncovering of the fuel elements are similar in pool leaking scenario and in pool boiling scenario. The difference is that the water might leak out and pool drain relatively fast in case the leak is large. Leak in a pool can be caused by a large variety of reasons. Possible causes for leakages are liner failures, leaks between pool gates and seals and leaks to connected systems. Pool leaking can be a result of human errors, system ageing or an external hazard.

In case of a leak in a pool, the water level starts to lower and the cooling might be disturbed due to the low water level. Effects on the fuel depend on the level to which the water surface decreases. If the fuel is uncovered, results are similar to boiling scenario. In case the fuel is only partly under water, temperature difference between the covered and uncovered parts of fuel element could be high.

Water mass in a spent fuel pools is large, so a leakage need to be quite wide to decrease the surface fast. For example, a significantly large leak of 2 kg/s decreases FH1 spent fuel pool water level 6 meters in 72 hours. In this case the level would still be 4 meters above the top of the fuel. This would not create a significant radiation dose increase to workers.

Leaking scenarios in at reactor-pools differ from those in away-reactor-pools. Pools connected to reactor have more possible gates and seals, like reactor cavity seals, that can damage and cause liquid level decreasing in SFP.

Probability of a liner error in SFP is relatively high. Operating experience study in USA shows that seven liner leaking incidents happened between years 1980–1997. None of these incidents however led to large leak rates. Besides liner leak, pool water can leak through connected systems. This option is even more likely in some types of pools, and leaks through systems can be relatively large. However this could be prevented by right pool design, especially in away-from-reactor pools. Water loss might occur also by leaking through seals. (Ibarra, Jones, Lanik, Ornstein & Pullani 1997, 13).

Leaks can be detected from liquid level or a detection system, depending of the type of leak. Pool water level in the pool is measured constantly. Liner leaks are detected with a leak detection system. The system consist of channels that are individually monitored. (Ibarra et al. 1997, 2.)

Finnish spent fuel storages are designed so that in case one storage pool is leaking, fuel can be moved to an empty pool. Regulation D.3 says that the storage facilities for nuclear fuel and their use shall be planned so that any storage pool or the reactor core can be emptied of nuclear fuel for the purpose of repair work. (YVL D.3 2013, §438.)

3.2.3 **Oxidation and Hydrogen Generation**

Zirconium is used widely for cladding material of PWR (Pressurized water reactor) fuel, because of great mechanical and corrosion properties, and low neutron absorption. Zirconium cladding however reacts with oxygen of water, steam or air forming zirconium oxide, which makes the material more fragile and eventually leads to degradation of the cladding material. Reaction occurs even in moderate temperatures (Causey, Cowgill & Nilson 2005, 9), but oxidation reaction accelerates when fuel temperature gets higher. In low temperatures < 700 °C the reaction is quite slow. There are some variance in oxidation of different cladding materials (Zircaloy-4, ZIRLO etc). (Steinbruck, Vér & Große 2011.)

Oxidation of cladding is an exothermic reaction which rises temperature rapidly. Release of energy depends on temperature and reaction rate. (Adorni et al 2015.) Reactions are presented in the following equations. (Barin 1995 [Durbin, Lindgren & Goldmann 2016, B-1])

$$\mathrm{Zr} + \mathrm{O_2} \rightarrow \mathrm{ZrO_2} \qquad \Delta H_{rxn} = -1095\ \mathrm{kJ/mol} \qquad (1)$$

$$\mathrm{Zr} + 2\mathrm{H_2O} \rightarrow \mathrm{ZrO_2} + \mathrm{H_2} \qquad \Delta H_{rxn} = -529\ \mathrm{kJ/mol} \tag{2}$$

$$\mathrm{Zr} + \frac{1}{2}\mathrm{N_2} \rightarrow \mathrm{ZrN} \qquad \Delta H_{rxn} = -365\ \mathrm{kJ/mol} \tag{3}$$

$$\mathrm{ZrN} + \mathrm{O_2} \rightarrow \mathrm{ZrO_2} + \frac{1}{2}\mathrm{N_2} \qquad \Delta H_{rxn} = -729\ \mathrm{kJ/mol} \tag{4}$$

where ΔH_{rxn} is the the energy released at 1500 K.

At first the reaction is rapid on clean zirconium surface, but then a protective oxide layer forms at the surface and the reaction rate decreases. After that the oxygen only reacts with zirconium after having diffused through the oxide layer. (Durbin et al. 2016:B-1.) The oxidation rate is low as long as the oxide layer remains intact, but eventually there will be a breakaway point, when the oxide layer no longer protects the cladding underneath from oxidation. The breakaway point will eventually be reached in case the fuel is exposed to steam or air for a long time.

Reaction rate increases again after this breakaway point, as the protecting ability of the oxide layer is lost. As presented in equations (3) and (4), zirconium reacts also with nitrogen, forming zirconium nitride, which also reacts with oxygen forming zirconium oxide. This makes the cladding material more fragile. Therefore the oxidation phenomenology in air differs from reactions in steam. Generally the oxidation is much faster in air. The barrier effect of the cladding is lost earlier in a case when there is nitrogen present, than in steam conditions. (Steinbruck & Böttcher 2011.)

In case of fuel is uncovered in pool partially or totally the temperatures rise and oxidation reaction accelerates. The overheating of fuel elements due to oxidation can eventually lead to releases of radioactive particles and gases and melting of the fuel, but also so called zirconium fire. This phenomenon is described in chapter 3.2.4.

Oxidation can be approximated quite accurately with correlations and by using kinetic data in low temperatures (below 700 °C), but in high temperatures and with high burnup fuel the correlations and data differ slightly. This may be due to difficulties in measuring the temperature accurately. Above 1500 °C predicting of the oxidation is even harder, and above the fuel cladding melting, there is no data at all. (OECD/NEA. 2009.) Melting point of Zircaloy is above 1900 °C (Sailor 1987, 50).

As a side effect of oxidation reaction, hydrogen is produced. The amount of generated hydrogen depends on the reaction rate of the oxidation reaction. When oxidation reaction accelerates, also the amount of hydrogen increases. When hydrogen mixes with surrounding air, it can cause an explosion in spent fuel storage. (Carlos, Sanchez-Saez & Martorell 2014.)

The risk of hydrogen production and explosion is taken into account in reactor plant designs, but hydrogen explosion prevention mechanisms are not included in most spent fuel storages. This is basically based on practical elimination of serious accidents: hydrogen explosion is avoided when spent fuel is kept covered with water and temperatures do not rise high enough to produce significant amounts of hydrogen. A draft of International Atomic Energy Agency (IAEA) regulations for spent fuel storage (IAEA 2017) mentions protection against hydrogen explosions even in spent fuel storages and therefore there may be a need to pay more attention to this in the future.

3.2.4 **Burning of Zirconium Cladding**

Zirconium fire when the fuel is exposed to air is probably the most dangerous accident scenario in spent fuel pools. The self-sustaining oxidation reaction makes temperature rise rapidly and causes ignition of zirconium cladding. It can cause melting of fuel and large radioactive releases. Zirconium fire might occur during a loss of coolant accident in fuel pools, if the fuel cladding temperature rises to ignition temperature after the fuel has been exposed to air. (Sailor, Perkins, Weeks & Connell 1987.)

Temperature required for zirconium fire is rather high. Some researches approximate ignition temperature to be around 1100–1200 °C. (Durbin et al. 2016). Ignition temperature is however complicated to solve. Realistic analyses require knowledge of several different aspects, and the calculations are often quite complex. Usually conservative analyses are produced using an assumption for minimum ignition temperature based on earlier test results. (Elias, Hasan, Nekhamkin 2015.)

Such high temperatures in fuel pool after uncovering can be a result of accelerating oxidation reaction in temperatures above 700 °C. Oxidation reaction is exothermic and produces more heat in addition to fuel decay heat. Heating during loss-of-cooling accident can be rapid and ignition might occur even with only partially uncovered fuel. After ignition fuel temperature rises rapidly and can reach almost 2000 °C.

It is assumed that zirconium fire could occur only with reasonably fresh fuel, when decay heat is high (Boyd 2000). Probability of zirconium fire depends on storage configuration. Reaching ignition temperature is more likely with high density racks and higher power density than low density racks. (Sailor et al. 1987, 107.) High burnup as well as dense storage configuration increase the temperatures in dry-out cases in pools. Earlier test and analyses results with different burnups and storage configurations are presented in chapter 3.3.

3.2.5 **Radioactive Releases**

One main difference between radioactive releases from reactor core and spent fuel pool is that if spent fuel is not located inside a containment, it is easier for releases to be carried to the environment. The storage building is usually not totally tight and releases from pool are possibly transferred out of the building. Storage building ventilation system however may include filters, which prevent some releases from spreading.

Leaking fuel under water is not likely to cause large emissions, whereas fuel exposure and damages may lead to radioactive emissions. Releases under water, for example releases from a leaking fuel rod are usually not transferred outside of the pool, because most particles stay in the pool water. From pool water they can be filtered with pool water cleaning system, which is normally included in wet storage concept.

Releases in case the fuel is exposed can be significant in case of a cladding failure. Cladding failure may occur in case the temperature in the pool increases to level in which cladding rupture occurs due to the internal pressure or melting of the element. (Benjamin, McCloskey, Powers & Dupree 1979, 12)

Isotopic composition of a release depends on the age of the fuel. Due to radioactive decay recently removed fuel includes more radioactivity than older fuel. Old fuel contains mainly long lived isotopes, whereas the isotopes with short half-live have decayed. Therefore the content of a release from a fuel rod differs according to the cooling time of the fuel. Another factor effecting to the release content is the accident phenomenology, for example fuel temperatures. (Sailor et al. 1987.)

3.2.6 Criticality

Criticality accidents with spent fuel are overall very unlikely. Based on public references, it seems there has been no criticality accidents in spent fuel storages. The fuel is usually removed from reactor, because it no longer can sustain a chain reactor in reactor conditions. However, lowering the fuel temperature increases reactivity, as does immersion in water (the moderator), hence the criticality risk is carefully studied when designing a spent fuel storage. Criticality accident could have severe consequences for retrievability of fuel but also to workers and environment.

Conditions in spent fuel storage, during handling and during transportation must be such that effective multiplication factor k_{eff} is in normal conditions kept under 0.95 and in other design basis conditions under 0.98 (YVL B.4 2013, §504). Effective multiplication factor depends on fuel parameters, configuration of the storage rack and void fraction of the coolant. In a storage pool the fuel racks must be designed so that obtaining criticality is impossible in all scenarios. The same principle is required during transport of fuel also.

Partial loss of coolant could in low density racks lead to positive reactivity feedback, especially if borated water is used. Loss of coolant and loss of neutron absorption in water cannot however cause criticality accident, because the rack configuration shall be designed to maintain k_{eff} under the criticality limit even when water is partially lost. Criticality could in theory become an issue in a storage, if the fuel rack configuration was changed due to for an example a load dropping accident, an earthquake or fuel melting during a long-term loss of coolant in the pool. Configuration change could make an overmoderated storage configuration less overmoderated and increase the reactivity. Criticality accident in case of a fuel melting would require fuel with significantly higher enrichment than what is normally used in light water reactors. Normal light water reactor fuel could not become critical without moderator.

3.3 Earlier Analyses

This chapter includes earlier test and modelling results on phenomena described in chapter 3.2. Loss of coolant accidents in spent fuel pools have been widely analysed in several countries already in 1980s but interests have grown again after Fukushima accident. NRC in USA have studied the subject of zirconium fires lately (Durbin et al. 2016). Also for example in France is a large ongoing research program called DENOPI, which considers for example the thermal hydraulics of a pool and fuel assemblies in 2013–19. (Trégourès, Mutelle, Duriez & Tillard 2015.)

One subject under consideration earlier and lately is the phenomenology of loss of coolant accidents. The temperature rise due to the loss of coolant and oxidation reaction has been studied, as well as the ignition of the zirconium cladding.

Cooling of elements after a loss of coolant accident depends on geometry and properties of the fuel. Partly uncovered elements are usually cooled only by steam flow from the lower part of the fuel. The cooling may be effective enough, if the water level is high enough. MELCOR calculations (Jäckel 2013) suggest that fuel temperature could be kept under 800 °C even if the water surface is 1.5–2 m under the top of fuel elements. This is however dependent on the fuel geometry. The more the water level drops, the less steam is produced in the bottom to cool down the upper part. Temperatures in cladding when water level decreases are presented in Figure 7.

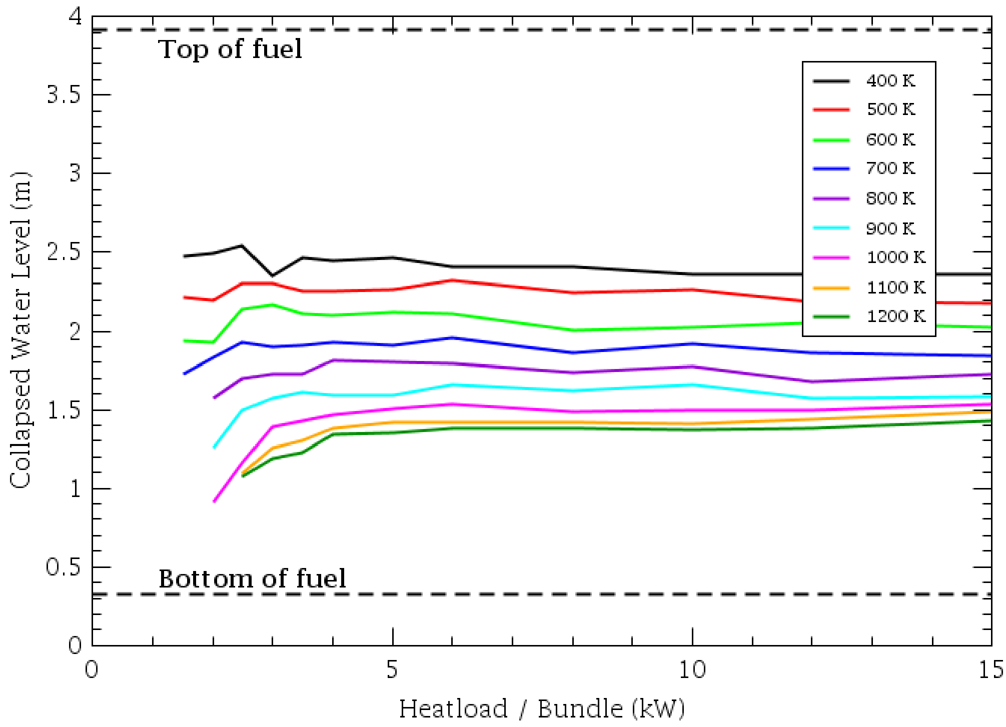

Figure 7. Maximum cladding temperature at different water levels (Jäckel, 2013)

Zirconium fire might occur if the temperature rises to ignition temperature. Fuel with higher burnup is more likely to produce enough decay heat for ignition. An example of effect of decay heat in drained spent fuel pool is shown in Figure 8 (Nourbakhsh, Miao, Cheng 2001, 4–5)

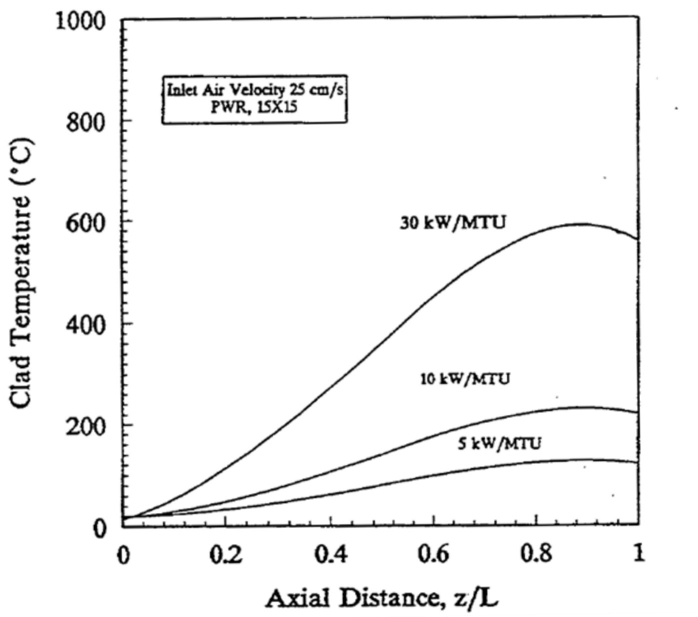

Figure 8. Effect of decay heat on axial variation of clad temperature. Channels between elements are only connected beneath the racks, and the space above racks (Nourbakhsh et al. 2001, 4–5).

In Figure 8 the effect of the higher decay heat on cladding temperature can be seen. The higher the decay heat is, the higher is the cladding temperature, and so the oxidation rate is also higher. This means also a higher risk for the zirconium ignition.

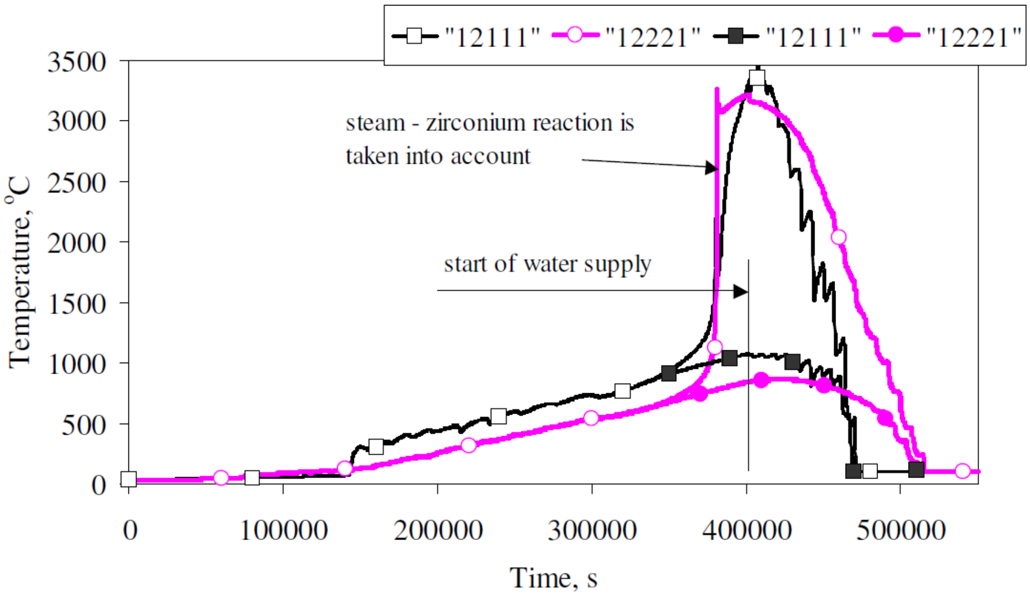

Figure 9. Comparison of maximal fuel temperatures calculated without evaluation of steam–zirconium reaction and when this exothermic reaction was taken into account. (Kaliatka et al. 2011.)

Kaliatka, Vileiniskis and Uspuras' RELAP5 analyses results (2011), presented in Figure 9 show effect of hydrogen generation on fuel temperatures. The geometry change due to fuel melting at 2500 °C however has not been taken into account, and therefore the results above the melting temperature are possibly unreliable and the temperatures unrealistically high. The fuel elements included in analyses are different aged with different decay heats. Storage times of all elements are relatively short compared to FH1 cooling time, as seen in Table 3, which includes the fuel characteristics.

Table 3. Fuel characteristics in analysis of Kaliatka et al. (2011)

	Groups of SFAs in RELAP5 and ASTEC models	Assumed storage time	Spent fuel assembly decay heat, kW	Amount of assemblies in a group	Group power, kW
	12111	8 days	5.21	166	864.9
	12211	137 days	1.281	1182	1514.1
	12121	2 years	0.489	892	436.2
in shipping cask	12221	3 years	0.254	5661	1437.9

Temperature rise with relatively fresh fuel according to Wu's MAAP5 calculation (2014) is presented in Figure 10. Pool is full of fuel placed on high density racks. Total decay heat of the pool is 8.9 MW, of which 7.9 MW is from 157 assemblies recently moved from reactor.

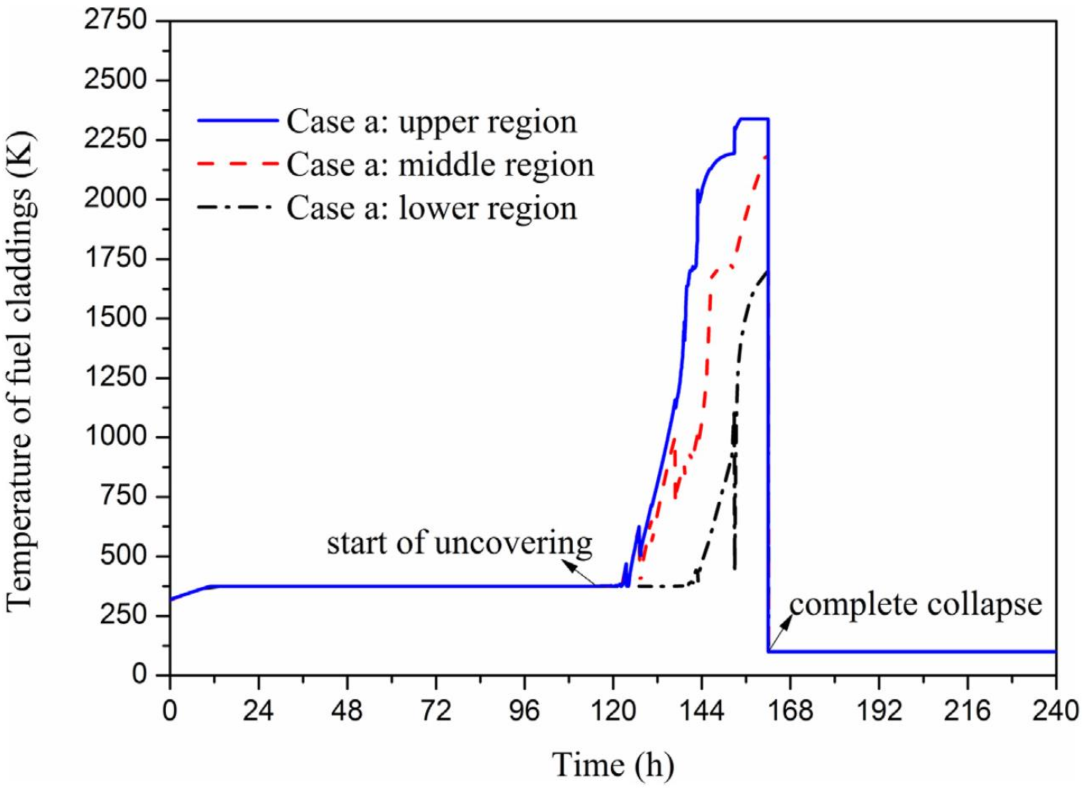

Figure 10. Fuel cladding temperatures at loss-of-cooling accident with high decay heat fuel (Wu et al. 2014, 202)

Temperatures in analysis presented in Figure 10 rise rapidly to 2000 °C after uncovering. Zirconium cladding ignition would occur in this scenario. The accident in this case leads also to radioactive releases.

MELCOR-calculations (Ahn, Shin & Kim 2016) with dense racks and decay heat power of 15 MW indicate also the probability of zirconium fire in pool. Pool includes different aged fuel mixed, and 177 of the total 1037 assemblies are recently moved from reactor. Results are presented in Figure 11.

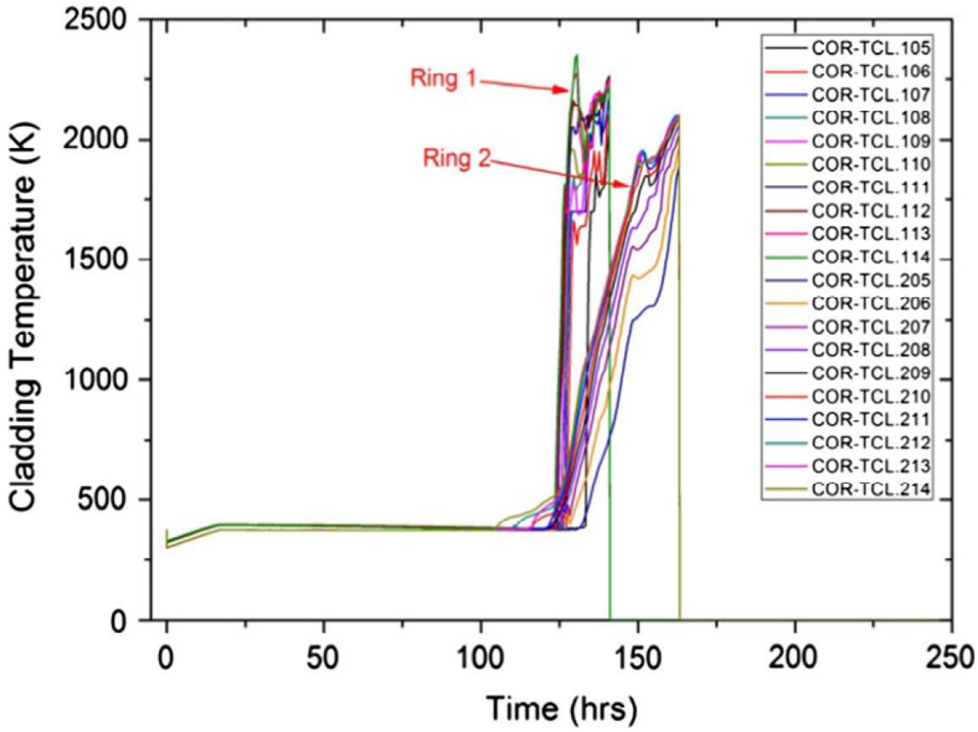

Figure 11. Cladding temperatures during LOCA in pool. Ring 1 consists of fuel elements with higher decay heat and ring 2 the rest of the bundles. (Ahn et al. 2016, 75)

Calculation results in Figure 11 are quite similar as in Figure 10. Temperatures rise rapidly after the pool has drain, especially in the elements with higher decay heat.

Alvarez (2003) claims that convective air cooling could however keep fuel cladding temperature below 900 °C even in dense racks, if fuel decay heat is below 15 kW/t_U. This is the decay heat of typical light water reactor fuel after one year's cooling. In Alvarez calculations it is assumed that air flow maximum is 0,34 m/s and there is no blockage of the flow. With an open rack configuration the fuel could be kept under the damaging temperature already five days after removal from reactor. (Alvarez 2003, 19–20; Benjamin et al. 1979, 85.)

The effect of possible air cooling is huge on spent fuel cooling after dryout. According to Nourbaksh et al. (2001, 4–5) there may be a difference of hundreds of degrees in cladding temperature depending on inlet air velocity, as shown in Figure 12.

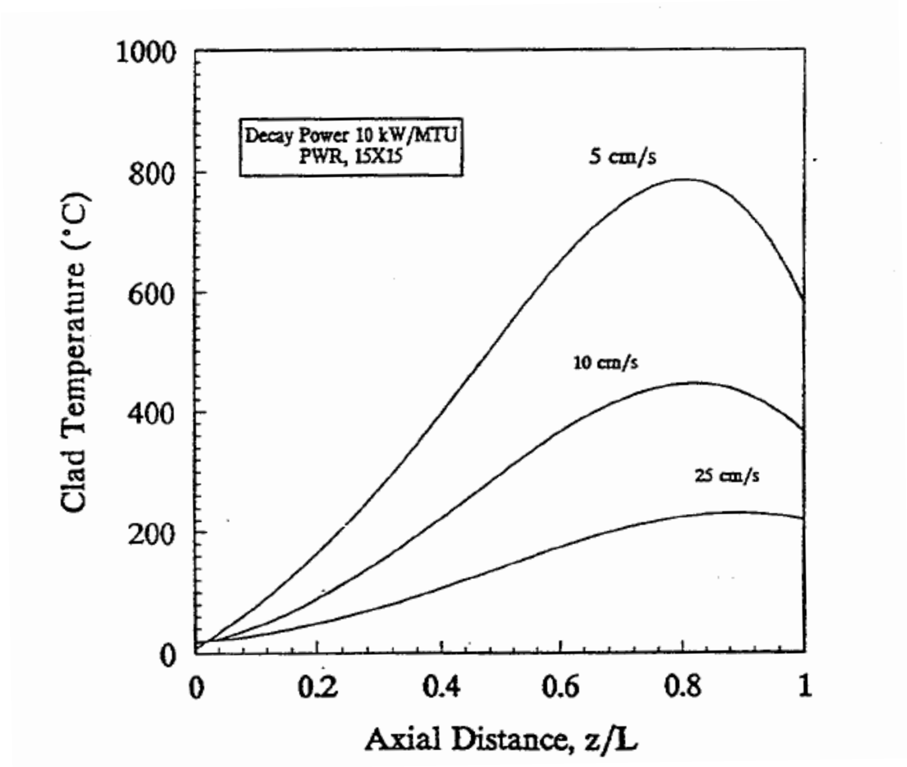

Figure 12. Effect of the air inlet velocity on cladding temperature. (Nourbakhsh et al. 2001, 4–5.)

In case of Hanhikivi 1 spent fuel storage the fuel burnup is relatively high 60 MWd/kgU, but decay time in SFP is quite long (typically at least 7 years for one batch when it is transported in to the storage pools). Most of the results in this chapter have been calculated with fuel with shorter decay time, but also smaller burnup.

According to Boyd's test results (2000) fuel with as long decay time as FH1 is not likely to generate enough heat to start a zirconium fire. For example fuel with burnup of 40 MWd/kgU and decay time of 2 years, fuel cladding temperature rises to 1047 °C, which is still lower than ignition temperature 1100–1200 °C (Durbin et al. 2013). For fuel with decay time of 6 years and same burnup 40 MWd/kgU, the maximum temperature is 445 °C. Increasing burnup from 40 to 50 MWd/kgU increases the maximum temperature from 573 °C to 712 °C with 4 years old fuel.

3.4 Past Accidents

Spent fuel pools have over 50 years of history, and operational experience during that time seems to be mainly positive (IAEA. 1999, 8). However, some incidents have taken place in fuel pools and systems linked to them during those decades. This chapter describes some past accidents and incidents in spent fuel pool storages. Accidents in dry storages are described in chapter 3.5

Number of accidents and incidents in spent fuel pools have been quite low during the last 50 years. According to Ibarra et al. (1997, 9–10) in United States between years 1984 and 1996 occurred 93 actual and 78 precursor events in spent fuel pool storages. The events were divided in two categories: pool cooling and pool inventory (meaning amount of water in a pool). Only 10 inventory events led to decrease in the pool level, and in two of them level decreased more than 1,5 meters. In 3 cooling events temperature increased more than 10 °C. Most of the loss of cooling events were caused by loss of electric power to pumps and most inventory events by problems in connected systems. Many of these events were caused by human errors. Due to lack of automatic functions in SFPs, detection and recovery actions rely on performance of human operation.

The most recent and well-known accident happened in Fukushima nuclear station in Japan in 2011. The consequences of this in spent fuel pools were however not as serious as was expected at the time. Other incidents discussed below are the cleaning tank -incident at Paks and the Bruce-A incident.

3.4.1 **Fukushima**

Fukushima accident started when an earthquake took place on March 11, 2011. Units 1–3 were operating and units 4–6 were under an annual outage. After the earthquake the off-site power was lost and the cooling was secured via emergency diesel generators. Tsunami caused diesel generator black-out and units 1–4 lost power supply and fuel pool cooling. One emergency diesel in Unit 6 continued to function and later power was supplied also for unit 5. (Adorni et al. 2015, 53–77)

After loss of the core cooling fuel damage occurred in reactors of units 1, 2 and 3. Explosions in units 1 and 3 were result of the hydrogen generated in damaged fuel. Hydrogen explosion in Unit 4 was probably result of hydrogen leaking from unit 3 to unit 4 building.

In Fukushima Dai-chi power plant the spent fuel pools were located in the reactor buildings in each unit. Pools were located in the secondary containment, outside the primary containment covering reactor. Apparently there were no fuel damage in spent fuel pools during the accident.

At unit 1 the explosion was caused by the hydrogen generated in reactor. Fuel pool was cooled by injecting water to compensate the evaporation until an alternative cooling system was started on August 10. According to Tokyo Electric Power Company TEPCO, that is the operator of Fukushima Daiichi, pool liquid level never decreased lower than 4 m above the top of the fuel racks (Adorni et al. 2015, 63). Water temperature was kept under 70 °C. Measurements show that there is some activity in the pool, but it has probably been transported from reactor as a result of the containment failure.

At unit 2 there was no explosion that could have damaged the upper containment ceiling. Nevertheless particularly high activity levels, 10^5 Bq/ml, were measured in the fuel pool soon after the accident. These releases are assumed to have come from the reactor. Later measurements have shown an increase in the amounts of cesium in the pool water about 1 year after accident. This 100 Bq/ml activity is assumed to be from leaking fuel elements. There is no evidence on large fuel damages in the spent fuel pool.

Unit 3 explosion caused large damage to the building and parts of the roof dropped to the spent fuel pool. Water level in the pool dropped slightly during the accident and was recovered by injecting water and later by using an alternative cooling system that was built. However there is no sign of fuel damages or leaks, and activity in the pool seems to be originally from reactor. Activity in the spent fuel pool was apparently all from reactor and no fuel damage occurred in the pool.

Many different explanations were proposed for the unexpected hydrogen explosion in unit 4. Unit 4 was under inspection and fuel was removed from reactor during the accident, so the reactor could not cause the hydrogen explosion. Hydrogen could have been generated in spent fuel pools, but this was unlikely since the decay heat in the pools was low. Later it was proven that water levels in SPF never dropped below top of the fuel. Estimated water level and temperature in the pool are presented in Figure 13.

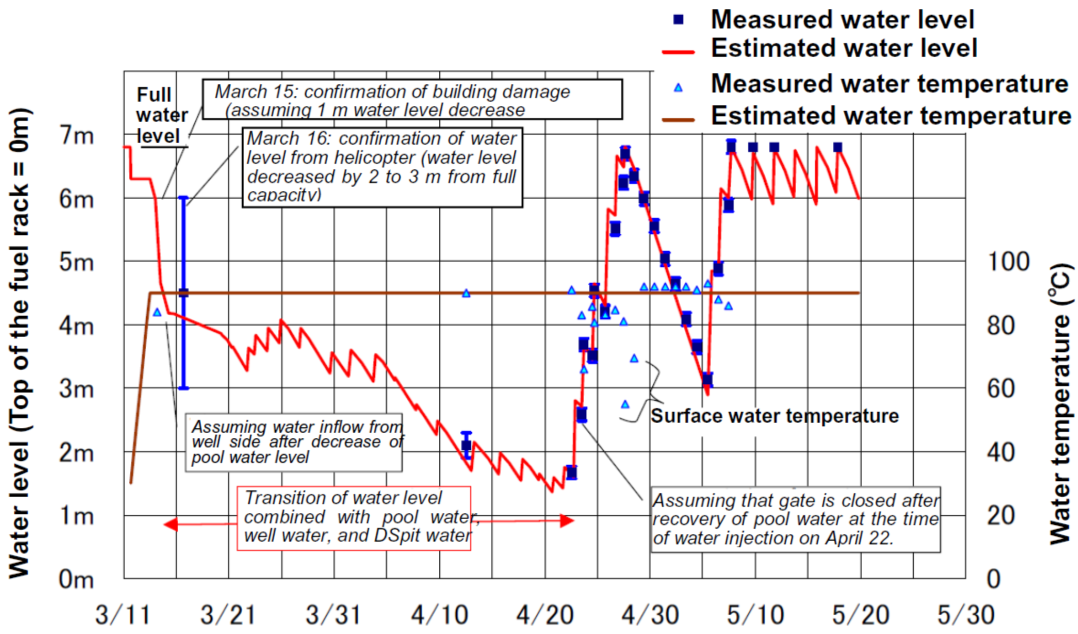

Figure 13. Unit 4 spent fuel pool level during the accident according to TEPCO (2012). Water levels in other pools were higher during the accident. (Adorni et al. 2015, 74.)

Significant fuel damage has not been detected in the fuel pool of unit 4. Activity levels in the fuel pool were not higher than in the other fuel pools and showed no evidence of serious fuel damage. Later measurements however indicated some possible slight damage of the fuel elements, but the damage would be smaller than in the SFP of the unit 2. (Jäckel, 2014)

The most likely theory of explosion in SPF of unit 4 is that hydrogen would have been transported from unit 3. This could have been possible through the pipes, because during the accident and a power break, the fans were not operating. (INPO 2011, 33)

At units 5 and 6 the fuel pools were cooled basically all the time. Short power breaks do not have significant effect on pool temperatures, because of the large water masses.

3.4.2 Paks cleaning tank

Cleaning tank incident in Paks nuclear power plant in Hungary is not a typical SFP accident, but gives information about fuel behavior during accident conditions. Accident happened in 2003.

Thirty fuel elements were closed in a tank for chemical cleaning. Cleaning was done in a service pit, where cleaning chemicals were circulating through tank via cleaning system.

After the cleaning operation was finished, tank cooling was continued using a submersible pump. Mass flow of the system was significantly lower than during the cleaning. Fuel was left to the tank for several hours, because the crane was proceeding to other tasks. Figure 14 shows the cleaning process.

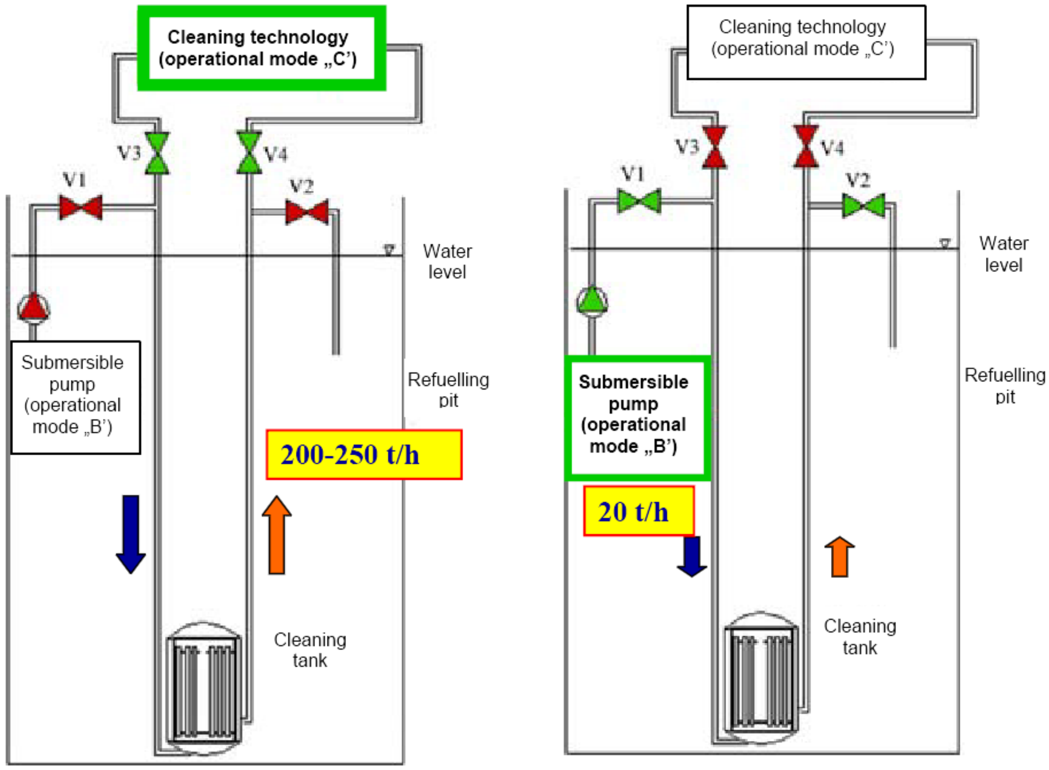

Figure 14. The spent fuel cleaning process in Paks (OECD–IAEA Paks Fuel Project Final Report 2009, 8)

Few hours later the measurements showed an increase in activity levels in the cleaning system. Tank cover was opened and the pool liquid level decreased 7 cm while the activity levels in the pool increased significantly. Measurements identified fission products in the pool water and noble gases in the reactor hall.

Later studies showed that mass flow in tank did not keep the fuel temperature low enough, even though the decay heat was low. Coolant started circulating only in the lower part of the cleaning tank leaving the top of the elements heating up. The perforation holes in the shroud enabled another circulating path when the flowrate was small. Upper part of the fuel was heated up and generated steam blocking flow in the upper part of the tank. The fuel was without cooling for several hours and heated up to above 1000 °C. Fuel rods oxidized and cladding was embrittled. Opening the tank cover and reflooding the tank caused damage to the cladding. (OECD–IAEA 2009, 10–12.)

Radioactive releases to the environment were significantly low in this case. Incident happened in a closed container under water, and most of the released activity was absorbed to the pool water and eventually the water was decontaminated. In case the tank would have been located above water surface, the results would have been more serious. Fuel damages released radioactive isotopes of iodine, cesium, xenon and krypton. (Hozer et al. 2014.)

After the accident the damaged fuel was removed from tank and placed in containers. Containers were stored in a spent fuel pool and will be reprocessed. (Adorni et al. 2015, 51.)

Paks incident indicated the fuel behavior in spent fuel pool accidents in a small scale. Accident did occur under water, when results were not as severe as they could have been. Emissions were practically avoided. However it shows how fuel can be damaged if cooling is lost, and fuel damages can occur even with low decay heat.

3.4.3 **Bruce-A**

In Bruce Candu-type nuclear plant in Canada fuel was damaged during fuel transfer in 1983. Fuel element was left in a transfer chamber for several hours due to problems with equipment. A discharge valve was left closed and the air injected to the chamber was trapped, causing uncovering of the fuel. Boiling occurred in the chamber and the fuel was uncovered overall approximately five hours, even though the chamber was filled with water once, when the valve was opened. After five hours the gate was opened and the chamber flooded. Radioactive releases were measured in the room. Fuel was damaged and ballooning occurred, even though the fuel was Candu fuel with only 0.7 % of U-235 and the burn-up was very low. (Adorni et al. 2015, 47–48.)

3.4.4 **Minor incidents**

In addition to accidents presented in earlier chapters, there have been some situations that could have potentially led to fuel damage.

At Kozloduy (VVER-440/230) nuclear power plant unit 1 in 1995 water level decreased below allowed level. During the refueling outage all fuel assemblies were placed in SFP on two levels. Emergency boron tank had been in process for heating up. Due to operator error a valve that was supposed to be closed was left open when cleaning was finished and other valves opened. 10 minutes later radiation levels in the room increased and level decreasing was noticed. Water level decreased 0.5 meters below the lower limit before the refilling was started. (Gantchev. 1996.)

Fuel pool level decreased also in Edwin I. Hatch Nuclear Generating Station (BWR with Mark1 containment) in USA in 1986. A single air supply valve was isolated to the six gate seals of the transfer canal, and seals partly deflated. During 24 hours the pool level decreased ~1.7 meters. Level was noted being low and make-up water was added several times but there was attempt to identify the cause of level reduction. Leak was not detected from the canals, because leak detection alarm was miscalibrated and a drain valve was left open. When the cause was noted the air supply was restored and the leak was stopped. After the accident there has been made some corrective actions, like alternate gate seals. (Ibarra et al. 1997, 12.)

At Haddam Neck PWR nuclear power plant in 1984 over 700 m^3 water was lost from pool due to a failure of reactor cavity seals. Due to a gross failure the seals were significantly misplaced, and in 20 minutes over 700 m^3 water was drained to the containment. Transfer of fuel was ongoing, but none of the elements was being moved at the time. That would have led to partial or complete fuel uncovering and possible increase in radiation level, cladding damage and activity releases. Similar failure occurred also at Surry Unit 1 (PWR) in 1988, and approximately 100 m^3 water was drained to the containment. Neither of these cases resulted any damage, but cavity seal problems have been studied and fixed since the accidents. (US. NRC 1984; Ibarra 1997, 12.)

A load dropping led to a liner leak in Hatch NPP in 1994. A core shroud bolt was dropped which caused liner failure in a pool. Approximately 2.65 l/min leaked between the liner and concrete structure of the pool. The level of the pool was restored and maintained with normal make-up water. (Ibarra et al. 1997.)

3.5 Accident scenarios in dry storages

Due to passive cooling and small amounts of fuel in one place, dry storages can be considered quite safe on a large scale. Dry storage casks are designed to withstand dropping, fire and submersion. Therefore casks are unlikely to break in normal conditions. Most of the problems in dry storages consider either the cask seals or long-term condition of the fuel inside the cask.

Cask leaking is possible during long storage periods. Leaks in cask seals are more likely with bolted than welded casks. The fuel may need to be evacuated from a leaking cask to another. This can be difficult depending on the condition of the fuel. Also the cask seals can be replaced in the case of a leaking cask.

Cask integrity has its limitations. During accidents casks withstand fire for 30 minutes. If they are kept in flames for longer times, it would lead to a cask failure and fuel damage. Also if cask is covered with for example remains of collapsed building, heat removal is disrupted, and fuel can heat up. Instant fuel failures in accident scenarios are however unlikely.

Cooling of a dry cask is based on natural convection and the air flow around the cask. In case the cask is covered with trash, leaves, snow or parts of a collapsed building, the cooling can be disturbed. Disturbance of cooling will in long term lead to overheating of the fuel, so it is important to remove debris from around the cask after such an event.

Also in case of an airplane crash to a dry storage fuel damages and releases are possible. Releases from one storage cask are not large, but in case many casks are damaged, the consequences are wider. Protection of the dry cask storage against an air plane crash is not specifically required, even though the options of an airplane crash shall be considered in design (IAEA 2012b, 54–55.)

Cask design by Sierra Nuclear Corporation has however caused hydrogen ignition events. Cask includes zinc-carbon coating, which protects the metal from borated water. Electrochemical reaction between zinc and zinc-carbon coating generates hydrogen inside the cask. (Macfarlane 2001, 217). In Point Beach nuclear station in Wisconsin, USA, hydrogen ignition occurred during welding of the shielding lid. The lid was displaced due to the explosion, but no measurable radioactive releases were detected and fuel was not damaged. Hydrogen generation in same type of casks has also caused cracking in the sealing and welds in Trojan and Palisades plant sites in USA. (IAEA 1999, 49.)

As a result to the Point Beach accident, US. Nuclear regulation Committee suggested evaluation of possible chemical reactions that might occur on current cask designs. Also consideration should be given on material choices on cask coatings and other materials. (US. NRC 1996.)

4 WET STORAGE MODELLING

Modelling of wet storages can give us information of the system behavior without experimental data or accident history. Different simulating tools can give us further information about fuel behavior, operating parameters of the cooling systems and the conditions in accident scenarios. Models and analysis can support design process as well as confirm the safety of a storage concept.

In Table 4 examples of calculation tools and programs for different phenomena important in spent fuel storages are presented.

Table 4. Different modelling tools that could be use in spent fuel storage examinations.

Physical phenomenon	Calculation	Example programs
Thermal hydraulics	Computational Fluid Dynamics	Ansys-Fluent, Neptune
	System codes	Apros (Finland), TRACE (USA)
Criticality	Monte Carlo codes	Serpent (Finland), MCNP (USA)
Fuel behaviour, fission product release		ASTEC (IRSN, France), MAAP (EPRI), MELCOR (US. NRC)

4.1 Apros

Apros - process simulation software is developed by Fortum and VTT since 1986. Apros is dynamic simulation software and can be used e.g. for modelling of different power plants, including their automation and electrical systems. Apros can simulate plant behavior and even fast transients. Apros has proven to be essential in various engineering tasks, like safety analyses, training and process optimization and design. (Fortum & VTT 2016.)

Apros code has been validated in more than 70 different cases. Separate effect tests has been used for validating the thermal hydraulic models and process component models. (Ylijoki, Norrman, Silde & Urhonen 2015.)

Apros calculation is mainly one-dimensional. Thermal hydraulic solution is based on equations for mass (5), momentum (6) and energy balance (7). (Apros User Manual 2005.)

$$\frac{\delta A\rho}{\delta t} + \frac{\delta A\rho}{\delta z} = 0 \tag{5}$$

$$\frac{\delta A\rho v}{\delta t} + \frac{\delta A\rho v^2}{\delta z} + \frac{\delta Ap}{\delta z} = S_1 \tag{6}$$

$$\frac{\delta A\rho h}{\delta t} + \frac{\delta A\rho vh}{\delta z} = S_2 \tag{7}$$

where S_1 and S_2 are source terms. The enthalpy in equation (7) is the total enthalpy including the kinetic energy.

Thermal hydraulic flow model in Apros can be homogenous, 5-equation (rarely used) or 6-equation-model. (Apros User Manual 2005.)

4.2 Model of Hanhikivi I interim storage

Apros nuclear version 6.05 is used for modelling wet storage for spent fuel. Apros model for spent fuel pool is based on Fortum's design and features are adapted to model in an adequate level. Some systems are left out, because they are unnecessary for the simulation. Spent fuel pool model consists of two pools, pool circuit, intermediate circuit and sea water system. It also has a cooling tower model and pool room included. Only one of two redundancies of the cooling system is modelled.

Model is one dimensional and flow model is mainly 6-equation-model. The pool room is modelled using containment model of Apros.

Cooling systems consist of pumps, heat exchangers, piping and valves. A schematic of the wet storage cooling system of Hanhikivi 1 spent fuel storage is presented in Figure 15.

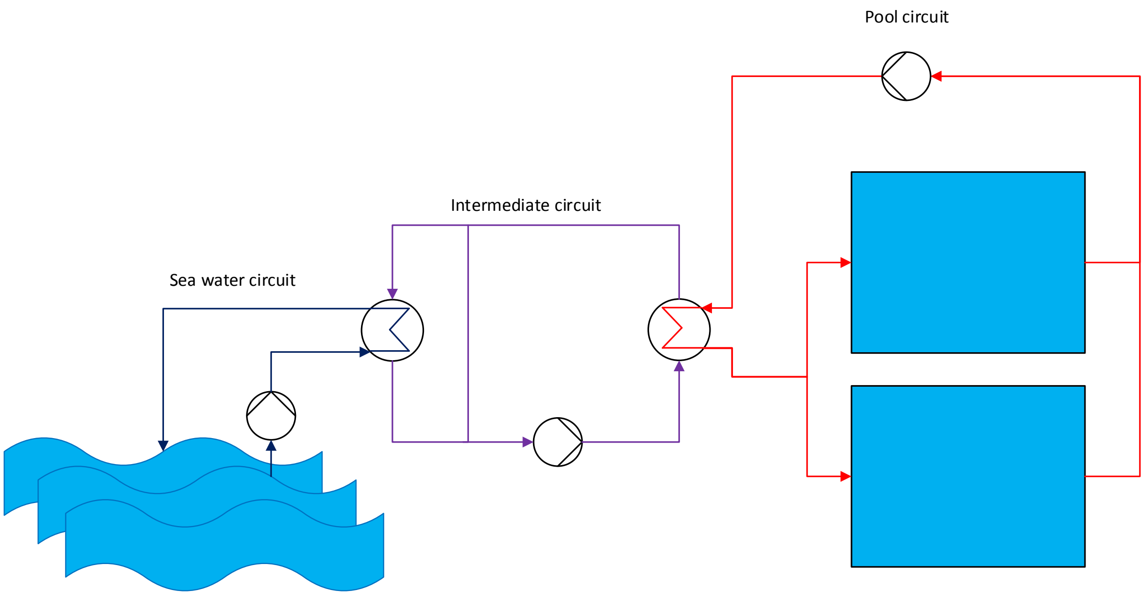

Figure 15. A schematic image of the wet storage cooling system of FH1.

The maximum temperature of the pools during normal operation is 45 °C, when the sea water temperature is at its maximum 25 °C. The temperature change in each counter flow plate heat exchangers is approximately 8 °C. Temperatures and mass flows in each circuit of the designed Apros model at normal operation conditions are presented in Figure 16. Temperatures of pool water and cooling circuit used in Apros model correspond to the design values, and the mass flows are scaled down according to the decay heat in pools compared to the actual design.

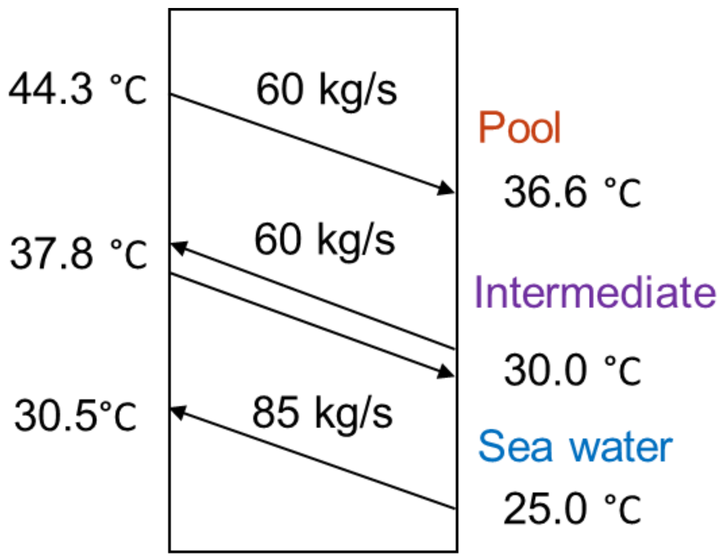

Figure 16. Mass flows and temperatures in cooling circuits at normal operation conditions in the Apros model.

Both fuel pools consist of 24 nodes, of which two are in the same level. Nodes are placed in two rows to enable water circulating in the pools. As 1-dimensional the calculation the natural flow however is not very accurate in pools. Nodes including the fuel elements are higher than the others, because they represent the height of the whole fuel rack. The lowest nodes are smaller than the rest. The rest of the nodes are similar. Two uppermost nodes are above the pool normal liquid level and below the pool cover. Pool 2 diagram is presented in Figure 17.

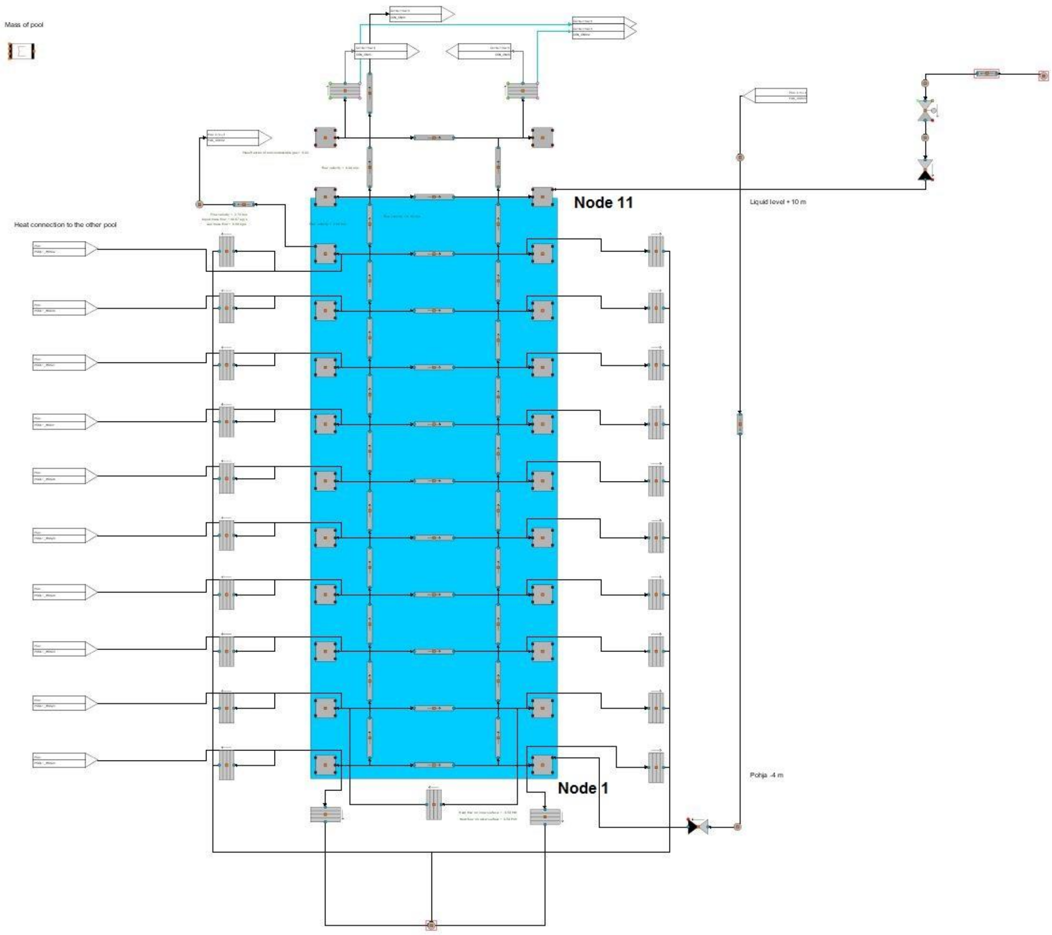

Figure 17. Pool 2 diagram in Apros model of spent fuel storage of FH1. 12 nodes in each side are numbered from bottom to top.

Fuel elements are modelled as a single heat element component. Component geometry includes all fuel elements. Fuel heating power in one pool is assumed to be 1 MW. This represents the conservative maximum load in one pool at the end of plant lifetime, if the total heat load 3.5 MW is not dispersed equally in four pools. Pool walls, pool floor and the pool cover are modelled with heat structure components of Apros. Pools are also connected to each other with a heat structure wall.

Besides fuel pools, the model includes one redundancy of the cooling system. Geometry of the Apros model corresponds to the storage design, but some component attributes are scaled down for the total heating power of 2 MW. This practically means scaling the mass flows in circuits down with factor 2/3.5. This is because only two pools of four are modelled, and the total decay heat of those pools is 2 MW while the actual cooling system is designed for 3.5 MW in four pools.

Pool circuit includes a pump, a heat exchanger, an equalization tank and also fire water connections to the tank and to the pool cooling lines. Equalization tank is connected to an environment node. Pool circuit diagram is presented in Figure 18.

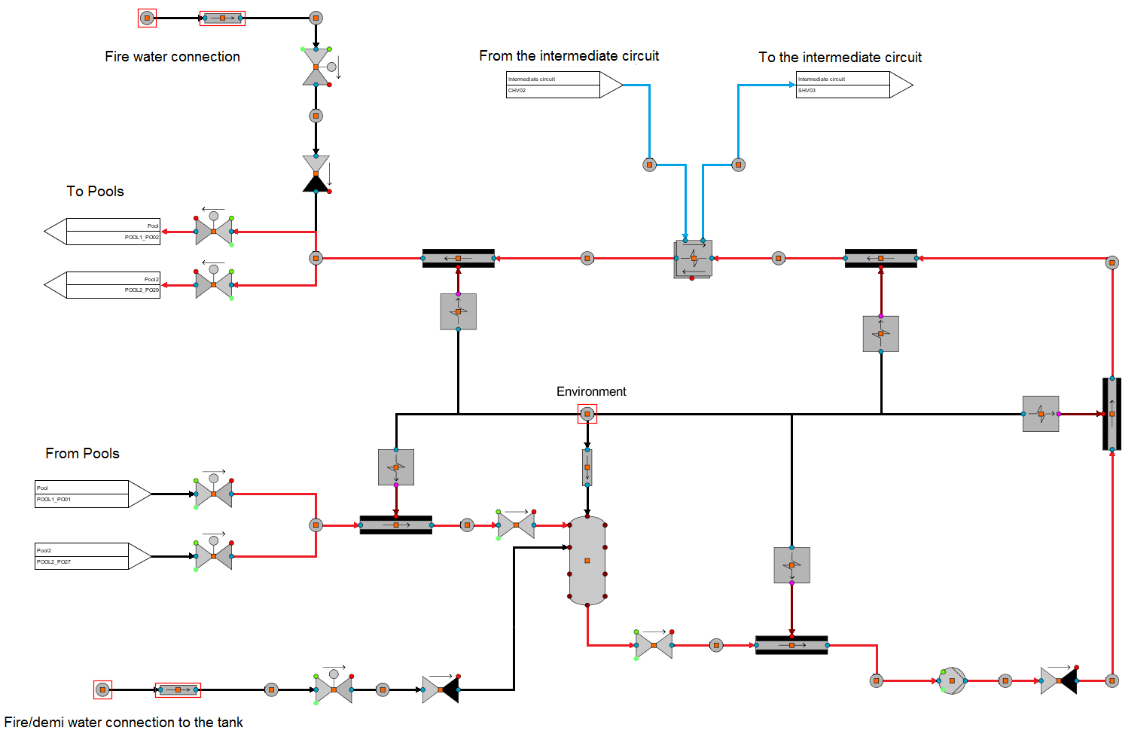

Figure 18. Pool circuit diagram. Pool circuit is marked with red lines and intermediate with blue lines. Connections to pools are in the left side and heat exchanger to the intermediate circuit on the top. Fire water connections are in the left upper and lower corners.

Most pipes in the pool circuit and the intermediate circuit are modelled with heat pipe components of Apros, and heat losses to environment are modelled. Environment is modelled with a single node with a temperature of 30 °C.

Intermediate and sea water circuits are presented in Figure 19.

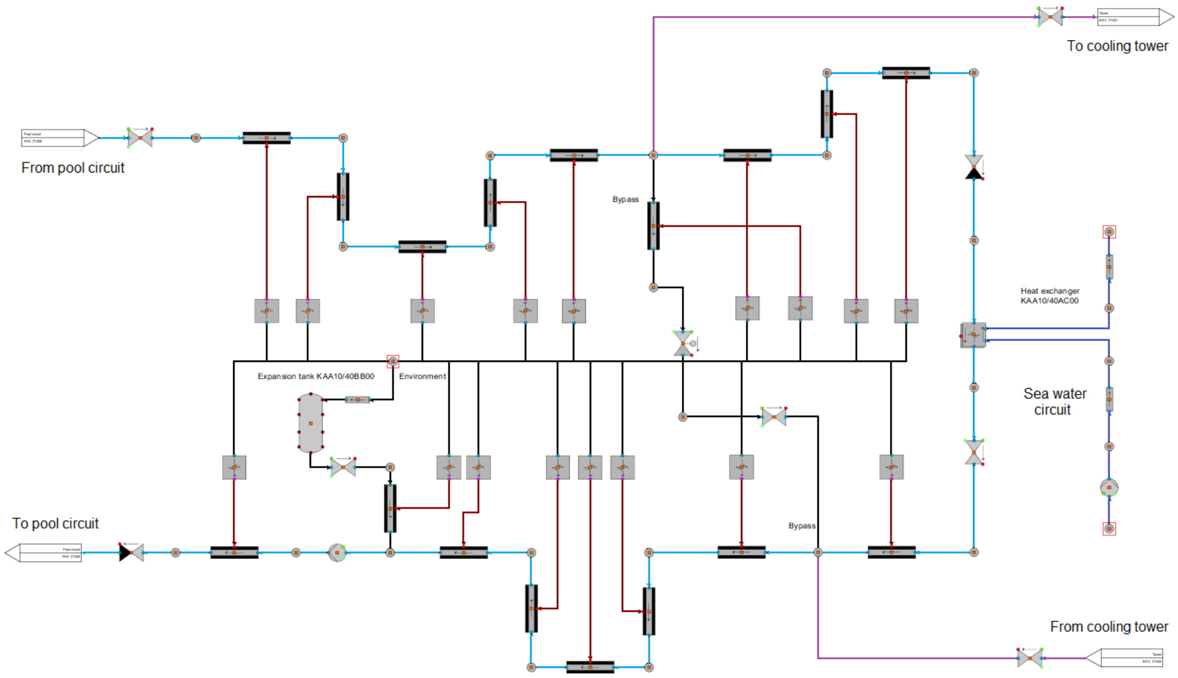

Figure 19. Intermediate circuit (light blue) and sea water circuit (dark blue) in the right side. Connections to the cooling tower (purple lines) and bypass line are located near the middle of the diagram.

Intermediate circuit consists of heat pipe components, heat exchangers and a pump. Also an expansion tank is included. The intermediate circuit is connected to a cooling tower, which can be used if the sea water circuit is lost. Cooling tower is presented in Figure 20.

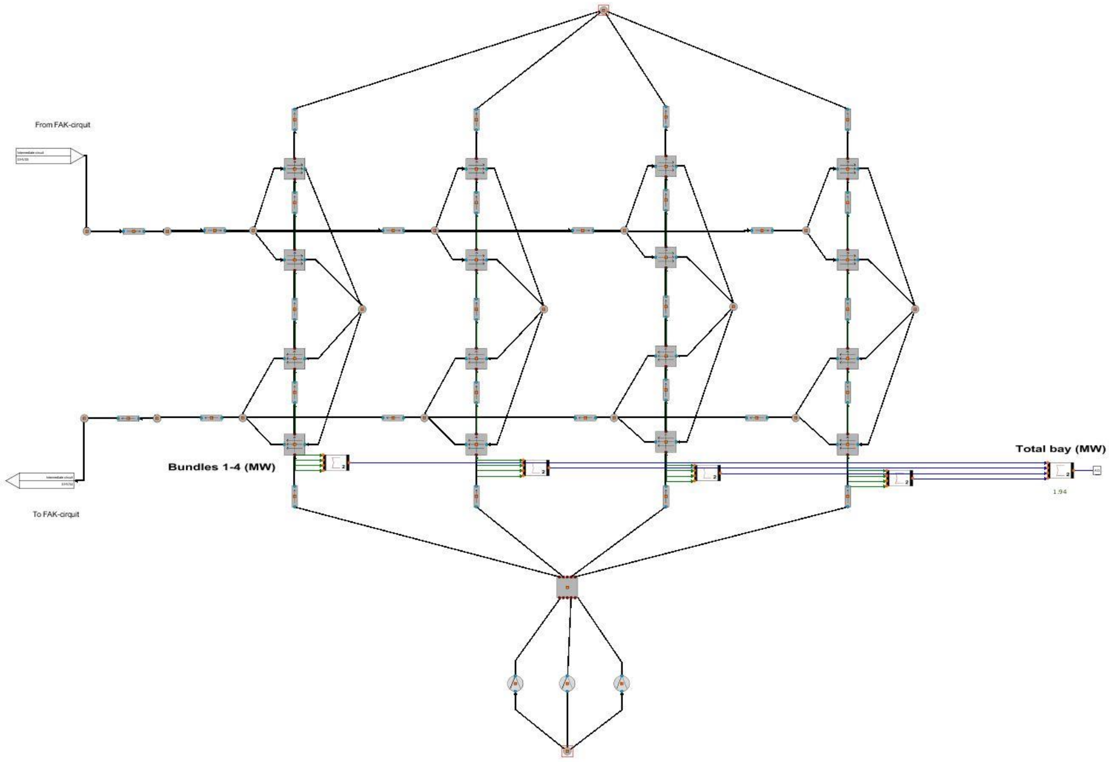

Figure 20. The cooling tower diagram of FH1 spent fuel storage model.

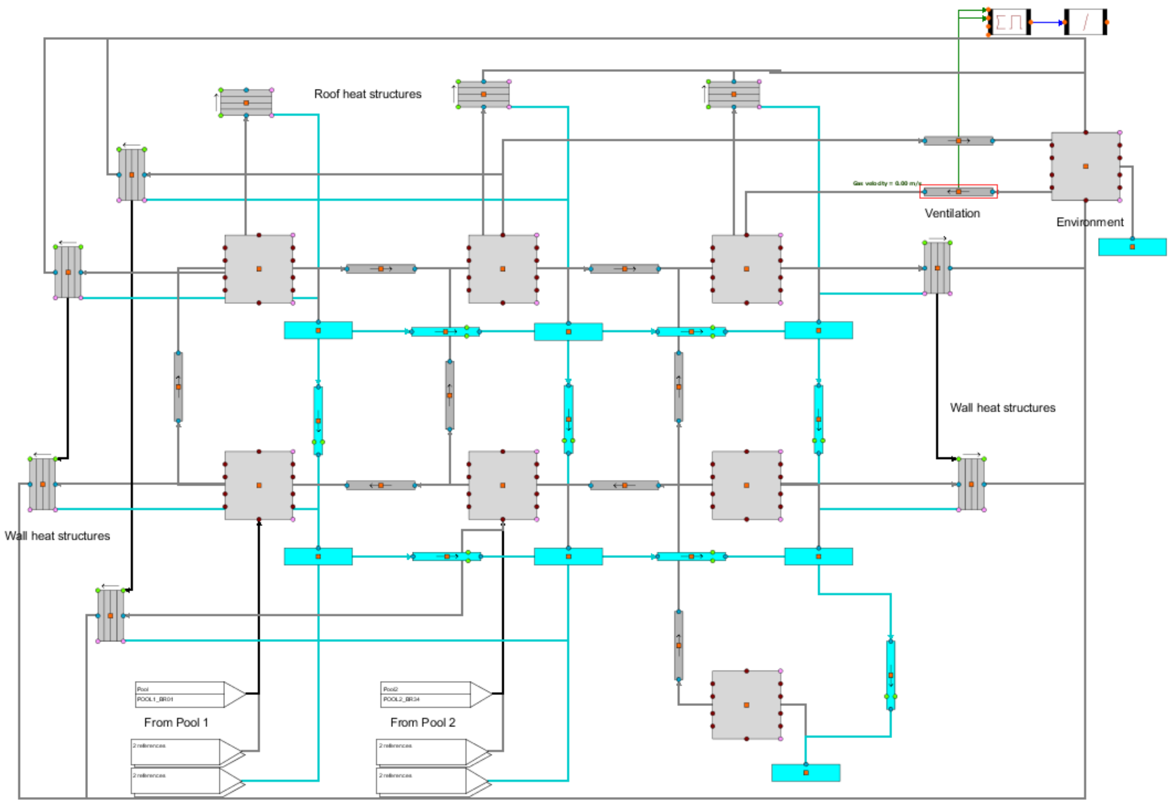

Figure 21. The pool room consisting of containment nodes. Environment node is in the top right corner and connections to the pools are located in the two lower left nodes.

Storage facility is modelled only as a single pool room (Figure 21), and the process building is left out. The room walls and the ceiling are modelled with heat structures. The ventilation of the room is modelled simply with two pipe components to environment. The evacuation pool is modelled with one containment node. Steam condensing on the walls is assumed to return to the modelled pools, if it condensates on walls near the fuel pools, and to the evacuation pool if it condensates to walls in the other end of the pool room.

A simple manual calculation can be made to approximate the boiling time of the pool. Assumptions which are made for the manual calculations are presented in Table 5.

Table 5. Assumptions made for the manual calculation of pool heating.

Heat of vaporization	2260	kJ/kg
Specific heat	4186	J/kgK
Pool water mass	1 143 000	kg
Pool water temperature	45	°C
Pool water boiling temperature (Higher than normal due to the hydrostatic pressure in pool)	103	°C
Heating power	1	MW

Based on the manual calculations with heating power of 1 MW and assuming that there is no heat losses to environment, boiling would occur in 3,2 days. In the Apros calculations boiling conditions are reached in 4 days. The difference is due to modelling of heat losses to the concrete walls and to the room above the pool in Apros model. According to these calculations, approximately 20 % of the heat produced by the fuel goes for the heat losses.

The nodalization of the pools is quite rough. This means that the temperature profile cannot be studied in very detailed level. Also the temperature profile of fuel elements is not very specific. All fuel elements in the pool are modelled only with one heat structure component, which therefore have equal temperature profile horizontally. They are also connected to only one thermal hydraulic node, and therefore the temperature profile in a node is not studied either.

Flows in the pool cannot either be studied specially. Apros is not a CFD calculation tool, and therefore the flow models in this kind of pool are simplified. Pools are modelled with two rows of nodes to enable simple water circulation in the pools, but other than that the flows are not studied.

5 SAFETY ANALYSES

Safety analyses help predicting plant behavior, possible accidents and human errors. In this thesis, thermal hydraulic safety analyses for the wet storage concept of FH1 are performed using Apros software. The model used is described in chapter 4.2.

5.1 Background

Finnish YVL-regulations set the requirements for deterministic safety analyses (YVL B.3 2013.) Thermal hydraulic analyses are required to be done using either conservative or best estimate values. In this case the conservative values are chosen. Further analyses and sensitivity study for heating power of the elements, boundary temperatures and nodalization of the pools are possibly performed at the later design phase of FH1 spent fuel storage.

Analysed cases are based on initiating events that are identified to be the most relevant in case of a spent fuel pool. Initiating event groups and main hazards are specified in tables 6 and 7 as follow.

Table 6. Initiating event groups (Rein 2016)

Group ID	Initiating event group	Event category
NOC	Normal operation	DBC 1
FUHA	Fuel mishandling	DBC 2
DCOOL	Disturbance in fuel pool cooling	DBC 2
LOOP_POOL	Loss of off-site power	DBC 2
FUHAL	Fuel mishandling leading to fuel leak	DBC 3
SLOCA	Break in the cooling circuit	DBC 3
DROP	Dropping of container containing fuel bundles	DBC 4
NOCOOL	Non-operability of fuel pool cooling	DBC 4
LLOOP_POOL	Long loss of off-site power	DEC A
LUHS	Loss of ultimate heat sink	DEC A

Table 7. Main hazards for spent fuel pools. (Rein 2016)

Group ID	**Initiating event group**	**Event category**
FIRE	Fire	DBC 4
EQ	Earthquake	DBC 4
LAPC	Light airplane crash	DBC 4
EQC	Earthquake	DEC C
APC	Airplane crash	DEC C

Calculated cases are based on the events listed in tables 6 and 7. Selection of calculation cases is justified in analyses specification (Tynys 2017a.) From the point of view of the process, many of the suggested hazards and initiating events lead to similar cases, for example to the loss of the whole cooling system. Some initiating events are covered with more than one analysis case depending on used assumptions, for example combining a single failure or loss of external grid with the initiating event. Some events, like dropping of the container, cannot be analysed with Apros, so such analyses are produced by other means and are not described in this thesis. The cases that are calculated using Apros are presented in Table 8.

Table 8. The calculated analysis cases and the initiating event groups they are based on.

<table>
<tr><th>Initiating event group</th><th>Event category</th><th>Analysis case</th><th>Actions</th><th>Case</th></tr>
<tr><td>Disturbance in pool cooling
(without single failure)</td><td>DBC 2</td><td rowspan="3">One redundancy functioning</td><td rowspan="3">Cooling system test with one redundancy</td><td rowspan="3">**Case 1:
1RED**</td></tr>
<tr><td>Break in the cooling circuit
(without single failure or loss of external grid)</td><td>DBC 3</td></tr>
<tr><td>Fire
(without single failure or loss of external grid)</td><td>DBC 4</td></tr>
<tr><td>Loss of ultimate heat sink
(normal functioning of the tower)</td><td>DEC A</td><td>Loss of sea water</td><td>Using the cooling tower</td><td>**Case 2:
TOWER**</td></tr>
<tr><td>Non-operability of fuel pool cooling</td><td>DBC 4</td><td rowspan="6">Loss of cooling system:
short
long</td><td rowspan="2">Cooling system failed and restored after 72 h.</td><td rowspan="2">**Case 3:
FAIL72h**</td></tr>
<tr><td>Break in the cooling circuit
(with single failure and/or loss of external grid)</td><td>DBC 3</td></tr>
<tr><td>Fire
(with single failure and/or loss of external grid)</td><td>DBC 4</td><td rowspan="4">Cooling system failed and restored after 5 d. Water injected through the fire water system.</td><td rowspan="4">**Case 4:
FAIL5d**</td></tr>
<tr><td>Loss of ultimate heat sink
(non-functioning of the tower)</td><td>DEC A</td></tr>
<tr><td>Disturbance in pool cooling
(with single failure)</td><td>DBC 2</td></tr>
<tr><td>Loss of off-site power</td><td>DBC 2 /
DEC A</td></tr>
<tr><td>Air plane crash</td><td>DEC C</td><td rowspan="7">Cooling system destruction</td><td rowspan="7">Regular fire water injection</td><td rowspan="7">**Case 5:
FIRE-WATER**</td></tr>
<tr><td>Earthquake</td><td>DEC C</td></tr>
<tr><td>Disturbance in pool cooling
(with single failure that cannot be repaired)</td><td>DBC 2</td></tr>
<tr><td>Break in the cooling circuit
(with single failure that cannot be repaired)</td><td>DBC 3</td></tr>
<tr><td>Non-operability of fuel pool cooling
(cooling cannot be restored)</td><td>DBC 4</td></tr>
<tr><td>Fire
(with single failure that cannot be repaired)</td><td>DBC 4</td></tr>
<tr><td>Loss of ultimate heat sink
(non-functioning of the tower and the ultimate heat sink cannot be restored)</td><td>DEC A</td></tr>
</table>

The analyses are postulated using mainly YVL B.1 and B.3 requirements (2013). By these analyses shall be proven that the 72-hour-self-sufficiency criterion is fulfilled. Analyses shall prove that the fuel integrity can be secured 72 hours without any operational actions or systems, that are not safety classified. As required in YVL B.3 (2013) requirement 413, the suitable time delays for all operator actions are assumed. A single failure and loss of the external grid is assumed for suitable event groups, as described in Table 8. More detailed description for the requirements used in analyses are described in Appendix 1.

Basically the analysis shall prove that the fuel integrity is maintained in analysed cases and the spent fuel pool can be brought to the safe state with designed functions. Functions planned to be used and functions needed in each case are presented in Appendix 2 and discussed more specifically in a separate more detailed analysis report (Tynys 2017b).

Analysis cases 1–4 are simulated at least until the safe state is reached or can be seen that the system is going towards it. Safe state in this spent fuel storage refers to a state where fuel storage pool temperature is low enough to maintain water clarity, decent working conditions in the pool area and the integrity of pool liners, there is no release and decay heat is transferred to the ultimate heat sink (Rein 2017). In this case the required temperature of pool water is determined to be below 80 °C, which is design basis in DBC 3 and DBC 4 and DEC conditions, and below 60 °C in case the cooling tower is used. These values are based on design values of the storage (Teräsvirta 2017a). Normal operation temperature of the storage is at maximum 45 °C, and cases are mainly calculated, until most of the nodes are near to this temperature.

Analysis case 5 shall prove that the fuel pool can be kept in controlled state (either boiling or non-boiling), which refers to a state where normal operation decay heat removal functions are unavailable and decay heat is heating the fuel pools (controlled state non-boiling) or the removal of decay heat is secured by boiling the fuel pool water (controlled state boiling) until cooling functions will be restored. (Rein 2017.)

Acceptance criterion for the analysis is that the pool water is kept at sufficient level. It can be assumed that the fuel remains intact as long as it stays under water. In this case the accepted water level is 4 meters above the top of the fuel racks. This is high enough to keep the fuel covered and to maintain the radiation level in pool room at an adequate level. The used criterion for water level also enables transfers of inside a pool or from one pool to another. Conditions where fuel is transferred into or out from pools are assumed to be such short time periods in a year that they are not taken into account.

5.2 Results

The main results of the analysis cases listed earlier in Table 8 are discussed in this chapter. More figures and results are presented in Appendix 3. More results can also be seen in a separate more detailed analysis report "Preliminary Thermal Hydraulic Safety Analyses for UFC" (Tynys 2017b). Conservative assumptions are made for initial and boundary conditions as specified in Table 9.

Table 9. Assumptions made for initial and boundary conditions.

Water level (from sea water level)	**[m]**
Normal conditions	+10
At the beginning of analysis 1,2,3,4	+9.55
At the beginning of analysis 5 (the same as after 5 days in analysis case 4)	+9.6
Boundary condition temperatures	**[°C]**
Air outside the cooling tower	30
Ground outside pipes	25
Air outside pool room	30
Ground around the pools	25
Sea water temperature	25
Fire water temperature	20

Before the analyses are performed, the Apros model is simulated for some time. This is done in order to ensure that a stationary state has been approached.

The results for each analysis case are presented in separate chapters. In addition to these cases, a situation, where no actions were taken after the loss of cooling has been analysed. In a case where all cooling systems were lost and not restored and no water was injected to the pools, the top of the fuel was uncovered in 25 days. The water level decrease in this case is presented in Figure 22.

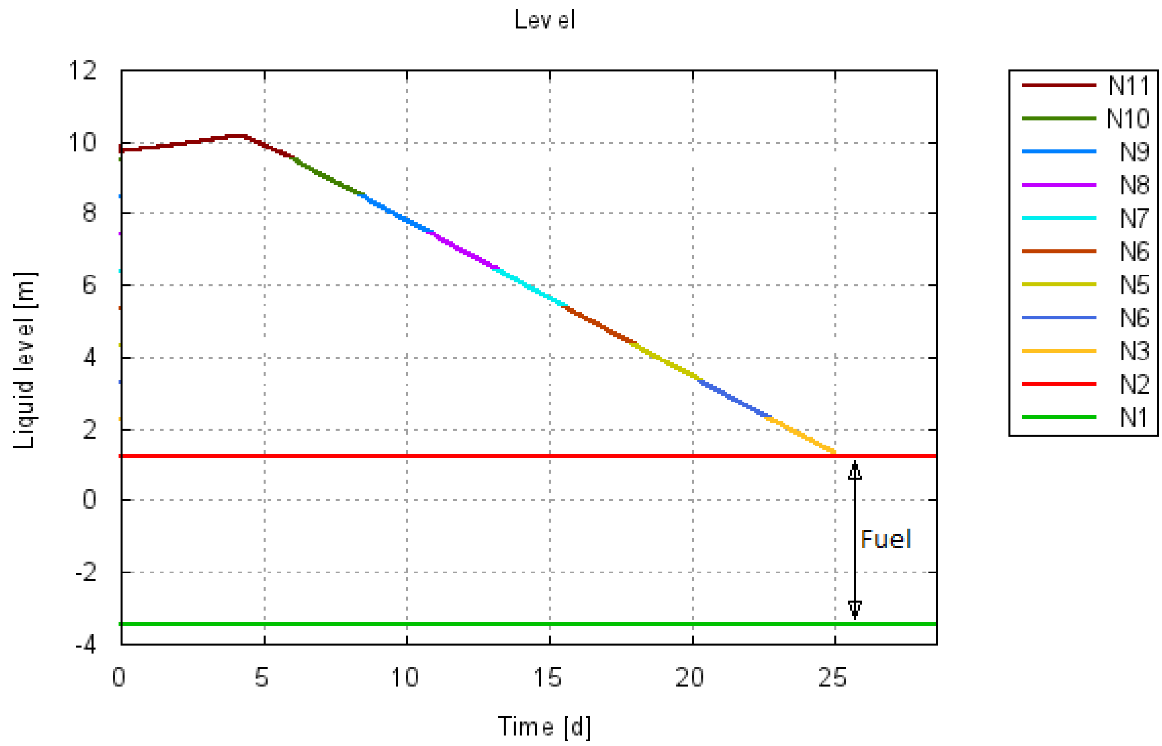

Figure 22. Water level decrease in a case when no cooling or cold water injecting is provided. Fuel elements are located between the horizontal red and green lines.

Vertical nodes in right side of the pool are presented in figures numbered from bottom to top. Normal water level is in the middle of node 11 (N11) and fuel elements in node 2 (N2). The pool level in left side nodes is similar to right side and therefore not presented to keep the figures more clear. After the top of the fuel is reached, fuel damages and releases are possible. However in this work, this is not analysed because the scenario where the fuel is uncovered is practically eliminated.

5.2.1 **Case 1: 1RED**

The cooling system of the wet storage concept of FH1 consists of two separate redundancies. If one redundancy fails, the other can be used. Losing of one redundancy can be a result of for example a component failure, local fire event or other disturbance in cooling. Progression of the analysis case is described shortly in Table 10.

Table 10. Progression of analysis case 1.

Time [hh.mm:ss]	Event
00.00:00	Beginning of analysis, pool level +9.5 m
00.05:00	Pool circuit pump shut down
00.10:00	Intermediate and sea water pumps shut down
01.05:00	Sea water circuit pump started again
01.10:00	Intermediate circuit pump started again
01.15:00	Pool circuit pump started again
03.00:00	Temperatures in pools stabilized back to normal level

In case a cooling redundancy is lost, the other can be started. In this analysis, it is assumed that the redundancy is started one hour after the other has failed. During this time the temperatures in pools do not increase significantly. Temperatures are presented in Figure 23.

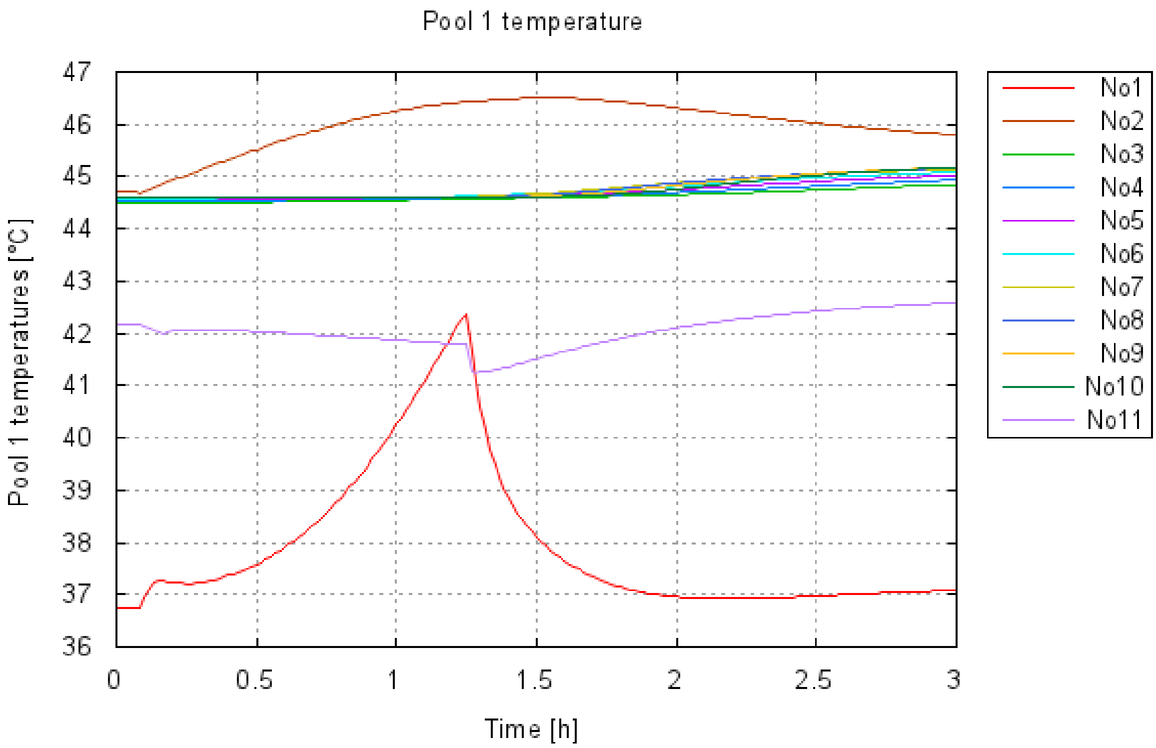

Figure 23. Temperatures in different nodes of pool 1 when the cooling is lost for an hour.

Nodes in figure are numbered from bottom (No1) to top (No11). Node 1 is below the fuel elements and connected to the cooling system cold water inlet, and therefore normally colder than the nodes above. Other results can be seen in appendix 1. This short period of loss-of-cooling does not have an effect on pool water level or the pool room temperature.

5.2.2 Case 2: TOWER

If sea water is lost due to natural phenomenon, accident or a common cause failure of sea water pumps, the cooling tower can be used. Progression of the analysis case is described shortly in Table 11.

Table 11. Progression of the analysis case 2.

Time [D hh.mm]	Event
00.00	Beginning of the analysis
00.05	Sea water pump shut down
05.00	Cooling tower valves opened
05.01	Sea water heat exchanger valve closed
8 d 00.00	Pool temperatures stabilized and analysis finished

Temperatures in pool when the sea water is lost and the use of cooling tower is started after 5 hours are presented in Figure 24.

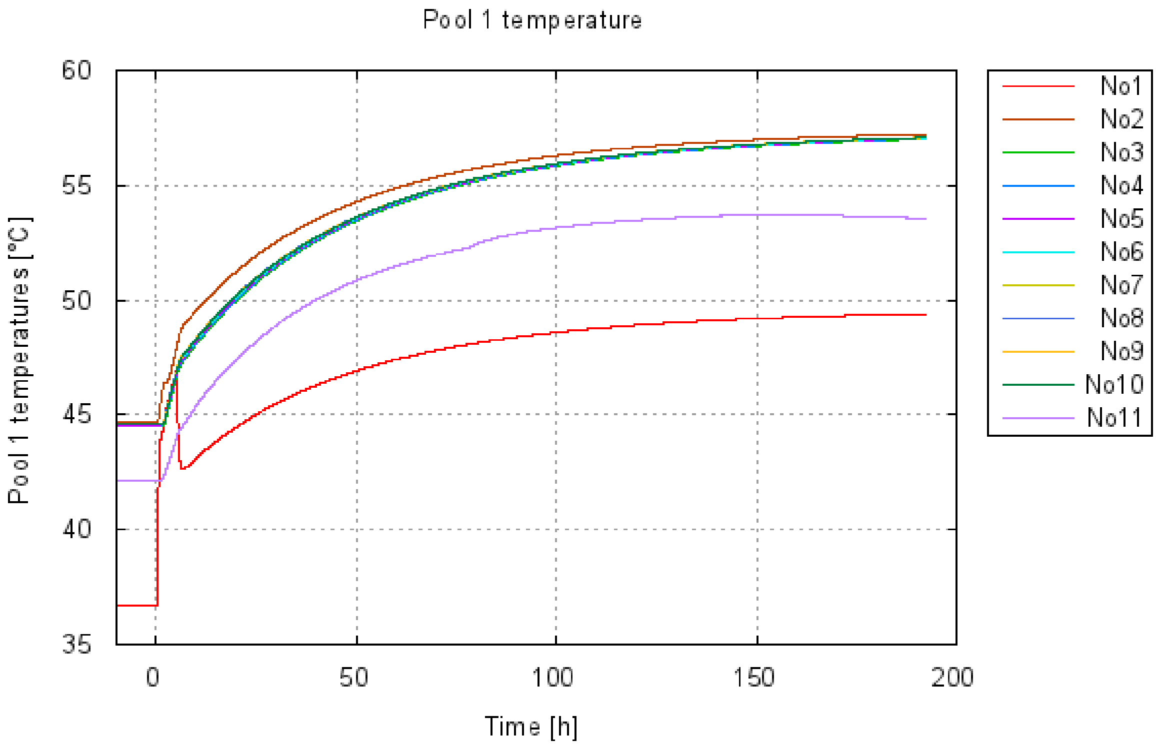

Figure 24. Pool 1 temperatures in different nodes when sea water is lost and cooling tower is on use.

When the cooling tower is used, the pool temperatures are higher than with the sea as the ultimate heat sink. In this analysis the pool temperatures settle below 57 °C when cooling tower is in use. The lowest node No1 is below the fuel elements and connected to the cooling system and therefore is colder than the other nodes. The uppermost node number 11 is only partly filled with water and therefore, as the room temperature is lower than the temperature of the pool water, the average temperature of this node is lower than the temperature of the other nodes. Temperatures rise to this level slowly during 8 days after the loss of ultimate heat sink.

Temperature in cooling tower inlet need to be above 50 °C for the tower to function properly. Pool temperature increases until this is reached. The cooling tower outlet temperature is then circa 44 °C. More figures of case 2 are presented in Appendix 3.

5.2.3 Case 3: FAIL72h

The pool cooling system is totally lost, when both cooling circuit redundancies are non-operable. This can be a result of for example a loss of external power or a common cause failure of pumps. In the case 3 an event when the cooling system is lost for 72 hours is examined. According to YVL guides (YVL B.1 2013) the fuel pool cooling shall fulfill the 72-hour-self-sufficiency criterion. This means that the fuel pool cooling shall be maintained for 72 hours without any active systems. In this case that means, that when the cooling system is lost, the heat must be transferred from the fuel to the water mass or by boiling during the first 72 hours. During the first 24 hours no actions shall be done, but during the next 48 hours material replenishments are allowed using the material reserves in the plant site. In this case only batteries of measurements and emergency lighting are needed to be powered.

Table 12. Progression of the analysis case 3.

Time [D hh.mm]	**Event**
00.00	Beginning of analysis
00.05	Loss of electricity, all pumps and ventilation shut down.
01.00	Valves in pool circuit closed to prevent pool circuit heating
3 d 00.00	Electricity restored
3 d 00.01	Pool circuit valves opened
3 d 00.05	Sea water and intermediate pumps started
3 d 00.08	Pool circuit pump started
3 d 00.30	Ventilation started
5 d 05.00	Pool temperatures stabilized and analysis finished

When the fuel pool cooling is lost, temperatures in the pool start to rise, as presented in Figure 25. The analyses show that within 72-hour self-sufficiency criterion the pool stays in a controlled non-boiling condition.

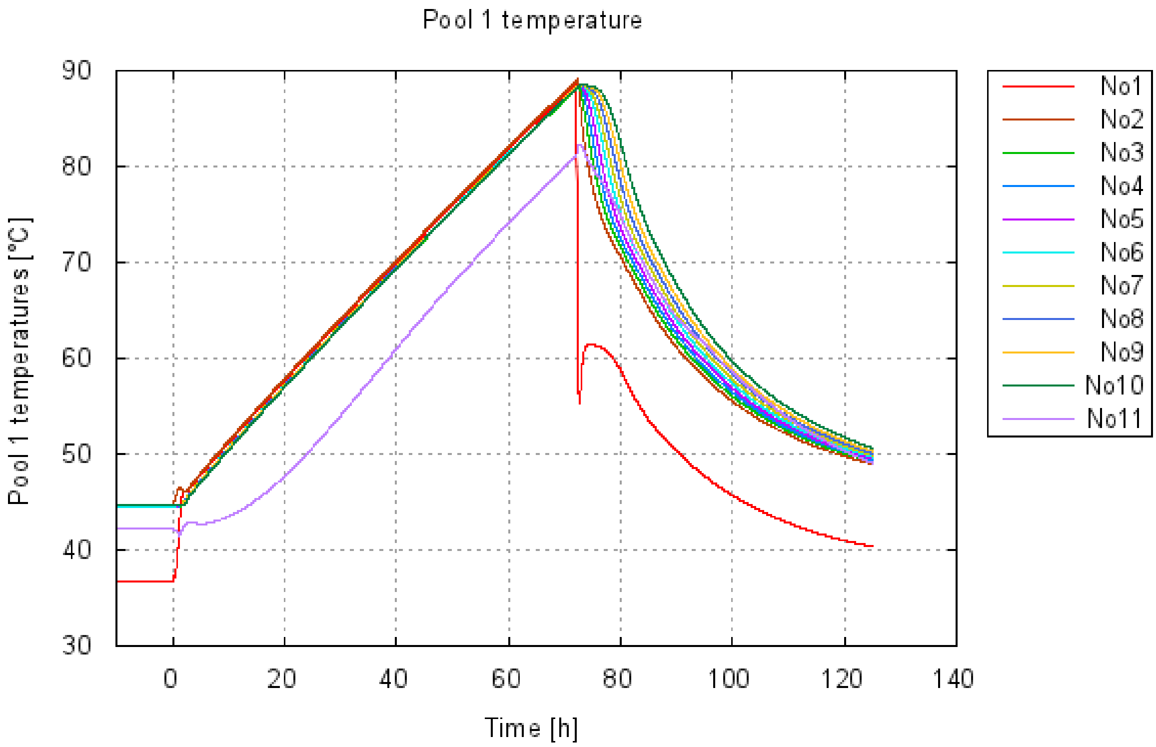

Figure 25. Temperatures during loss of cooling and restoring of cooling system. In 72 hours the pool temperature rises near to 90 °C. Boiling does not occur and cooling system can be normally restored.

After 72 hours temperatures in the pools have increased to over 80 °C and the liquid level has increased due to density change. The cooling system can be restored normally without a cold water injection to pools.

5.2.4 Case 4: FAIL5d

If cooling system is lost due to for example a loss of external power, a common cause failure, or some other cause, boiling will eventually occur in the pools. In analysis case 4 the cooling system is lost for 5 days. Progression of the analysis is presented in Table 13.

Table 13. Progression of the analysis case 4.

Time [D hh:mm]	Event
0 d 00.00	Beginning of analysis.
0 d 00.05	Loss of electricity, all pumps and ventilation shut down.
0 d 01.00	Valves in pool circuit closed to prevent pool circuit heating.
4 d 00:00	Pool starts to boil.
5 d 00:00	Electricity restored.
5 d 00:00	Cooling circuit valves opened.
5 d 00:05	Water injection 15 kg/s to the pools 1 and 2, from demi/fire water connections above the pools.
5 d 00:45	Pool water level reaches 10 meters. Injection to pools stopped.
5 d 00:47	Sea water and intermediate pumps started, pool lines open.
5 d 00:50	Pool circuit pump 30 %
5 d 01:00	Pool circuit pump 50 %
5 d 01:02	Pool circuit pump 70 %
5 d 01:10	Fire/demi water injection 5 kg/s to the equalization tank.
5 d 04:30	Pool circuit pump 100 %
5 d 08:15	Fire/demi water injection to the equalization tank decreased to 2 kg/s.
5 d 09:00	Pool water temperature decreased below the boiling temperature,
5 d 09:00	Fire water injection to the equalization tank. stopped.
6 d 00:00	Ventilation started.
8 d 00:00	Pool temperatures stabilized near the normal temperature and analysis finished.

Boiling temperature in the pool is reached in 4 days if cooling system is lost. Temperatures in different elevations settle between 100 and 115 °C, as shown in Figure 26.

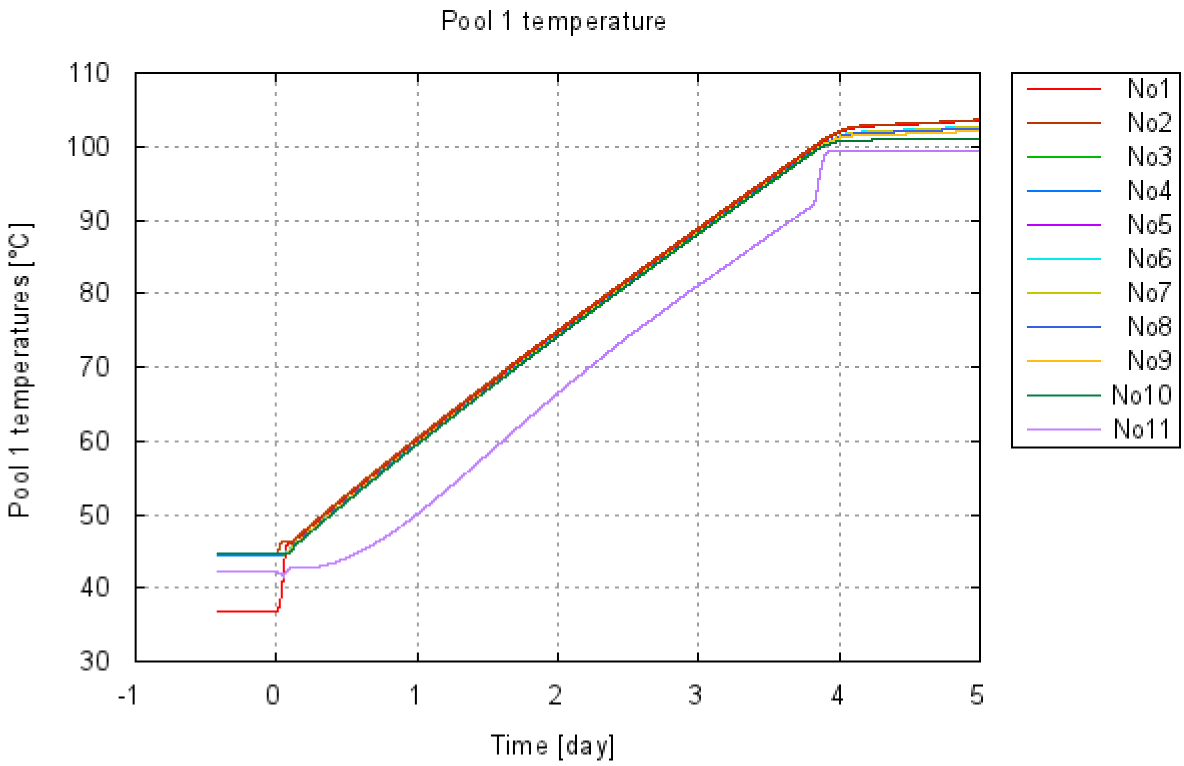

Figure 26. Temperatures in different nodes of pool 1 when cooling system is lost for 5 days. Boiling occurs after 4 days.

After boiling in the pools has started, it is not possible to restore the cooling system without a cold water injection, because of the effects of the boiling in cooling system components. Restoring is hardest when pool liquid level has not yet decreased significantly. When pool level decreases, the pool water level must be increased to the level of cooling system connections before the cooling can be started. Fire and demineralized water connections to the pools can be used for filling the pool to suitable level to be able to use the outlet connection of the cooling system. Filling the pool with cold water decreases the pool water temperature making restoring of the cooling system easier.

Injection to the equalization tank is needed to keep the water in the pool cooling circuit under the boiling point. Condensation in the heat exchanger can cause pressure surges which can damage the heat exchanger. Also cavitation in the pump inlet may occur in high temperatures, damaging the pump. Boiling in the cooling circuit must be prevented in all cases when the cooling circuit is used.

Cold water injection to pools and equalization tank are presented in Figure 27.

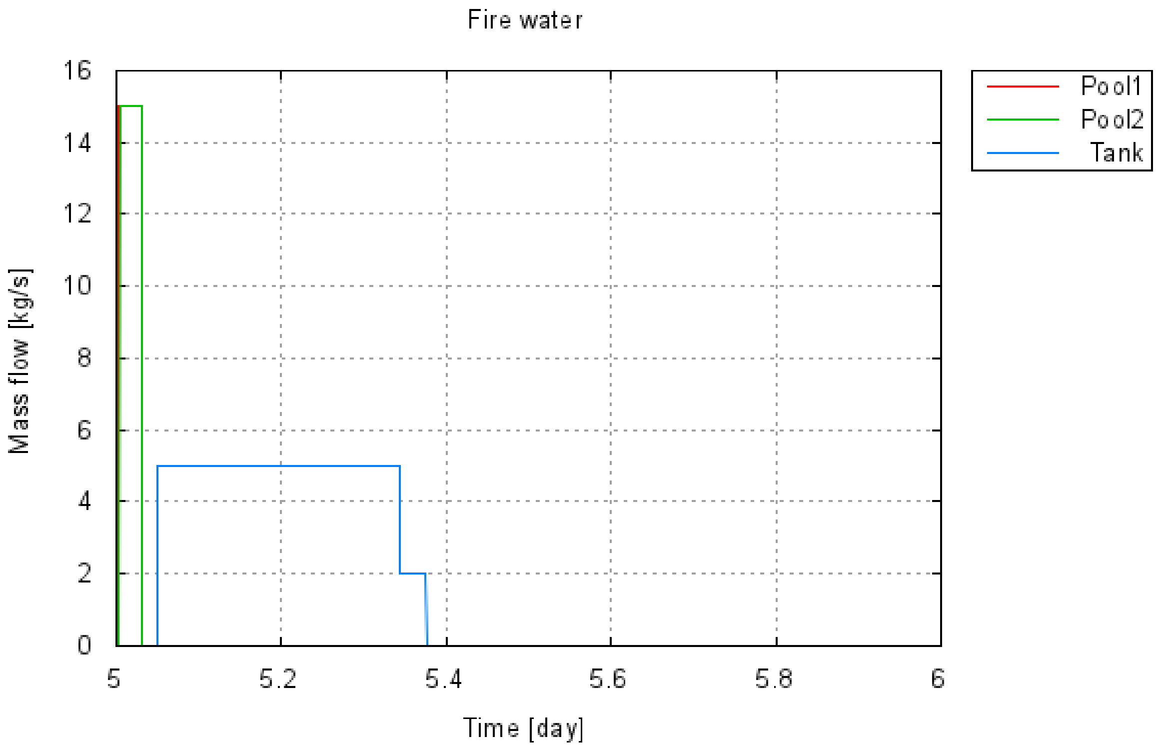

Figure 27. Water injected to pools 1 and 2 and to tank. The amount is equal for both pools. Injection to the tank is continued for almost 8 hours.

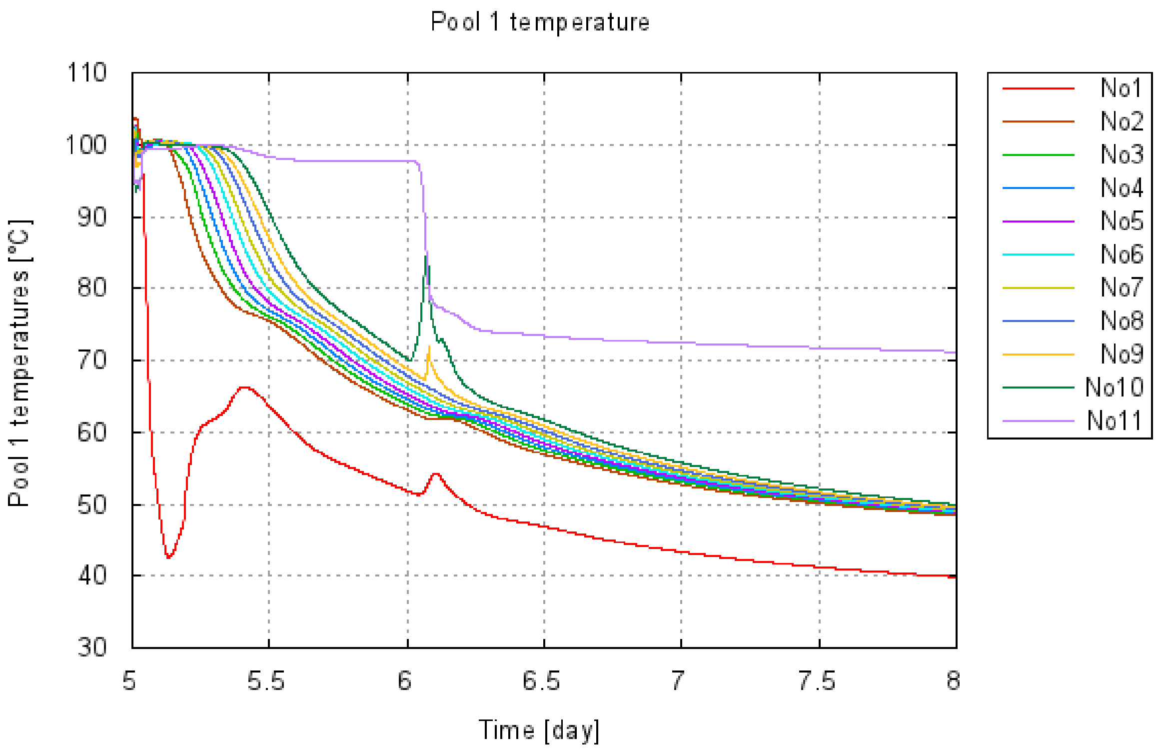

Figure 28. Temperatures in pool 1 when cooling system is restored after 5 days power break. Nodes are numbered from bottom to top.

Pool temperatures (Figure 28) mainly decrease near to normal level after three days of cooling. The analysis is calculated until the temperature in most nodes is below 50 °C. The uppermost node is in significantly higher temperature than lower nodes at the end of the analysis. This is because the cooling system connection is below the node and water does not mix very effectively when the hot water is above the cold water. The mixing is temporarily more effective when ventilation is started after 6 days, as can be seen in Figure 28. Temperature of node 11 would eventually decrease to same level as the other nodes. All temperatures are below 80 °C, which is the limit for these specific conditions.

5.2.5 Case 5: FIREWATER

In case of total loss of cooling system, due to for example an earthquake or plane crash, the pool can be cooled by injecting water through the fire water system. Progression of the analysis case where this is analysed is presented in Table 14.

Table 14. Progression of the analysis case 5.

Time [D hh:mm:ss]	Event
5 d 00:00:00	Starting point after 5 days of boiling
5 d 00:00:00	Boiling
5 d 00:05:00	Injecting 20 kg/s fire water to the pool
5 d 00:09:10	Water injection stopped
5 d 04:09:10	Injecting 20 kg/s fire water to the pool
5 d 04:13:20	Water injection stopped
5 d 08:13:20	Injecting 20 kg/s fire water to the pool
5 d 08:17:30	Water injection stopped
5 d 12:17:30	Injecting 20 kg/s fire water to the pool
5 d 12:21:40	Water injection stopped
5 d 13:21:40	Analysis finished

When pool is boiling the vaporization from one pool to the room is in Apros model 0.3-0.4 kg/s. Sufficient amount for water injection is then a little over 1 m^3/h. This water mass can be transferred for example with fire trucks if all plant site water connections and inventories are lost.

Temperatures in case 5, when water is injected to the pool, are shown in Figure 29.

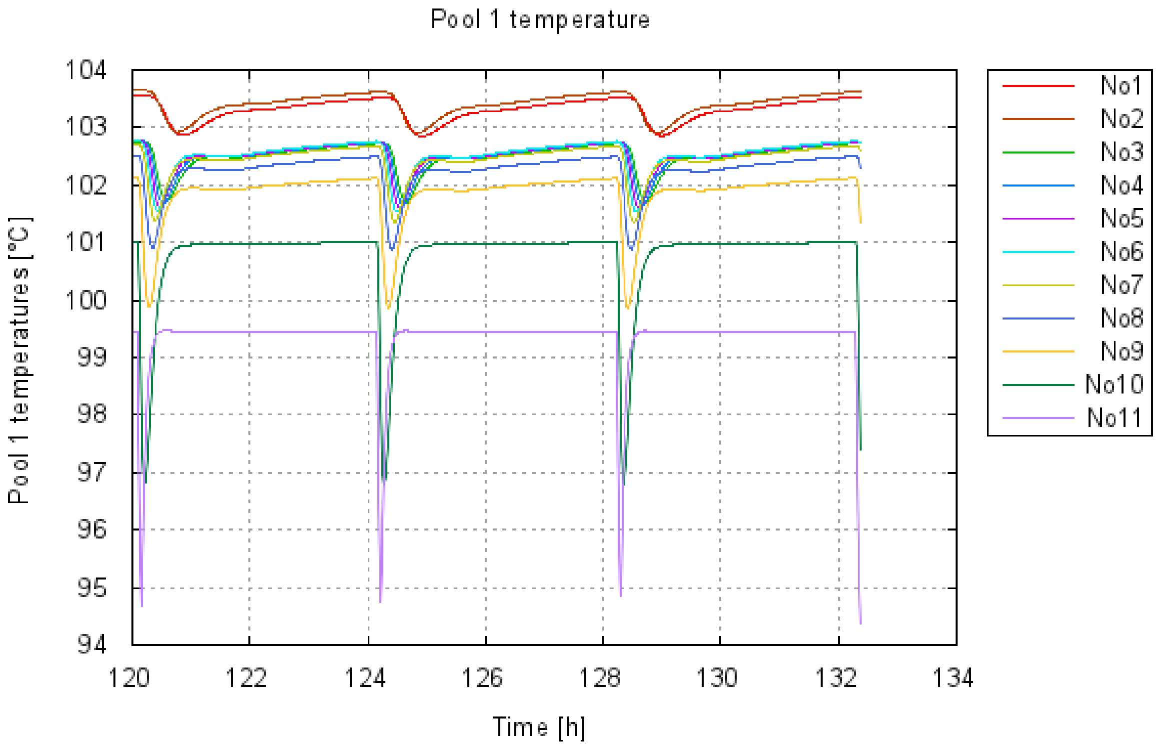

Figure 29. Pool temperatures when cold water (temperature 20 °C) is injected four times every 4th hour from the fire water connections above the pool.

In analysis case 5, 5000 kilograms water is injected to the pool approximately every 4th hours. This amount is sufficient to keep the water level approximately constant. Injected amount is similar to the minimum capacity of a fire truck. Mass flow of regular water injection to the pool after 5 days without cooling and liquid level during injection are presented in Figure 30 and Figure 31.

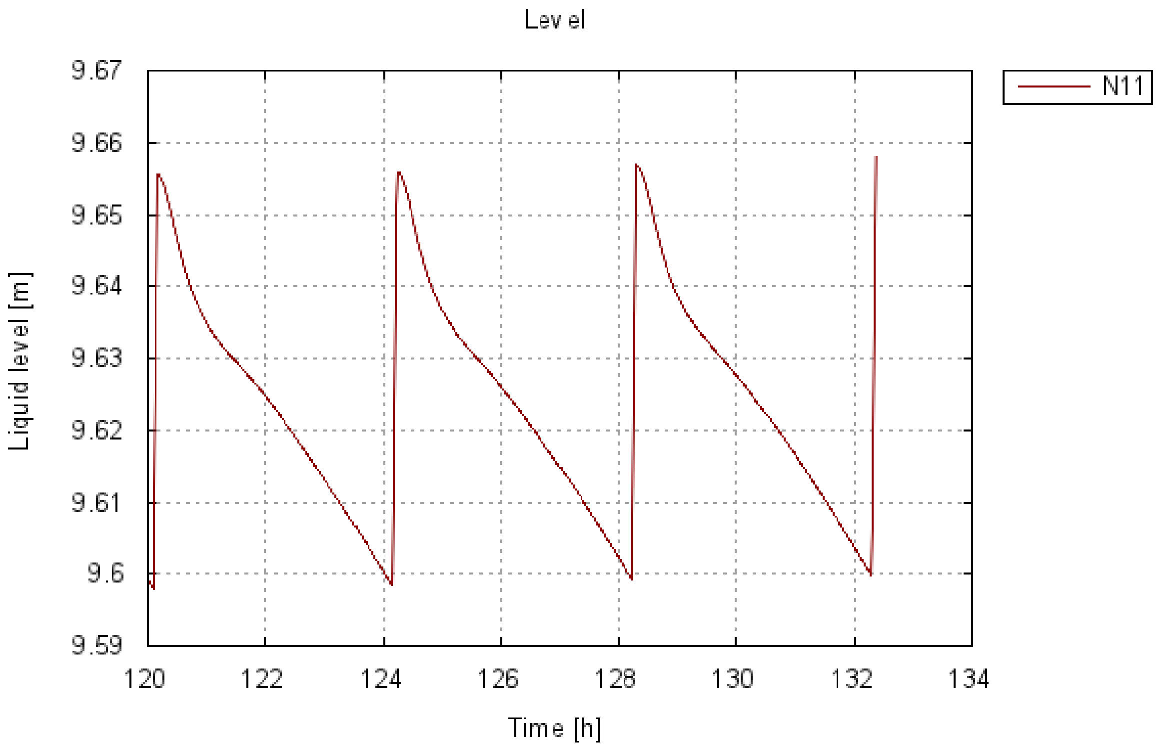

Figure 30. Pool liquid level during boiling and water injection.

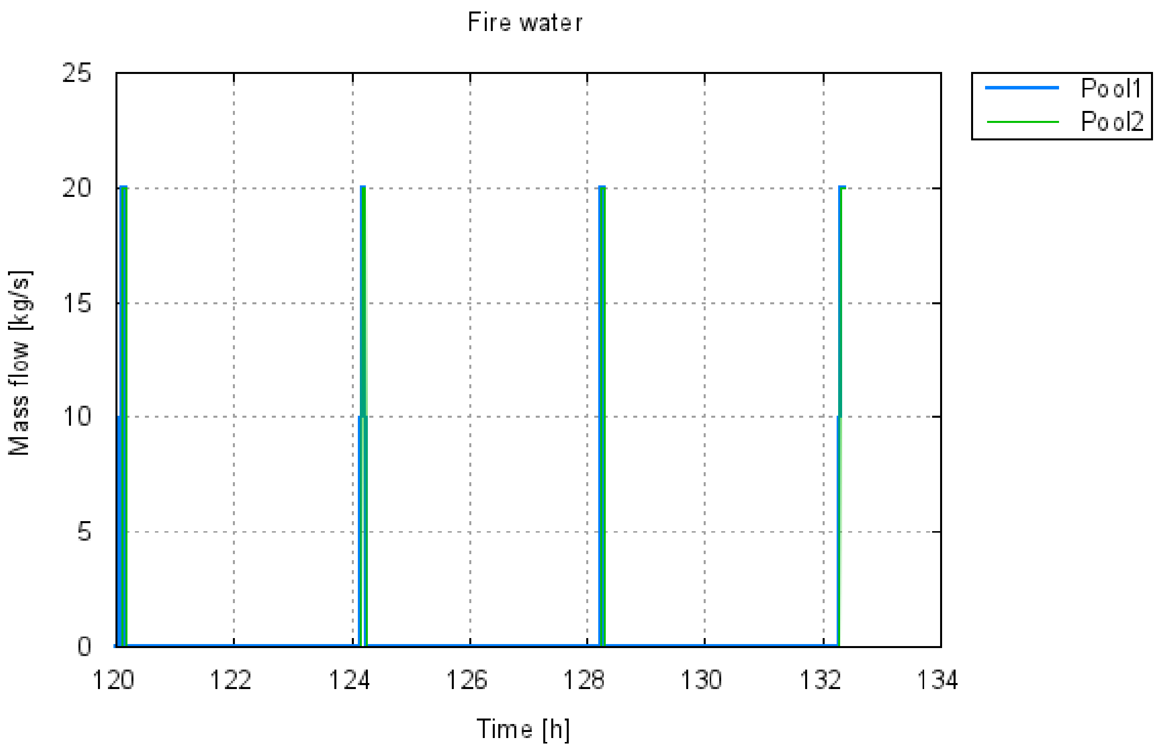

Figure 31. Fire water injection to the pools when cooling system is lost.

6 CONCLUSIONS AND FURTHER RESEARCH

Both wet and dry storages have their own challenges and advantages. Wet storage is more vulnerable to hazards and human errors, but it has benefits in fuel condition monitoring and suitability for fuels with different decay heating powers. Dry storage is based on passive cooling and needs only few operational activities, but has not been licensed in Finland before. Limited capacity for managing decay heat flux of fuel with high burnup can also be an issue in dry storage.

In case of FH1, the most suitable storage option seems to be a wet storage. The fuel burnup and the decay heat of the chosen fuel are relatively high. The limiting factor is the heat removal capacity of a dry cask, and none of current cask designs meet the requirement for decay heat removal capacity of the fuel planned to be used in FH1. Fuel should be cooled for quite a long time period in a pool, and the pool storage capacity in FH1 reactor building is limited, so it would be necessary to either build also a wet storage or fill up the dry casks only partly full. Neither of the options seems to be economically feasible. (Hautojärvi et al. 2016.)

FH1 spent fuel storage has two cooling redundancies, a cooling tower and a large water mass in pools. Uncovering and exposure of the fuel is therefore highly unlikely. The cooling tower that can be used as an ultimate heat sink also reduces the probability of boiling in case the sea water is lost. Boiling is very slow, and with multiple water injecting possibilities in the design the pool level can be maintained in an accurate level in boiling scenarios.

Operational experience shows, that many of the scenarios in which pool water level has decreased significantly are leaking events. Such events have occurred due to failures in gates or seals in pools. In the design of FH1 spent fuel storage there are not any penetrations below level +9.6 meters, which is over 7 meters above the top of the fuel. The only pipes which are located lower than that, are the cold water inlet pipes, which have an anti-siphon mechanism to prevent leaks through those pipes.

If the pool water level however decreases below the top of the fuel elements, the consequences depend on geometry and properties of the fuel. In the worst case scenario zirconium cladding could be ignited. Zirconium fire occurs most likely with fuel that has been recently removed from a reactor, when decay heat is high. Freshly moved fuel is usually stored temporarily (a few years) in at-reactor-pool, typically inside a containment. Environmental consequences in case of a zirconium fire, would be in this case less serious, as the containment prevents releases.

In case of FH1 away-from-reactor-pool, based on public sources referred in this thesis, the risk of zirconium fire seems to be very low due to cooling time of several years before the fuel is transferred to the interim spent fuel storage. However zirconium fire cannot be totally excluded without further research. Temperature in a loss-of-coolant scenario depends on energy produced by hydrogen generation and efficiency of convective air cooling between the fuel elements. Possibility of fire should be studied in case of the elements are totally exposed, and in case they are partially covered with water.

In accident conditions the energy produced by oxidation and hydrogen generation could multiply the heating power of the fuel in the spent fuel pool, and the temperatures could increase significantly. Further analyses would be needed to estimate the temperature rise in severe accidents.

The air circulation plays an important role in zirconium ignition. Air flow and heat removal depend on configuration of a fuel rack. Air circulation could be calculated using computational fluid dynamics model, which could give us information whether or not ignition temperature is reached. If the fuel racks were covered for example due to debris from collapsing building, air cooling could be disturbed, and temperatures might rise locally causing ignition.

In a case when upper parts of the fuel elements are partly exposed in air and lower parts are below water surface, cooling of the fuel is based on steam production of the lower part of fuel, as was earlier shown in Figure 6. In a case the water level is only slightly above the bottom of fuel elements, the amount of steam flow is very low. In contact with air the oxidation reaction rate is also bigger than in steam. The cooling can be adequate even in this case, but there is also a possibility that it is not, and the temperature for zirconium ignition is reached. In this case there also is no air circulation, if there are no horizontal flows between the elements. Horizontal air flows can be enhanced by drilling holes between the elements. Criticality shall however be considered in case the holes are drilled. (Alvares. 2003:17) The possibility of drilling holes to walls of fuel racks of FH1 should be investigated when designing the racks in more detail. Flows when horizontal flows are allowed and when they are not are presented in Figure 32.

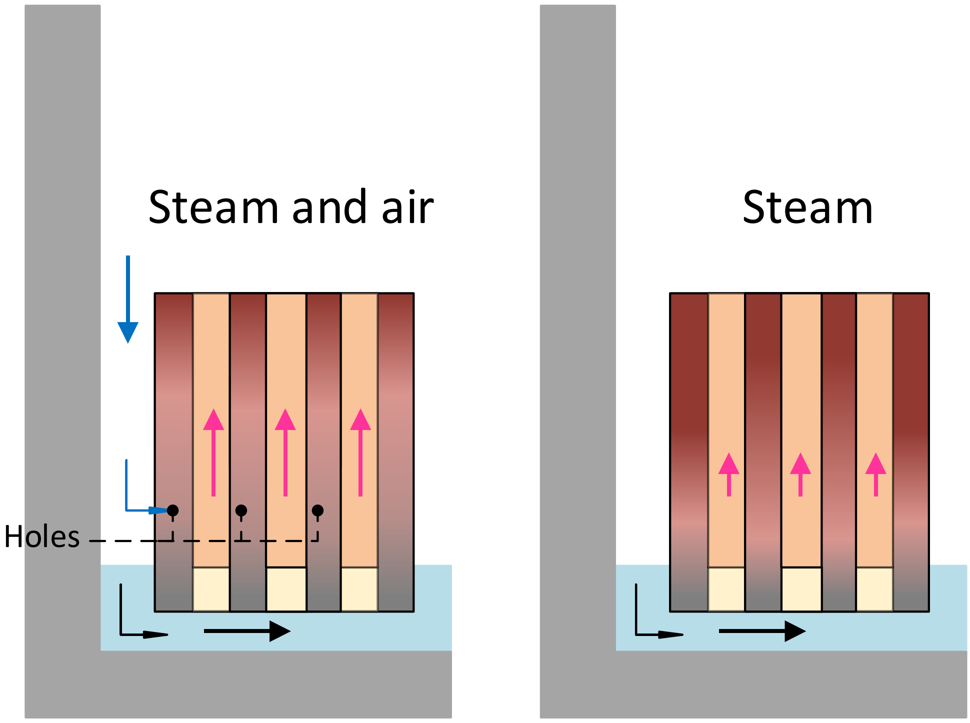

Figure 32. Cooling flows when there are holes between elements and when there is not, in case the fuel is partly uncovered.

One way to reduce the risk of a zirconium fire is to use low-density racks. Using dense racks with borated steel plates between the elements, enlarges pool capacity, but prevents air flow between the elements. In lower-density-racks the cooling of uncovered fuel is more effective.

Use of lower-density-racks reduces the storage capacity significantly, and economic feasibility should be studied carefully. According to designer calculations (Mayer. 2016) in case of FH1, the storage capacity would be reduced over 50 % from 804 to 396 assemblies per pool. From economic point of view some compensation to reduced storage capacity per pool could be gained in using lower-density-racks as the need for use of very expensive borated steel is reduced. (Hautojärvi et al. 2016.)

Risk of zirconium fire can be reduced also by mixing older and fresher fuel in spent fuel pools (=dispersed loading pattern). This is a recommended procedure of operating spent fuel pools in USA. In dense racks dispersed loading pattern will however be less effective than in low-density racks, as the horizontal flows between the fuel elements are usually prevented by solid neutron absorber plates (e.g. borated steel). In case of FH1 using a dispersed loading pattern should be considered.

According to previous incidents and operational experience human factors are in an important role when it comes to safety of spent fuel storages. Past experiences have shown that guidance to operators and following the guidance are important in preventing incidents. In many cases where pool water level decreased it was due to an open valve or other mistake made by the operator. Human factors were also involved in Bruce-A accident, where fuel was left in a tank, or chamber for a longer time than was intended.

Human factors are possibly in the future considered more in regulatory level. Draft of IAEA safety regulations for safety of interim storages (IAEA 2017) suggest that human interference in actions should be assessed whenever the safety of the storage depends on them, also in case of an accident. According to new safety guide draft feedback of operational experience should be implemented also into manuals, guidelines and training.

In case of FH1 spent fuel storage criticality accident is highly unlikely to occur. The fuel shall remain subcriticality even if the coolant is partially or totally lost. Maximum burnup of the fuel of FH1 is very high 60 MWd/kgU. Fuel however contains still approximately 1 % of U-235 (4 kg/bundle) and also approximately 3.6 kg Plutonium Pu-239 per bundle (Gren, Zák & Vočka 2016.) The fuel includes also fission products, of which some are effective neutron absorbers. This fuel could possibly obtain criticality in optimal configuration, but criticality is highly improbable. However, subcriticality margin for irradiated fuel has not been analyzed and, therefore, possibility of criticality cannot be categorically excluded. Water density should be significantly lower than 1 kg/m^3 and a reflector would be needed even in optimal configuration. (Lahtinen 2017.) Possibilities for deformation and thus configuration change of fuel in a case of a load dropping accident on top of the fuel rack and elements will be studied in later phase of the design process of FH1.

The analyses which have been performed for FH1 spent fuel pools show that the fuel is likely to remain covered with water during the initiating events discussed. Loss of cooling system leads to pool boiling in 4 days and fuel uncovering in 25 days when conservative values are used. In the analyses the air temperature (30 °C) as well as sea water temperature (25 °C) are conservatively high, and the pools contain their maximum capacity of spent fuel. This means that the pool temperature in the beginning is 45 °C, and the boiling occurs sooner than with colder and more likely values.

The vaporization from the boiling pool is ~0.3–0.4 kg/s. To remain the water level above the fuel elements approximately 5000 kg water shall be added to one pool every 4th hour. This amount of water can be added to the pool using demineralized water or fire water connections. A minimum capacity of a fire truck is 5 m^3, which means that one fire truck every 4th hour is enough to ensure fuel integrity (Kulmala, Silvennoinen, Seppälä & Särmä 2010).

The heat load in one pool is in analyses higher than the average decay heat of pools. In case the cooling was lost, the pool gates could be opened and the pools with highest decay heat could be cooled with water from other pools with lower decay heat. Also the gates to the evacuation pool and unloading pool, which normally do not contain fuel, could be opened. This would slow down temperature rise in the pools with highest decay heat.

According to the Apros analyses restoring the cooling system can be difficult if boiling is taking place in the fuel pools. Water temperatures in the cooling system shall be kept under boiling temperatures to prevent pressure transients in the heat exchangers. As an outcome of the Apros analyses, a connection to inject cold water to the equalization tank has been added to cooling system design. The restoring of the cooling system after boiling should be studied further and instructions for such case should be compiled.

The ventilation in the Apros model is simplified. The temperature rise in the pool building can however be approximated based on Apros model. The conditions in the pool room are likely to be the most dependent on the pool water temperatures. Temperatures in modelled pool room during the analysis cases are described in Appendix 3. In the model the building consists of only one room, which means that the conditions in the other rooms of pool and process buildings cannot be studied with this model. In case the working conditions in the process building during pool boiling wanted to be studied, this could be done with more specific Apros model. The pressurizing of the building cannot be very accurately predicted with the model, but the building contains a steam release pipe, that will withstand even an earthquake and therefore the pressurizing is impossible. Pressurizing of the building can however be tested when the storage is built. This would give information about conditions in buildings during accident scenarios.

7 SUMMARY

This master's thesis was done for Fortum Power and Heat ltd as a part of design project of interim spent fuel storage of Hanhikivi 1 nuclear power plant (FH1) that is planned to be constructed in Finland. In this thesis overall safety and accident scenarios in spent nuclear fuel storage concepts were considered both in generally and in the point of view of FH1.

There are two main types on interim spent fuel storages: a dry and a wet storage. Both types have their advantages and weaknesses. In Finland there are currently only wet storages, and therefore current licensing procedures and requirements are strongly oriented towards a wet storage.

In case of FH1 spent fuel storage, the most suitable option is a wet storage, mainly because of the high burnup and enrichment of the fuel. Taking into account the available cooling time in FH1 power plant, current cask designs are not able to efficiently cope with the decay heat of fuel of FH1. An additional wet storage capacity besides the in-containment fuel pool would be required to enable sufficient cooling time in pool before transferring the fuel into current cask designs.

Initiating events and hazards that could have an effect on safety of spent fuel storages, especially a wet storage, were identified. The most vital threats in wet storages are those that can lead to loss of coolant in spent fuel storage pools. Loss of cooling system due to a loss of power, fire in storage or other hazards studied in this thesis, will not lead to exposure of the fuel immediately. During several days or weeks they can result a loss of coolant due to boiling, if the cooling system is not restored.

Operational experience shows that many of the scenarios in which pool water level has decreased significantly are leaking events. These events have occurred due to failures in gates or seals in pools. In the design of FH1 spent fuel storage there are not any penetrations below level + 9.6 meters, which is over 7 meters above the top of the fuel. The only connections which are located lower than that, are the cold water inlet pipes, which are placed inside the pool and have an anti-siphon mechanism to prevent leaks through those pipes. The pools are designed to withstand an earthquake and an airplane crash, so major leaks due to failure of the pool structures are practically impossible.

In case the water however is lost, fuel elements are possibly damaged without sufficient cooling. Severe accident in spent fuel storage can lead to radioactive releases to environment, especially when the fuel pool is not located inside a containment. As the temperature of the fuel elements rise, the internal pressure of the elements may cause rupture of the cladding and lead to releases. Oxidation reaction of the zirconium cladding also accelerates as the temperature rises, causing damage to the elements, but also generation of hydrogen in the pools. Increase of hydrogen concertation in the room may cause explosion. Oxidation reaction is exothermal and generated heat increases temperature in the pool.

In case the fuel is recently removed from reactor and the burnup is high, the temperature of the dry uncovered fuel in a pool in an accident situation can reach the ignition temperature of zirconium cladding. Zirconium fire can lead to significant fuel damages and release of radioactive particles and gases to environment. Reaching the ignition temperature is not likely when the decay heat of the fuel is low. Besides the fuel properties and oxidation rate the temperature depends on storage configuration. Using dense storage racks increases the risk. In principle, it is possible to enable horizontal flows between individual fuel elements even in dense racks, and this should be explored in more detail as cross-bundle flows seem to promise significant improvement of fuel coolability in cases where pool water level is within the fuel bundles.

Analyses performed for FH1 spent fuel storage using Apros simulation tool show that the fuel integrity can be maintained during accident conditions. Conservative assumptions were used for initial and boundary conditions. In case the cooling is lost, boiling will occur after 4 days. Analyses show that in the first 72 hours no actions, except for loading the batteries of emergency lighting and measurements, are needed to maintain the fuel integrity and after that time the cooling system can be normally restored. Restoring the cooling system after the boiling state is reached requires additional water injection to pool and/or the equalization tank.

Apros analyses show that even with conservatively high decay heat in the pool, the water level could be maintained above the fuel elements with 0.3-0.4 kg/s water injection to the pool. This can be done for example by adding circa 5 m^3 water every 4th hour through fire-water or demineralized water connections. In case no actions are done, the top of the fuel racks is uncovered in approximately 25 days.

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APPENDICES

APPENDIX 1: Analysis requirements

Table 1. YVL B.1 requirements used in thermal hydraulic analyses and their elaboration for calculated cases. (YVL B.1 2013)

Requirement	Requirement text	Elaboration
B.1 453	In the event that the reactor is not directly brought to a safe state as a result of an anticipated operational occurrence, a postulated accident or a design extension condition, it shall be possible to maintain the reactor in a controlled state long enough to ensure that the systems required for achieving a safe state are operable. Provisions shall be made to enable the repair and service of the systems needed for cooling the reactor from a controlled state to a safe state.	If reaching the safe state can't be proved, the analyses shall prove that the storage can be kept in controlled stage for long enough.
B.1 456	The following systems performing functions relevant to safety shall satisfy the (N+1) failure criterion: -Systems designed to ensure the cooling of spent fuel	Only N+1 failures are taken into account. N+2 failure criterion is not required, so these failures are not analysed either.
B.1 448, 451, 452	448. In the event of anticipated operational occurrences or postulated accidents, it shall be possible to accomplish decay heat removal from the reactor and containment by one or several systems that jointly meet the (N+2) failure criterion and the 72-hour self-sufficiency criterion in such a way that the limits set forth for fuel integrity, radiological consequences and overpressure protection in the respective design basis category DBC2, DBC3 or DBC4 are not exceeded. If the decay heat removal systems or their auxiliary systems have passive components that have a very low probability of failure in connection with the anticipated operational occurrence or postulated accident, the (N+1) failure criterion may be applied to those components instead of the (N+2) failure criterion. 451. For a loss of the on-site power distribution system, provisions shall be made for decay heat removal to outside the containment and control of reactivity by ensuring that the systems required for this purpose operate without any external power source or operate on an independent power source; and that a sufficient inventory of water and fuel and capability to recharge the DC batteries exist at the plant site to maintain these arrangements for a period of 72 hours. The single failure criterion does not need to be applied to the systems necessary for such arrangements, and	72-hour-self-sufficiency criterion is used for UFC. Analyses shall prove that the fuel integrity can be secured 72 hours without any operational actions or systems, that are not safety classified.

Requirement	Requirement text	Elaboration
	the related containment isolation valves including actuators and cabling and the pipelines between the reactor and steam generators may be shared with a system intended for a different use. Direct current (DC) systems are deemed to be serviceable when properly electrically isolated. Such a situation is governed by the design basis category DEC's fuel failure criteria and dose limits. No assumption needs to be made in the course of design for this type of situation arising concurrently with an independent initiating event, rare external event (DEC) or other multiple failure event (DEC B). 452. The nuclear power plant shall have in place arrangements that can guarantee sufficient cooling for the fuel placed in fuel storage facilities during rare external events in accordance with requirement 450. These arrangements shall make it possible to supervise the water level in the spent fuel pools for a minimum of eight hours without recharging the DC batteries. Furthermore, it shall be possible to keep the fuel reliably submerged during the loss of the plant's internal electricity distribution system in accordance with requirement 451. A sufficient inventory of water and fuel and capability to recharge the DC batteries shall exist at the plant site to maintain these arrangements for a period of 72 hours.	

Table 2. YVL B.3 requirements used in thermal hydraulic analyses and their elaboration for calculated cases. (YVL B.3 2013.)

Requirement	Requirement text	Elaboration
B.3 402.	Anticipated operational occurrences and accidents shall be analysed starting from the initiating event and ending in a safe state.	Analyses shall be started from normal operation condition, and analysed until can be shown that safe state will be reached. If reaching the safe state can't be proved, the analyses shall prove that the storage can be kept in controlled stage for long enough (YVL B.1 §453)
B.3 408, 409.	408. The accepted methods to be used in the plant behaviour analyses are either the conservative analysis method supplemented with sensitivity studies or the best estimate method supplemented with uncertainty analysis.	Conservative method shall be used for thermal hydraulic safety analyses.

	409. Sensitivity studies supplementing conservative analyses shall define how sensitive the results are for the models used, the initial conditions and the main paraeters.	Sensitivity studies are not produced at this point of design process. No parameters that could have such significant effect on analyses results, that the acceptance criteria could not be covered have been identified.
B.3 411.	The initial conditions of the conservative analyses and the conservativeness of the paraeters chosen shall be justified. If the choice that is the least beneficial in terms of the acceptability of the end result is not unambiguous, analysis results covering the paraeter's entire range of variation shall be presented.	Initial conditions and conservativeness of the chosen parameters shall be discussed.
B.3 413.	The selected consideration time preceding operator actions and the time to accomplish the actions shall be sufficiently long. The durations chosen shall be justified. Operators can be assumed to act on each analysed event in accordance with the procedures available in written or electronic form.	Suitable time delays are used in analyses. Analyses shall prove that controlled state can be maintained 72 hours without any actions.
Assumptions for anticipated operational occurrence analysis		
B.3 414.	Anticipated operational occurrences shall be analysed in two ways as follows: 1. All plant systems operate according to design, with the exception of the failure or operator error analysed as the initiating event and the consequences of the initiating event. 2a Actuation of non-safety classified systems shall not be postulated as systems mitigating the consequences of the initiating event. Operation of non-safety classified systems shall be postulated if a system's designed operation could aggravate the consequences of the initiating event. 2b The most penalising failure in accordance with the failure criteria given in chapter 4.3 of Guide YVL B.1 shall be postulated in safety class 2 or safety class 3 systems designed for anticipated operational occurrences or postulated accidents. 3c Performance values for functioning components shall be chosen conforming to the acceptance limits in periodic tests.	Anticipated operational occurrences are analysed with way 1. Way 2 is in DBC 2 events (case 2:TOWER) covered with cases belonging to higher design basis categories, as was described in Table 8.
Assumptions for postulated accident analysis		
B.3 415.	Safety-classified systems shall be assumed to operate at their minimum system performance during postulated accidents.	Due to early design phase, some main parameters are not defined. Thus all systems are assumed to be operating at their minimum

		performance in all analysis cases.
B.3 416.	Actuation of non-safety classified systems shall not be postulated as systems mitigating the consequences of the accident. Actuation of non-safety classified systems shall be postulated if a system's designed operation could aggravate the consequences of the initiating event.	Analyses shall prove that the fuel integrity can be secured 72 hours without any operational actions or non-safety classified systems. There has not been identified any spurious actuations that could have an effect on safety.
B.3 417.	In analyses of category 2 postulated accidents, only safety class 2 systems may be assumed to be systems mitigating the accident from the initiating event to the controlled state. Operation of systems in lower safety classes shall be postulated if a system's designed operation could aggravate the consequences of the initiating event.	Analyses shall prove that the fuel integrity can be secured 72 hours without any operational actions or non-safety classified systems. Functions in safety class 3 are assumed to be functioning normally, except for assumed failures.
B.3 418.	Loss of the external grid shall be combined with postulated accidents if it could aggravate the consequences of the initiating event.	DBC 4 events combined with loss of external grid, are covered with analysis cases in other event categories, as was described in Table 8.
Assumptions for design extension condition analyses		
B.3 419.	For DEC A accidents, the most penalising single failure shall be assumed in one of the systems whose operation is required to accomplish a safety function in the event in question. For DEC B and C accidents, a single failure need not be assumed. The consequences of an initiating event shall be assumed in the analyses.	DEC A events combined with single failures are covered with analysis cases belonging to other design basis categories, as was described in Table 8.
B.3 420.	Loss of the external grid need not be combined with other initiating events in design extension condition analyses unless it is the likely consequence of an initiating event.	Loss of external grid is combined in analysis cases where it is likely consequence.
B.3 421.	In design extension condition analyses, best estimate methods can be applied concerning assumptions of the plant's initial state and the performance of operating subsystems.	In preliminary analyses, all cases are calculated with conservative assumptions.

APPENDIX 2: Functions of UFC

Safety functions of each task category used or planned to be used in each analysis case. Some functions are not used in events that are calculated using Apros. (Rein 2016; Tynys 2017b. Modified.)

SF ID	Description	Case 1: 1RED	Case 2: TOWER	Case 3: FAIL72 h	Case 4: FAIL5d	Case 5: FIRE-WATER
NPC$_{UFC}$						
BA2_41P	Siphon prevention	x		x	x	
BA2_42M	Pool auxiliary water	x	x	x	x	
BC2_41	Liner leakage control	x		x	x	
BC2_42M	Pool separation in initiating events	x		x	x	
CB2_41	Building isolation			x	x	
CB2_42	Fire dampers	x		x	x	
XA2_41M	Battery re-charging					x
XC2_41	Pool level monitoring			x	x	
XC2_42	Pool temperature monitoring			x	x	
PREV$_{UFC}$						
BA3A_31M	Pool water from fire water connection					
BB3A_31M	Pool cooling	x	x	x	x	x
BB3A_32P	Boiling			x	x	x
BB3A_33P	Pool water content, heat accumulation	x		x	x	x
CA3A_31M	Vapour discharge			x	x	x
XA3A_31	Internal power supply	x	x	x	x	
XA3A_32	Battery power supply				x	
XB3A_31	Process room cooling	x	x	x	x	
XB3A_32	Sea water pump room cooling	x	x	x	x	
XB3A_33	I&C room cooling	x	x	x	x	
XB3A_34	Switchgear room cooling	x	x	x	x	
XB3A_35	Control room ventilation	x	x	x	x	
XC3A_31	Pool level monitoring	x	x	x	x	x
XC3A_32	Pool temperature monitoring	x	x	x	x	x
XC3A_33	Radiation monitoring	x	x	x	x	x
MAMBU$_{UFC}$						
BA3a_31M	Pool water from fire water connection	x		x	x	x
BB3a_31M	Pool cooling	x		x	x	
XA3a_31	Internal power supply	x		x	x	
XA3a_32	Battery power supply				x	x
XB3a_31	Process room cooling	x	x	x	x	

XB3a_32	Sea water pump room cooling	x		x	x	
XB3a_33	I&C room cooling	x	x	x	x	
XB3a_34	Switchgear room cooling	x	x	x	x	
XB3a_35	Control room ventilation	x	x	x	x	
XC3a_31	Pool level monitoring	x	x	x	x	x
XC3a_32	Pool temperature monitoring	x	x	x	x	x
XC3a_33	Radiation monitoring		x	x	x	x
MAM$_{UFC}$						
BA3b_41M	Pool auxiliary water		x	x	x	x
BB3b_41M	Cooling tower		x	x	x	
XA3b_41M	Battery re-charging				x	
XC3b_41	Pool level monitoring		x	x	x	x
XC3b_42	Pool temperature monitoring		x	x	x	x

The functions are divided into four task categories, that divide the functions to DiD-levels. These categories are NPC$_{UFC}$ (Fuel Pool Normal Process Control), PREV$_{UFC}$ (Fuel Pool Prevention), MAMBU$_{UFC}$ (Fuel Pool Manual Accident Management Back-Up) and MAM$_{UFC}$ (Fuel Pool Manual Accident Management). The first two (NPC$_{UFC}$ and PREV$_{UFC}$) are short term accident management categories and the other two (MAMBU$_{UFC}$ and MAM$_{UFC}$) are long term accident management categories.

APPENDIX 3: Analysis results

CASE 1: RED1

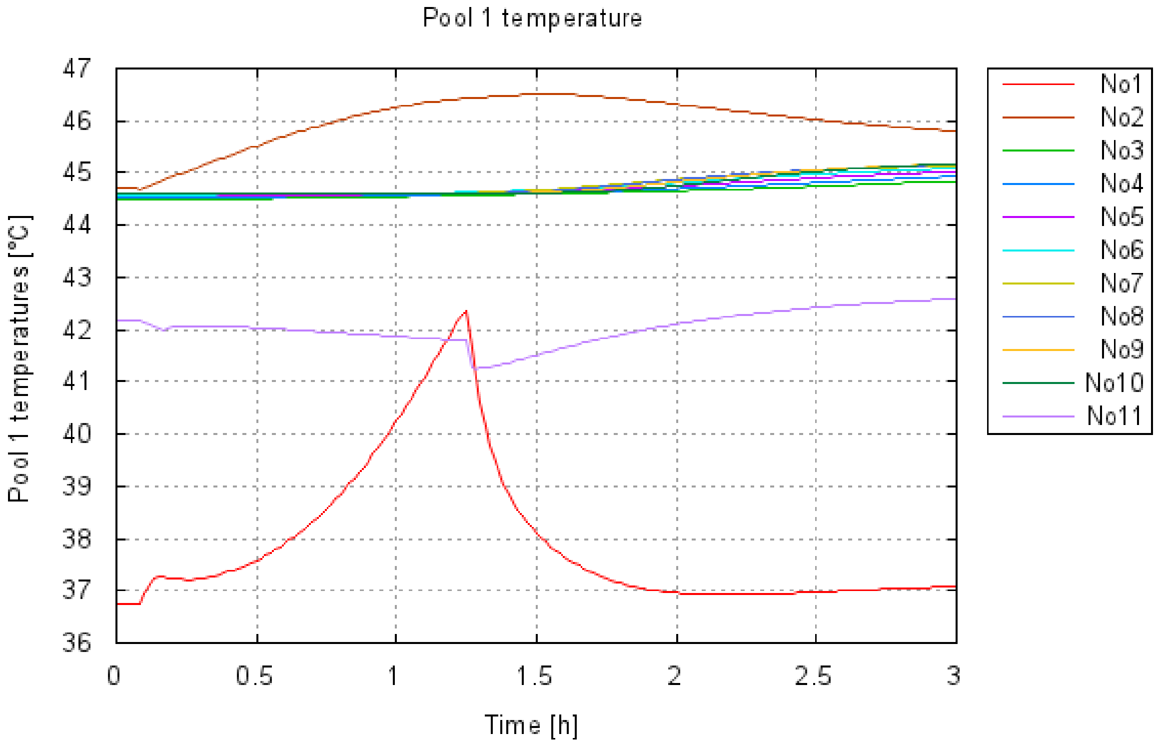

Figure 1. Temperatures in pool 1. Temperature profile in pool 2 is similar. Node 11 is the uppermost, and 1 the lowest in the right side of the pool. The cold water inlet to pool is connected to node No1, which is also significantly smaller than the other nodes.

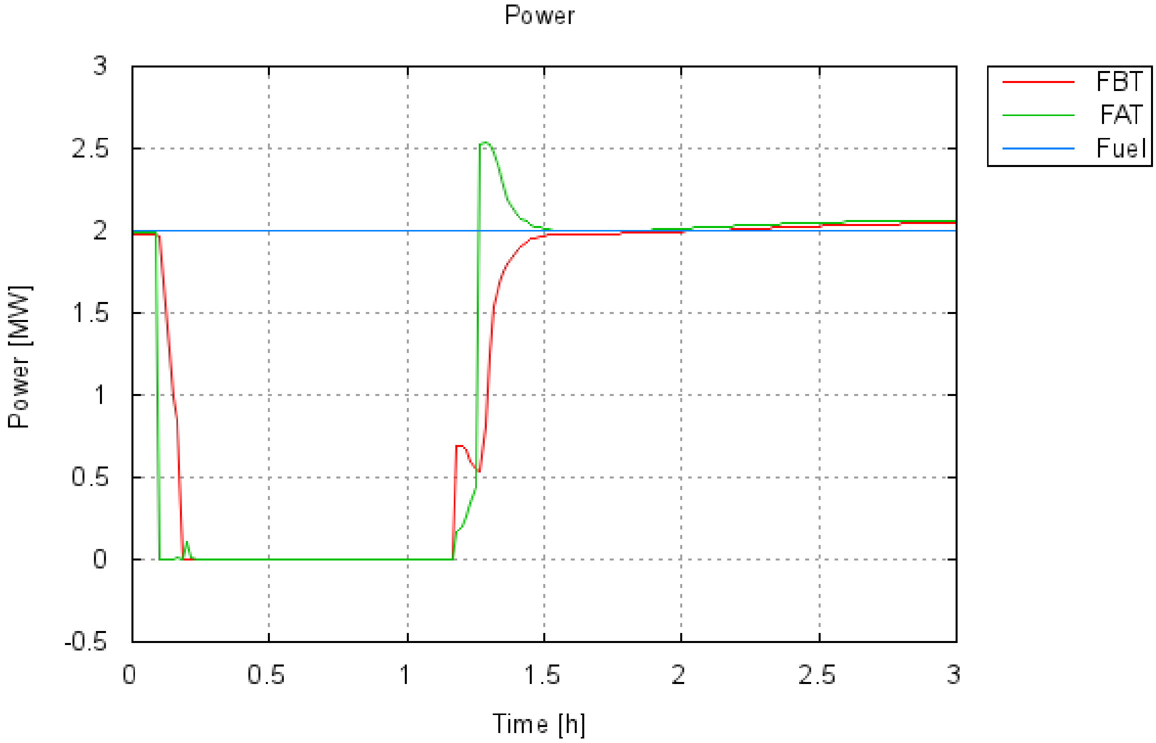

Figure 2. Decay heat of fuel elements in pools and power removed in heat exchangers. FAT is the heat exchanger between pool circuit and intermediate circuit, and FTB between intermediate circuit and sea water circuit.

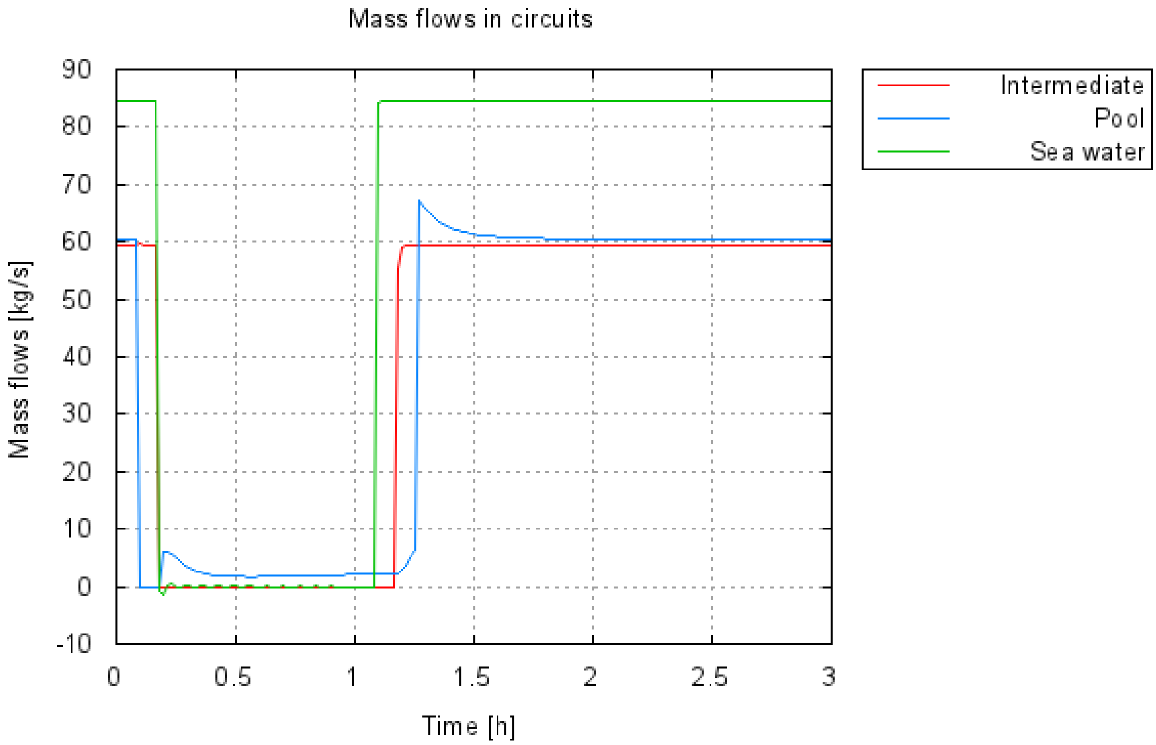

Figure 3. Mass flows in different circuits

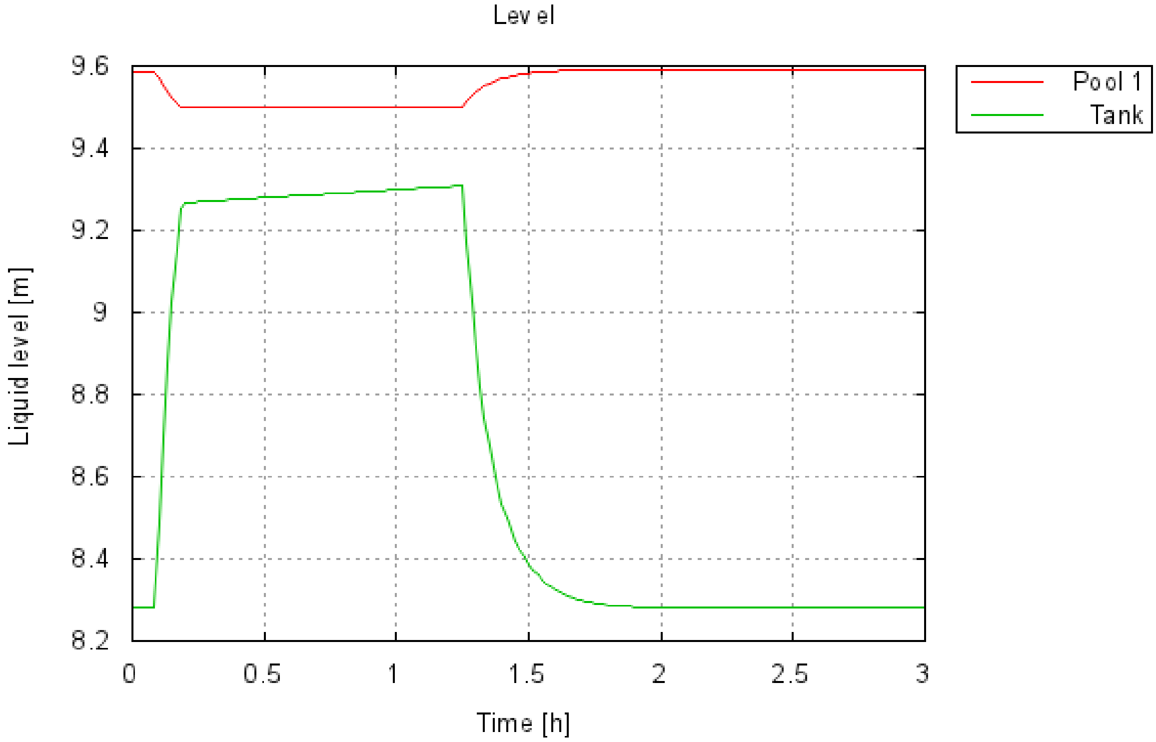

Figure 4. Liquid levels in pool 1 (similar in pool 2) and equalization tank of pool circuit.

CASE 2: TOWER

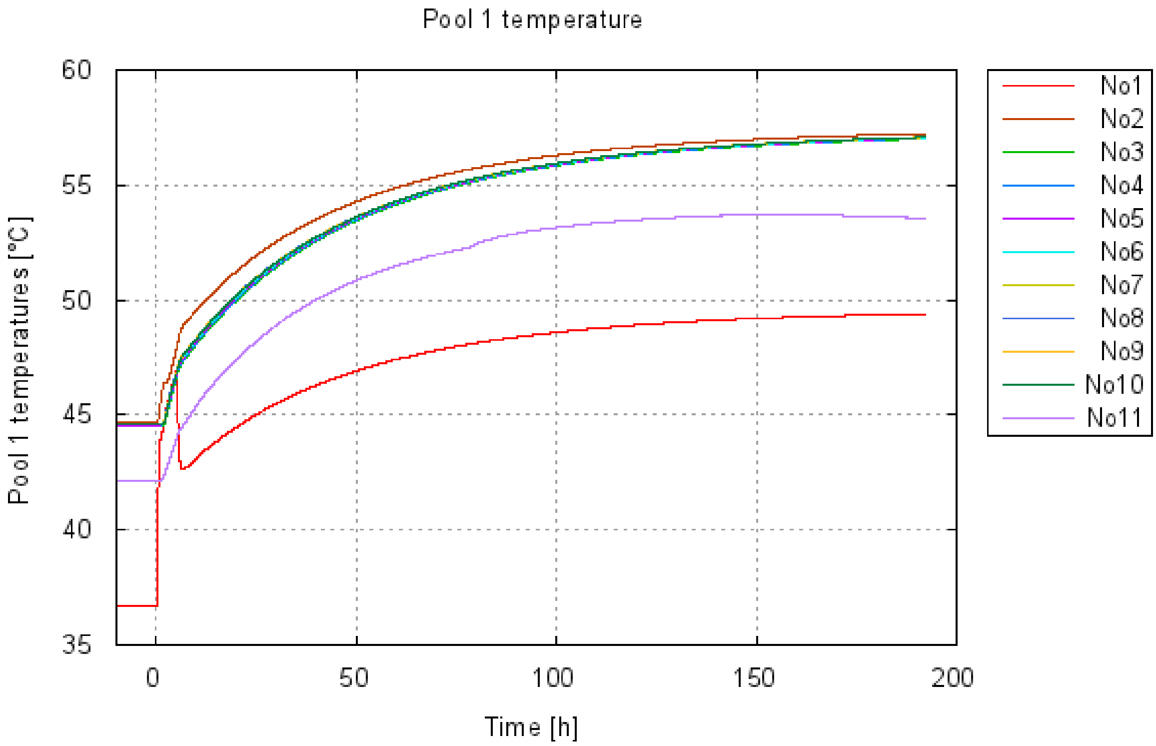

Figure 5.Temperatures in pool 1 during analysis case 2.

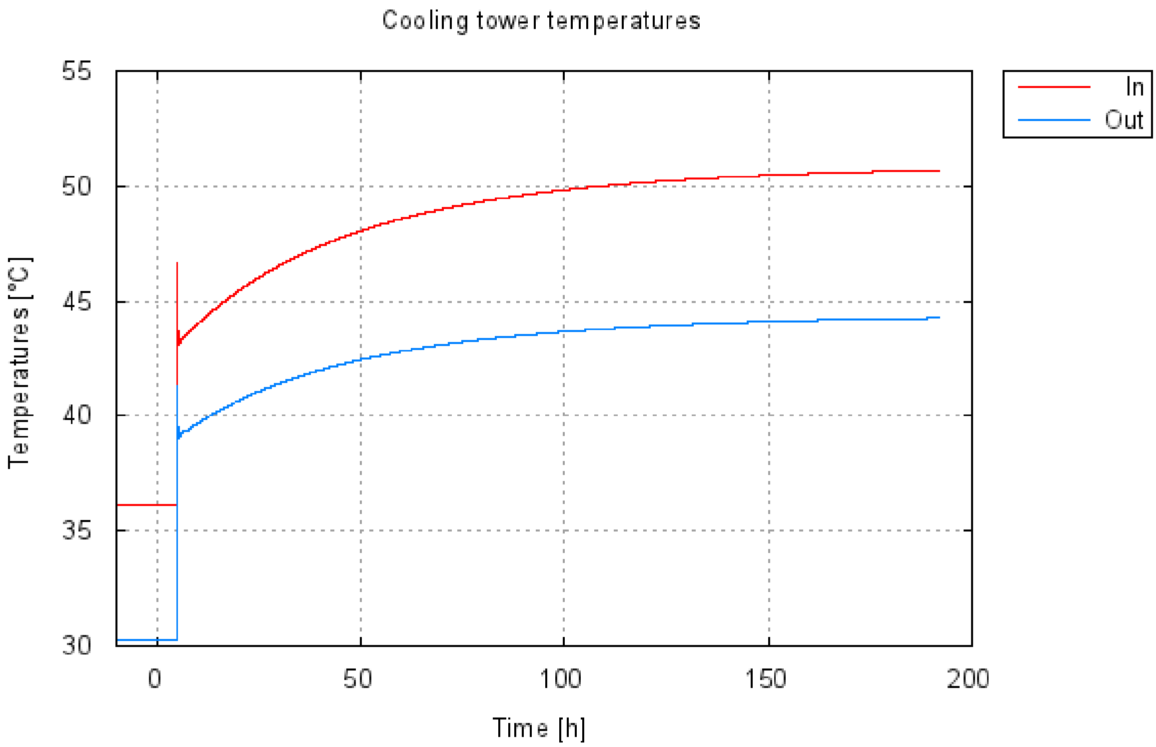

Figure 6. Temperatures in the cooling tower inlet and outlet connections.

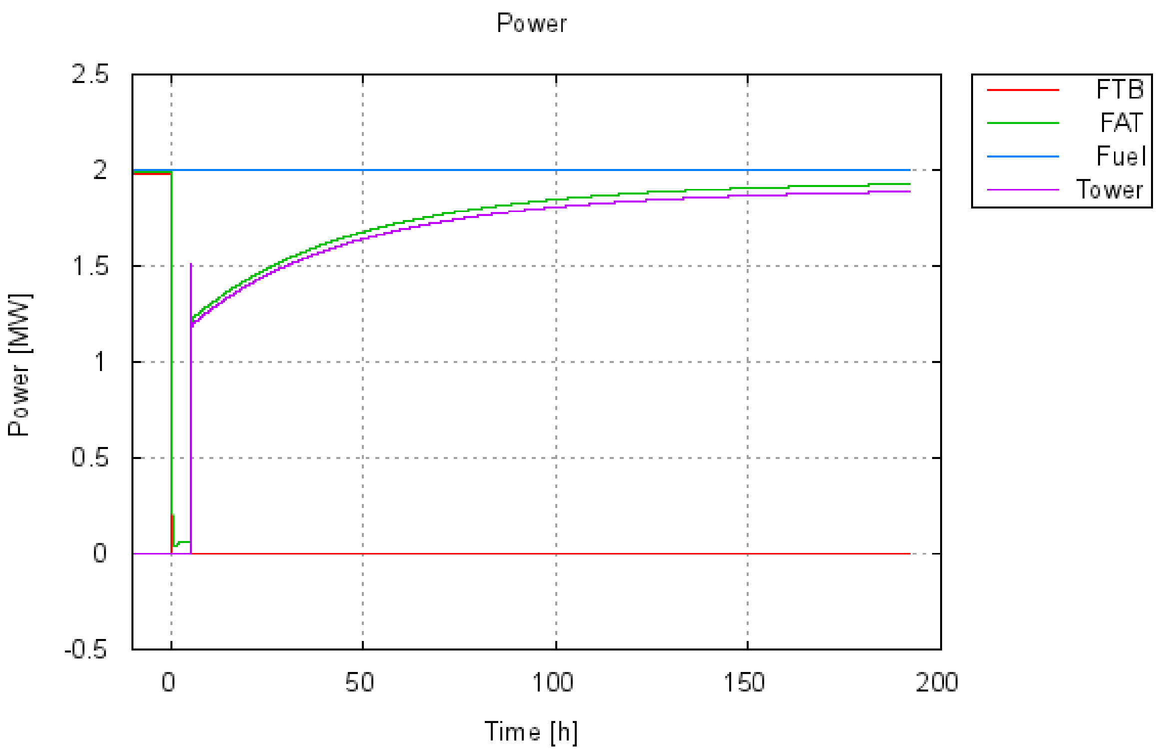

Figure 7. Heating power of fuel elements and removed heat in tower and heat exchangers during the whole analysis time. FAT is the heat exchanger between pool circuit and intermediate circuit, and FTB between intermediate circuit and sea water circuit.

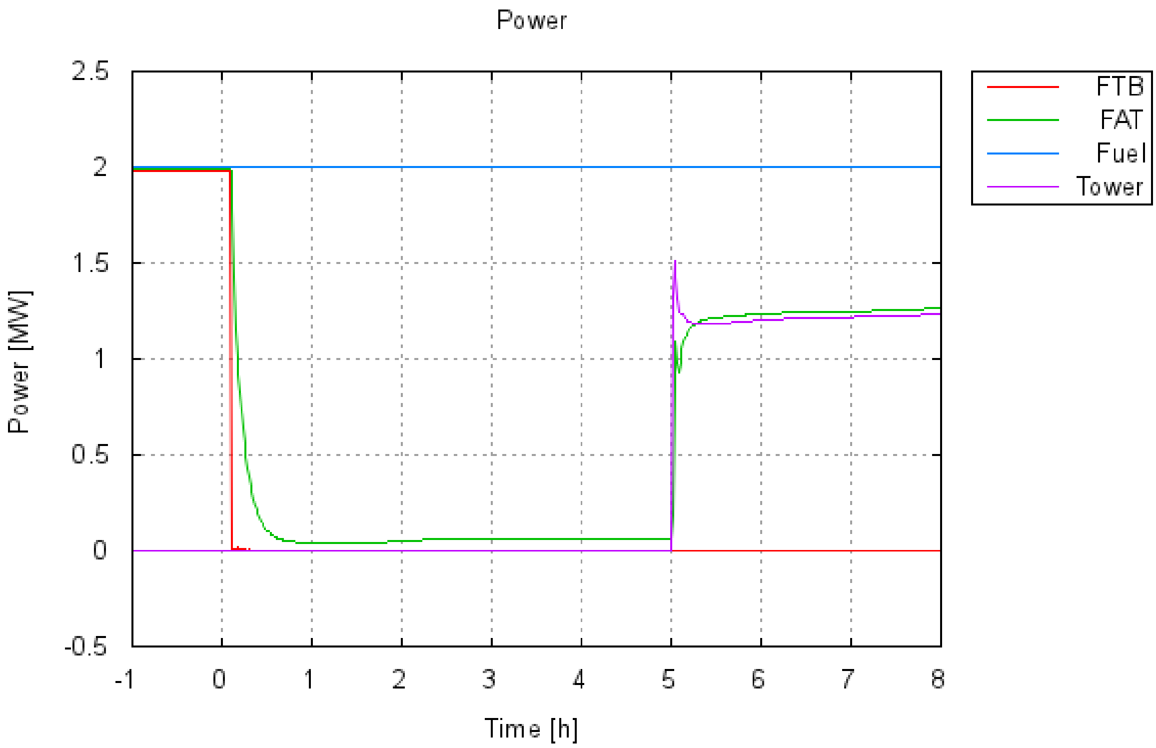

Figure 8 Heating power of fuel elements and removed heat in tower and heat exchangers during the beginning of analysis. FAT is the heat exchanger between pool circuit and intermediate circuit, and FTB between intermediate circuit and sea water circuit.

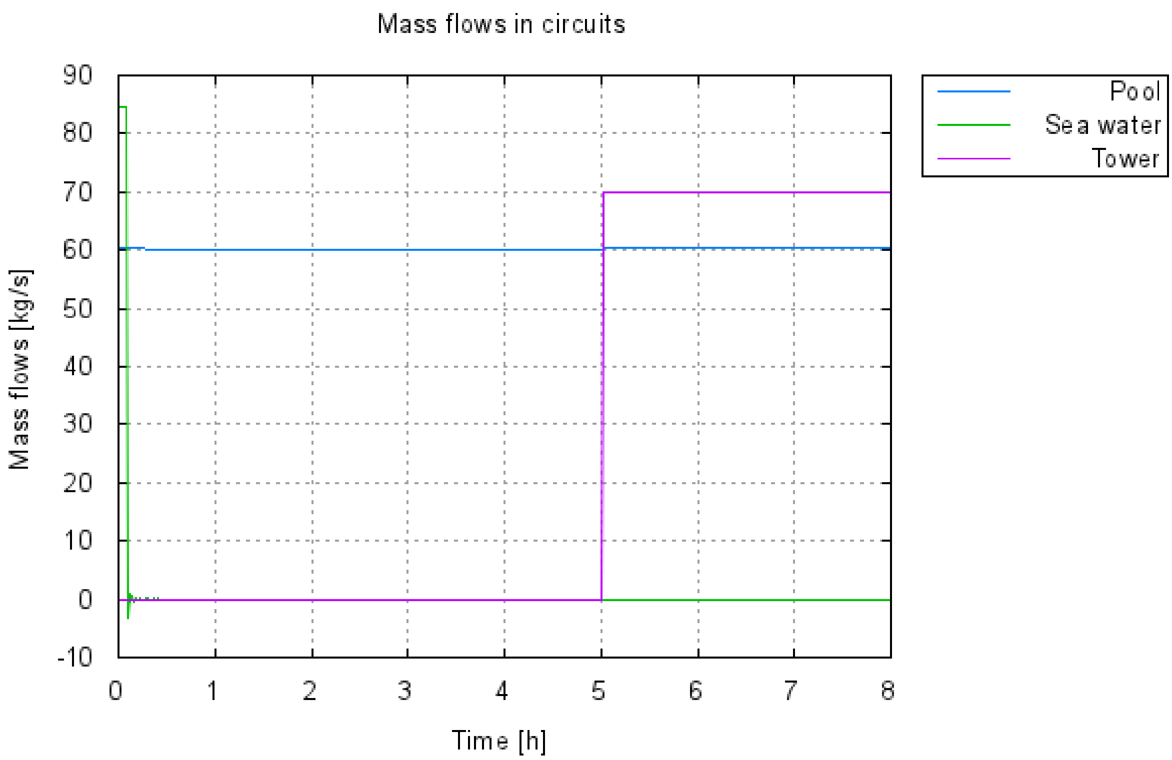

Figure 9. Mass flows in circuits during the first hours of simulation.

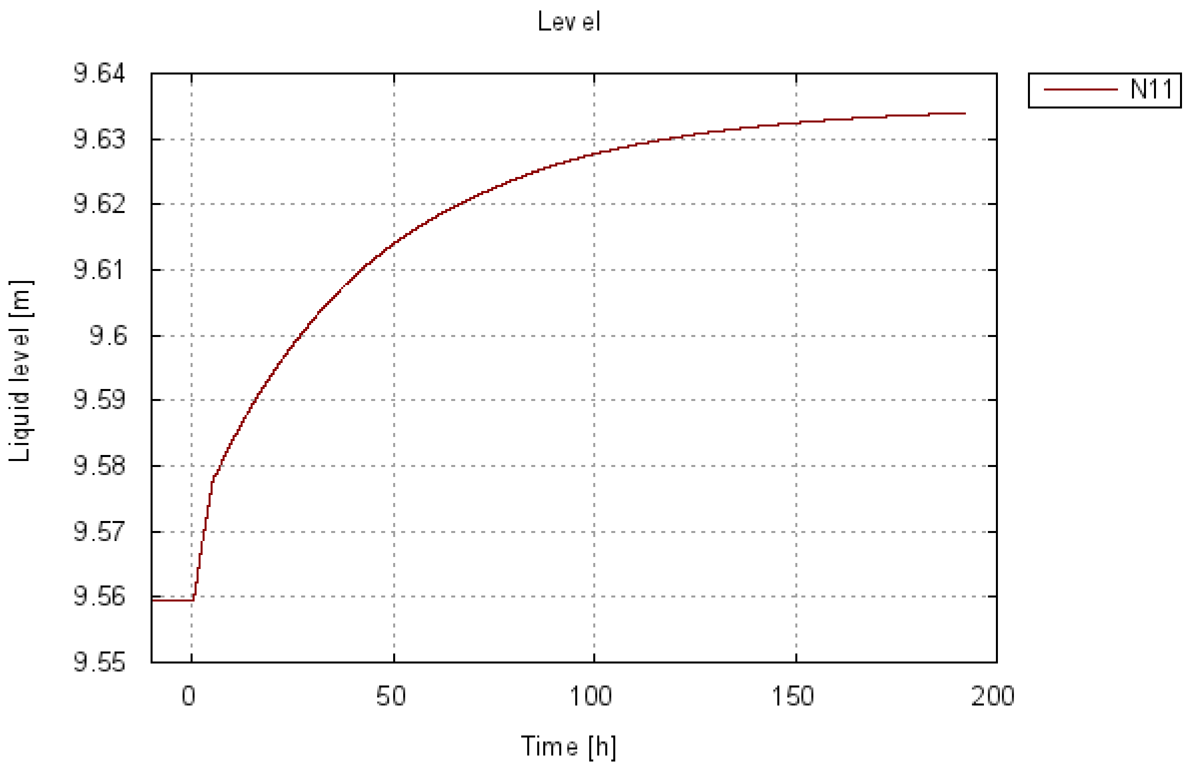

Figure 10. Pool 1 liquid level in analysis case 2. Level in pool 2 is similar.

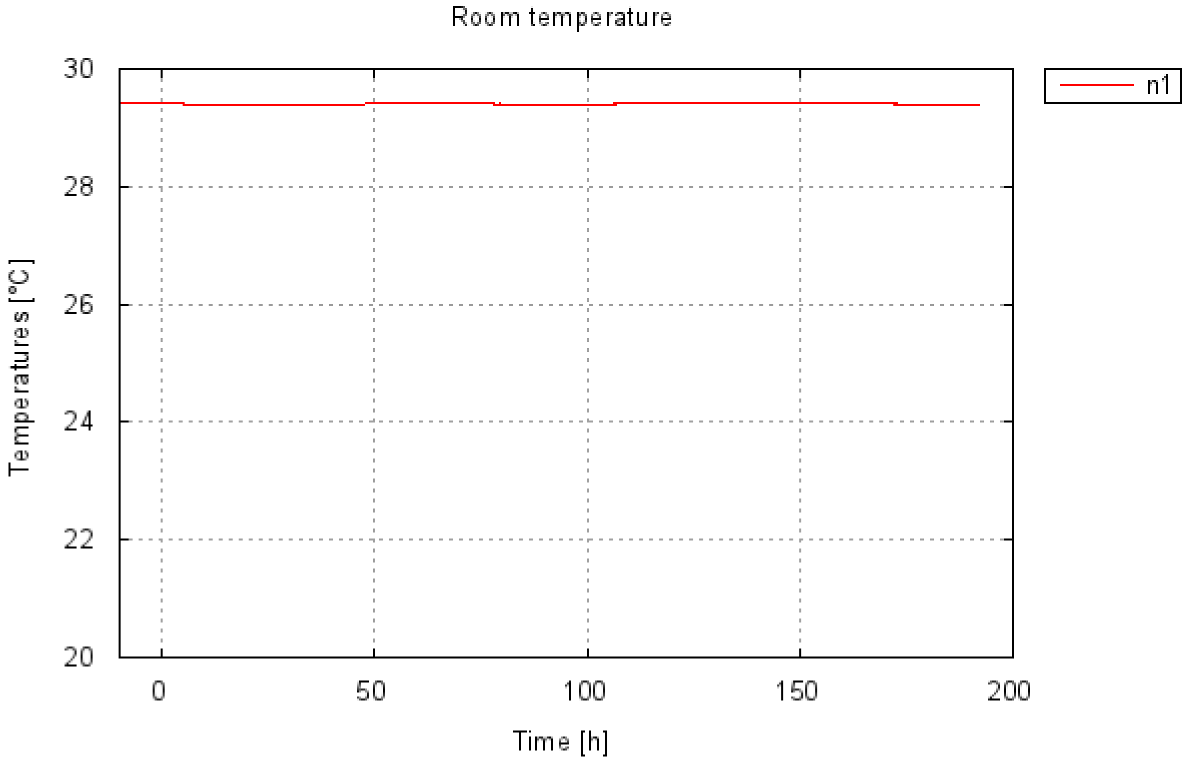

Figure 11. Temperature in pool room node n1 above pool 1 during analysis case 2.

CASE 3: FAIL72H

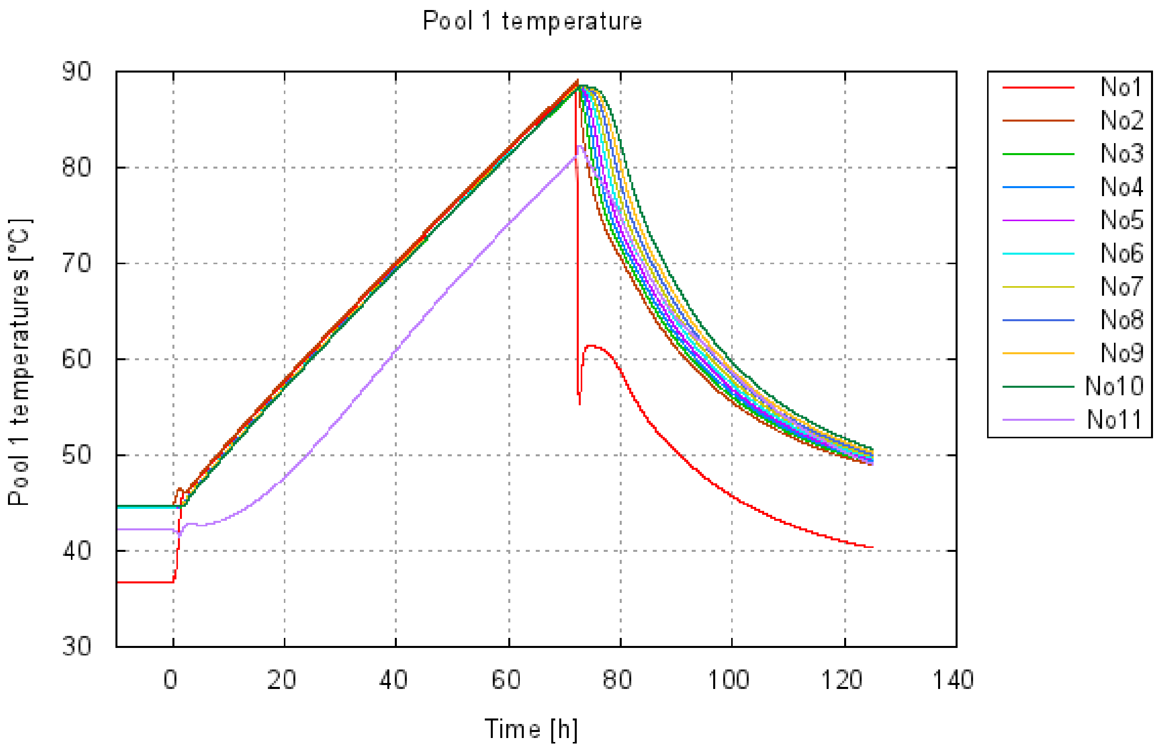

Figure 12. Temperatures in pool 1, pool 2 temperatures are similar.

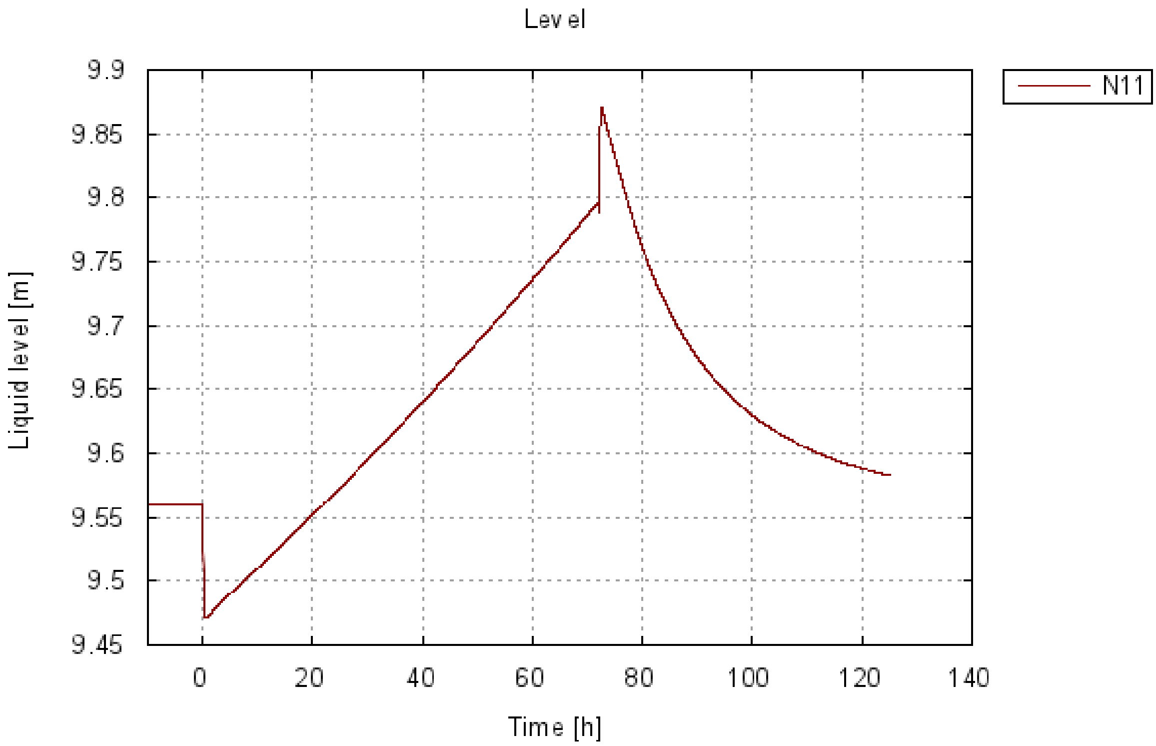

Figure 13. Pool liquid level

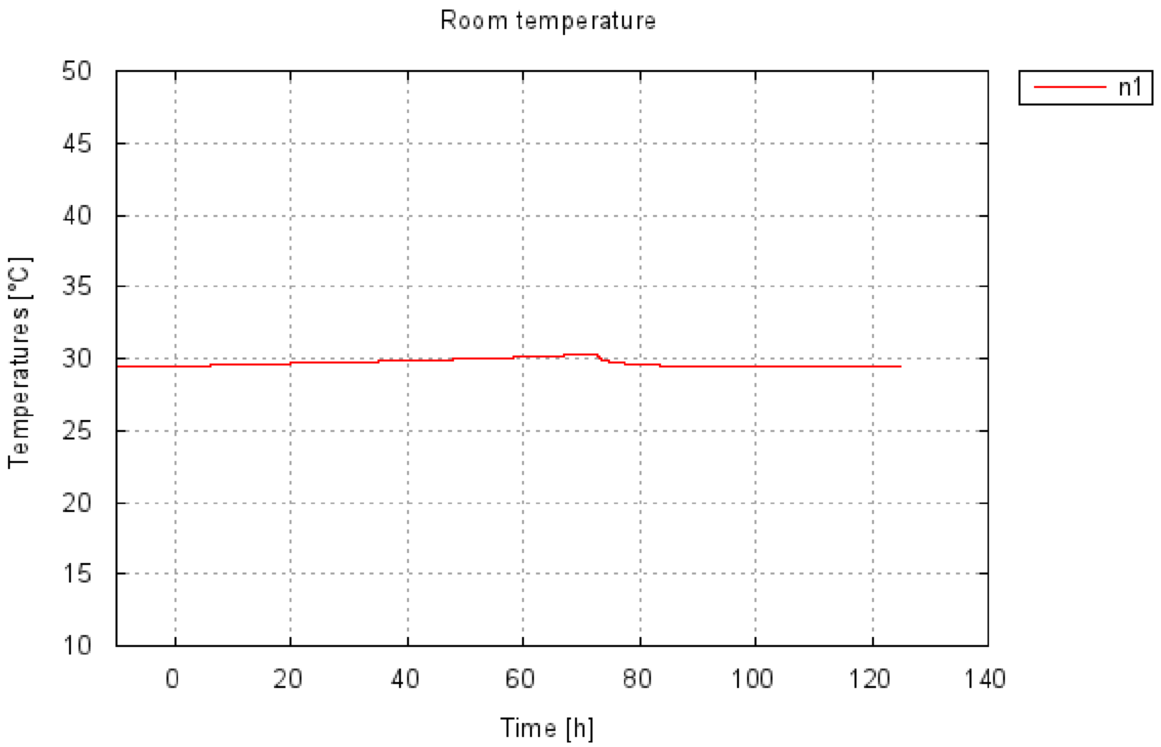

Figure 14. Temperature in pool room.

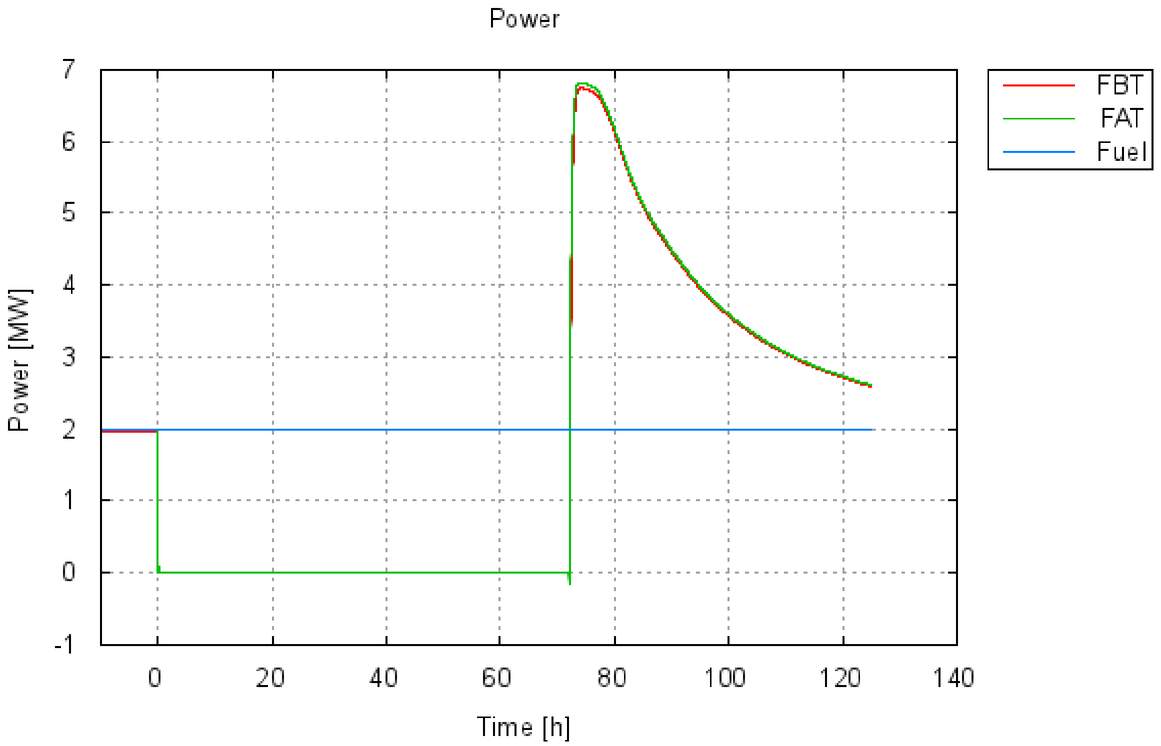

Figure 15. Heating power of fuel elements in one pool and removed power in heat exchangers. FAT is the heat exchanger between pool circuit and intermediate circuit, and FTB between intermediate circuit and sea water circuit.

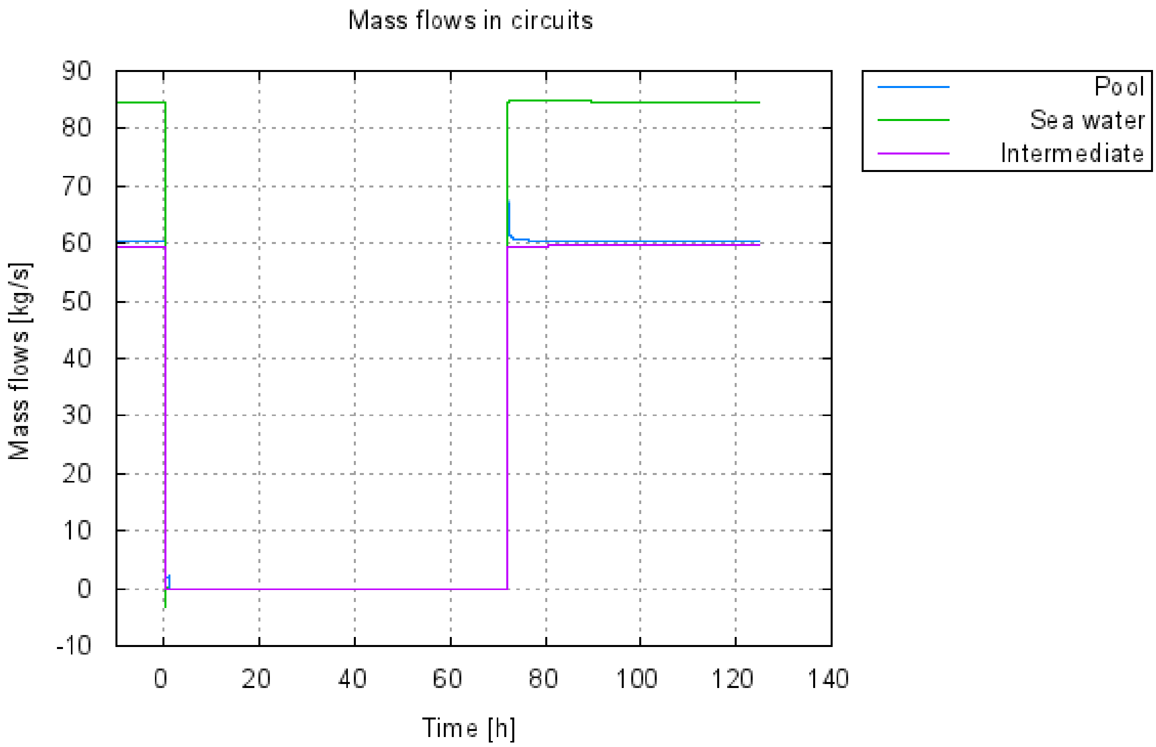

Figure 16. Mass flows in cooling circuits.

CASE 4: FAIL5D

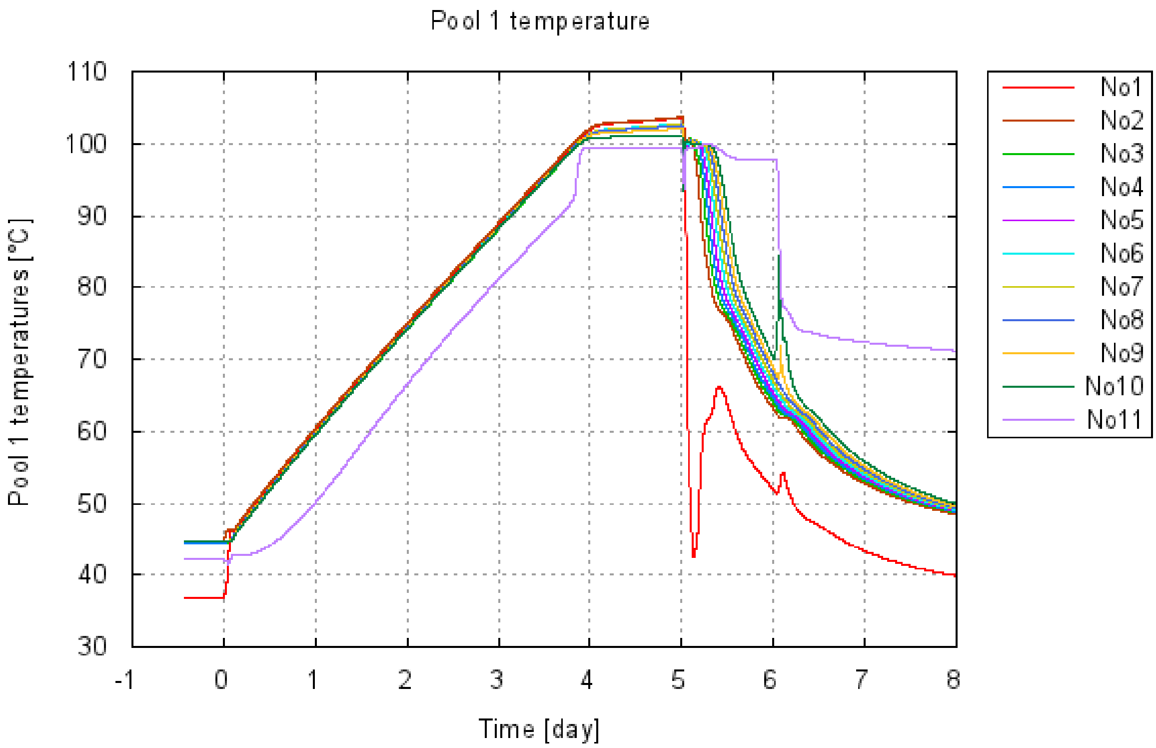

Figure 17. Temperatures in pool 1, pool 2 temperatures are similar.

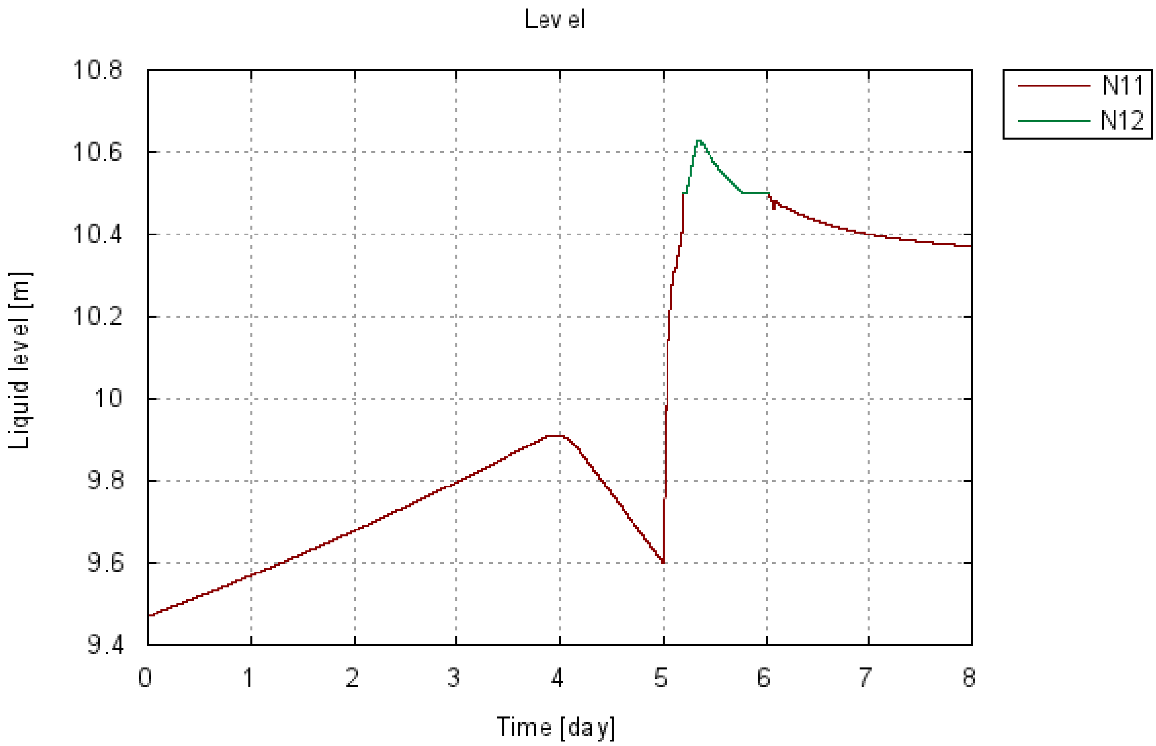

Figure 18. Liquid level in pool 1.

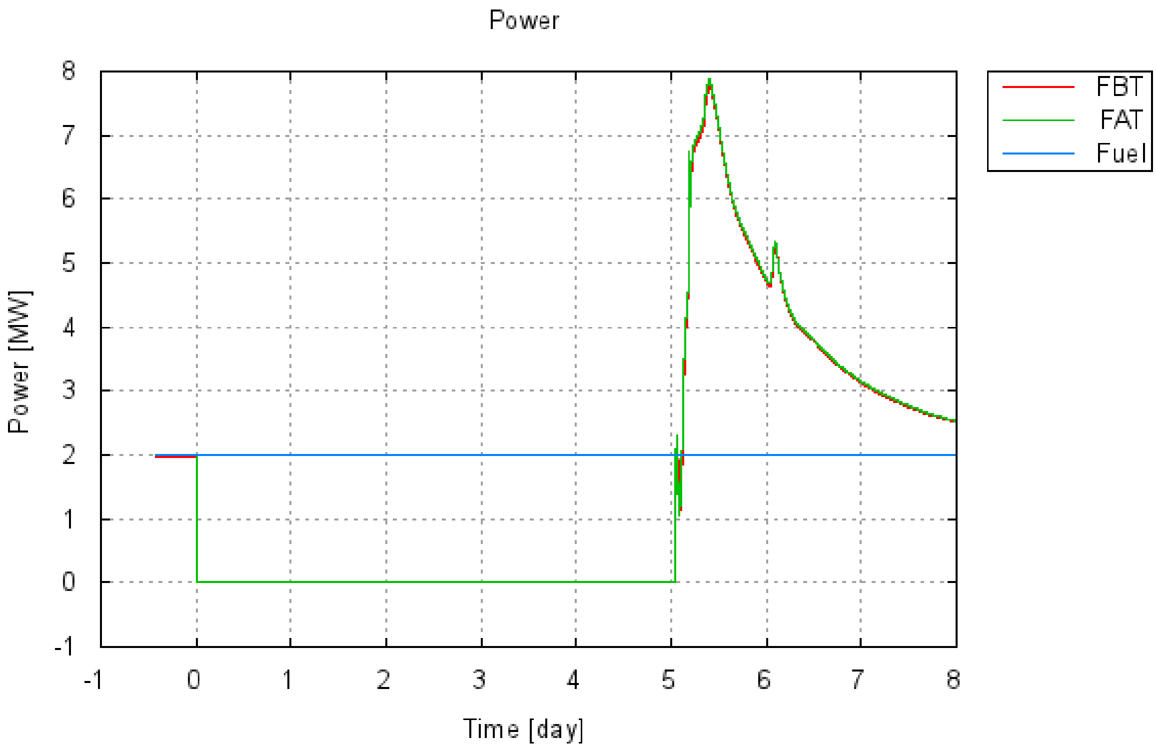

Figure 19. Heating power of fuel elements in one pool and removed power in heat exchangers. FAT is the heat exchanger between pool circuit and intermediate circuit, and FTB between intermediate circuit and sea water circuit.

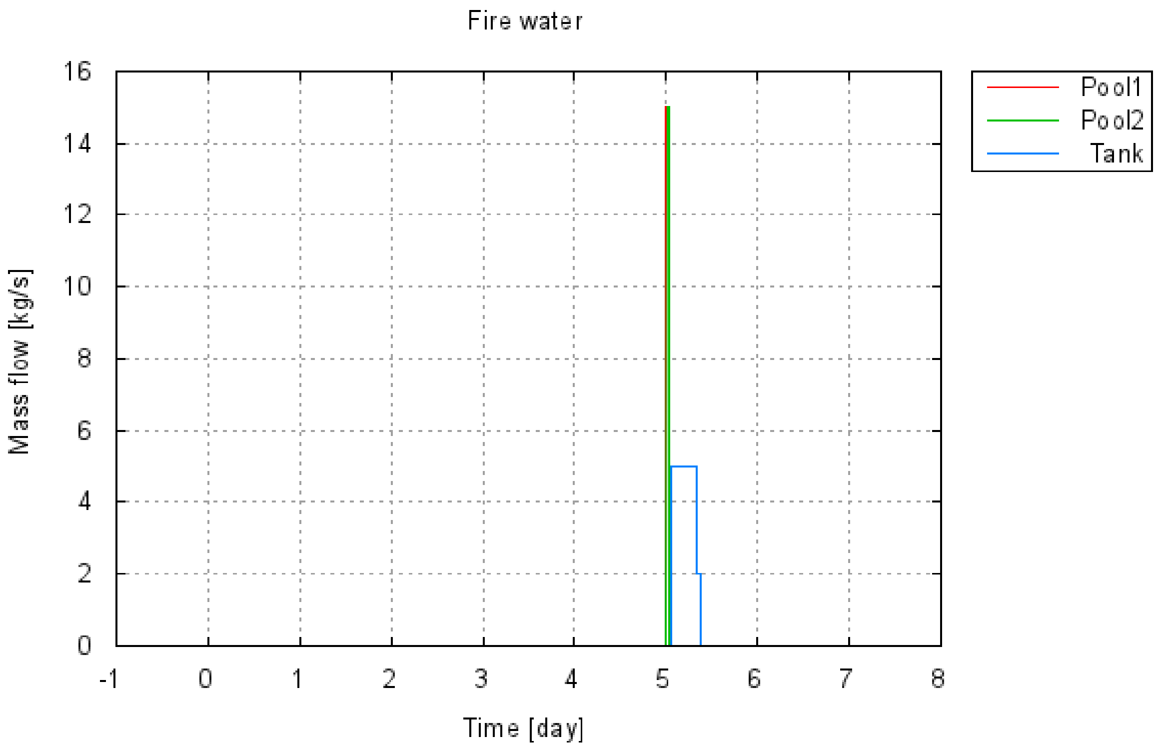

Figure 20. Water injection to pools 1 and 2 and to the equalization tank. Mass flows to pools are equal.

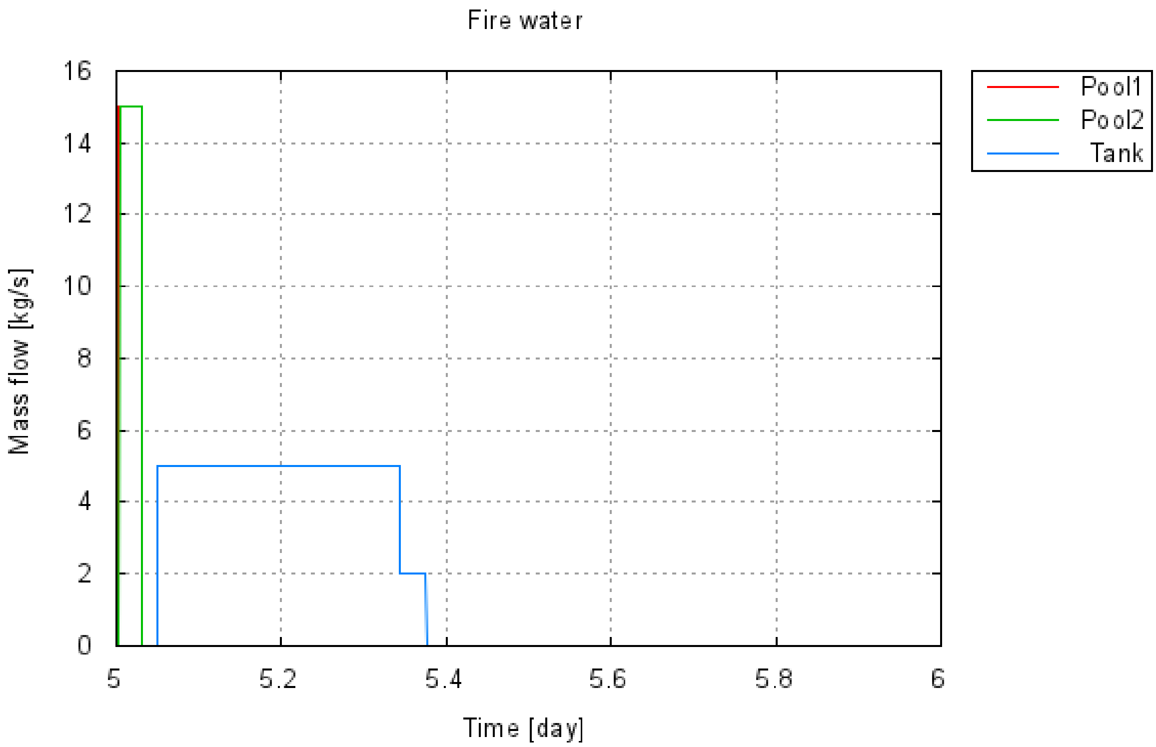

Figure 21. Water injection to pools and to the equalization tank during the restoring of cooling system.

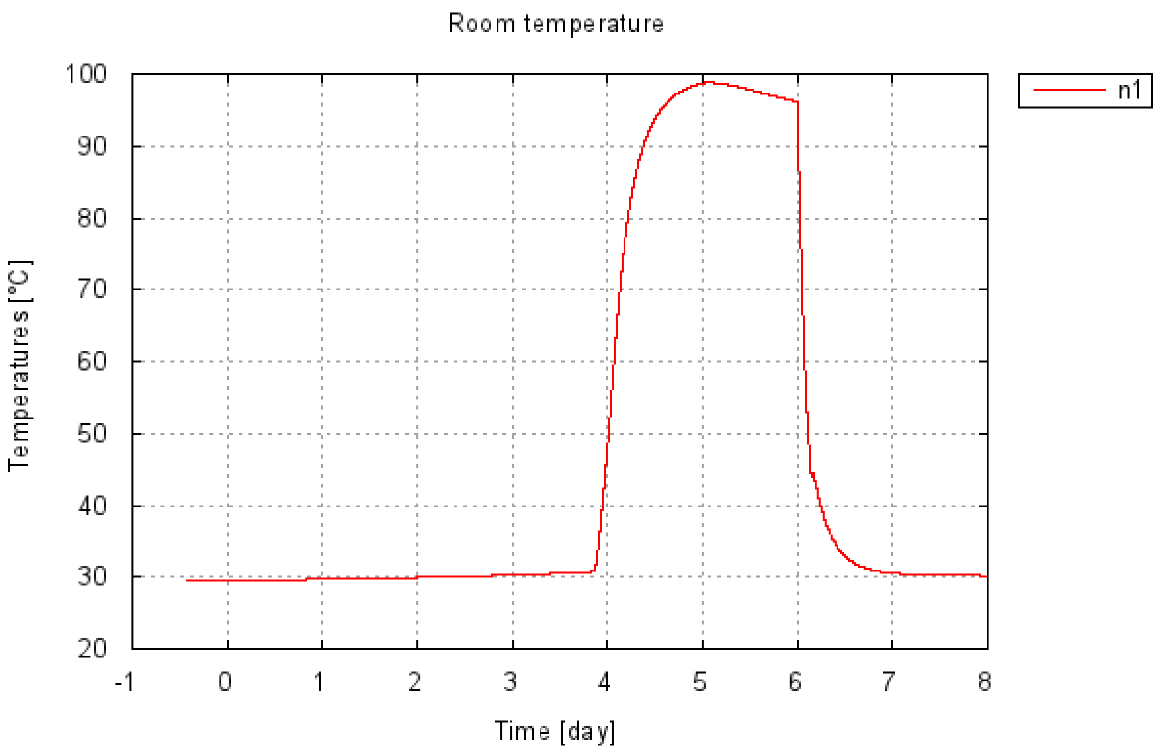

Figure 22. Temperature in pool room node n1 above pool 1. Temperature decreases quickly when the ventilation in the pool room is started.

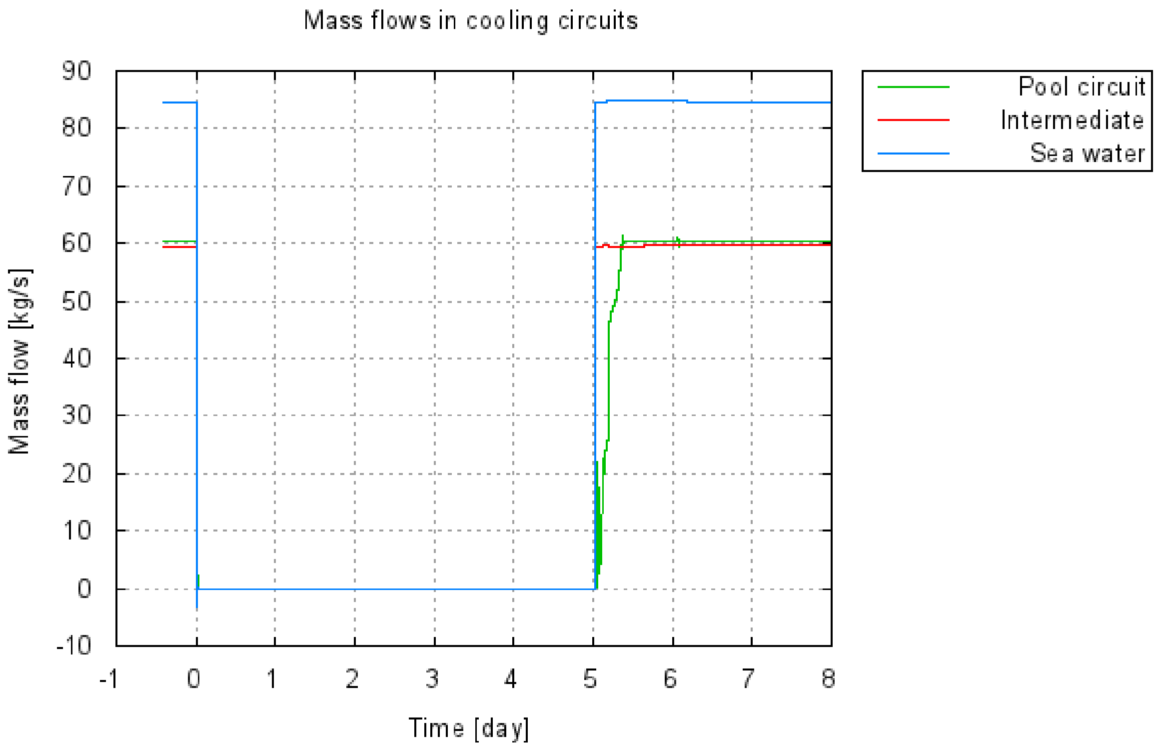

Figure 23. Mass flows in cooling circuits.

CASE 5: FIREWATER

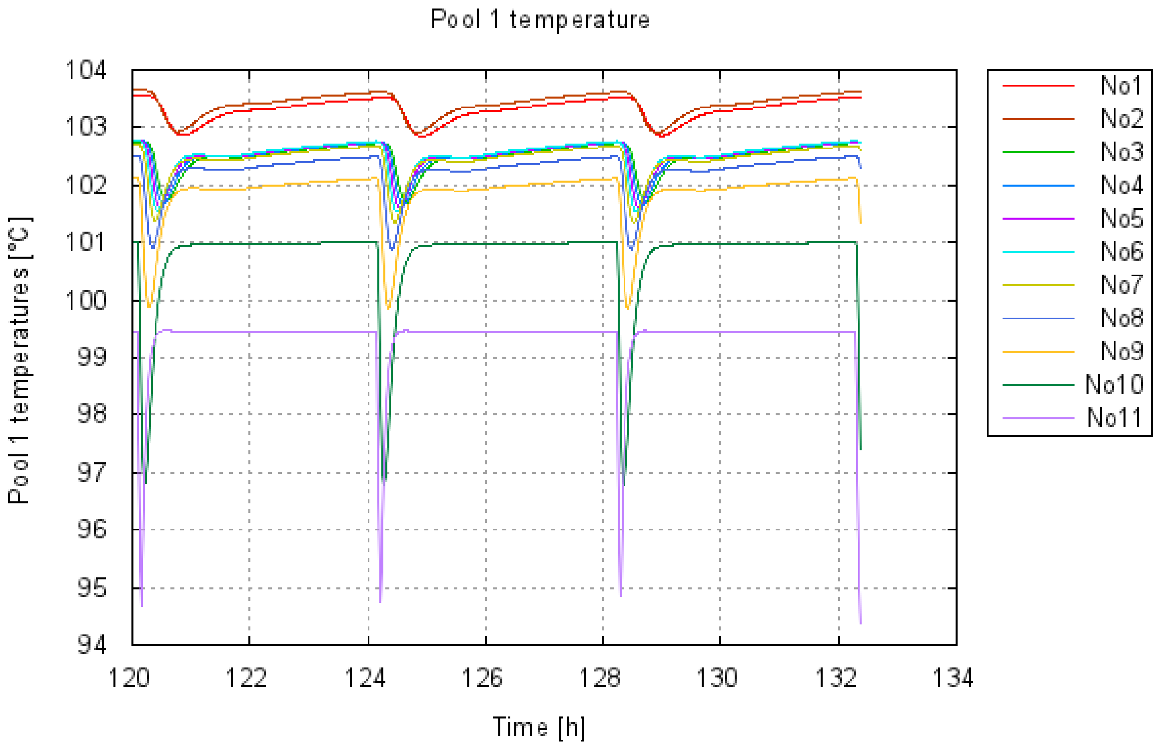

Figure 24. Temperatures of different nodes in pool 1. Pool 2 temperatures are similar.

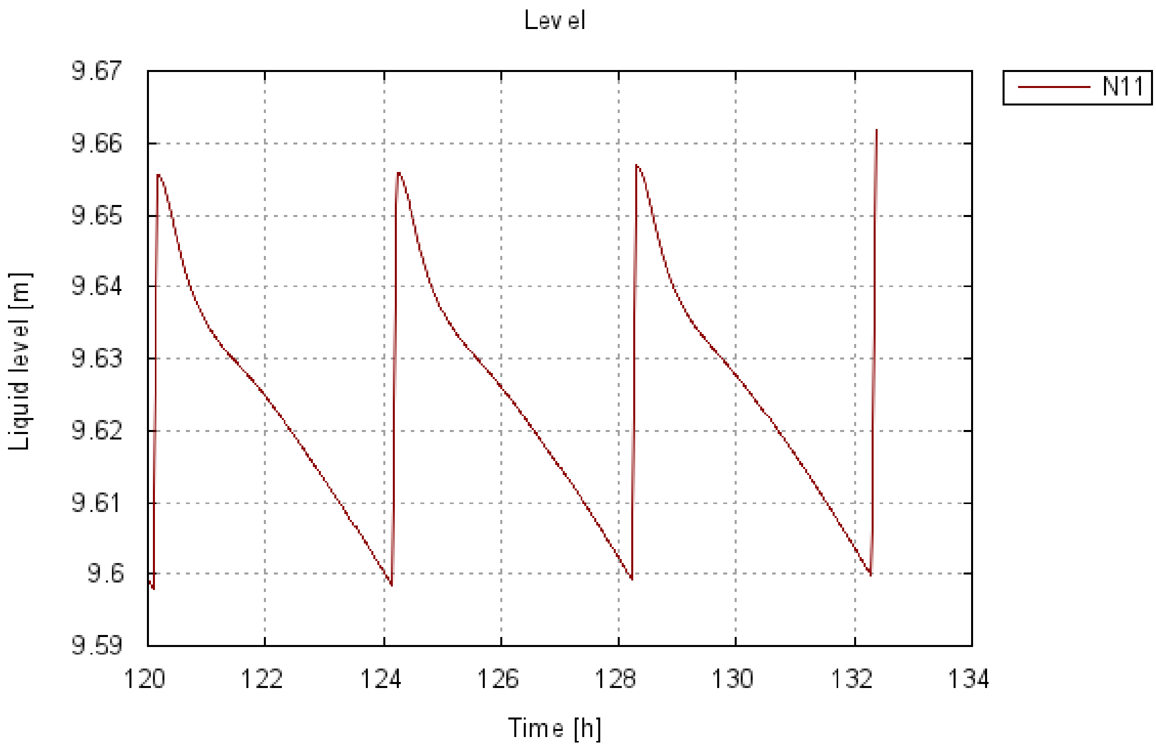

Figure 25. Liquid level in pool 1. Pool 2 water level is similar.

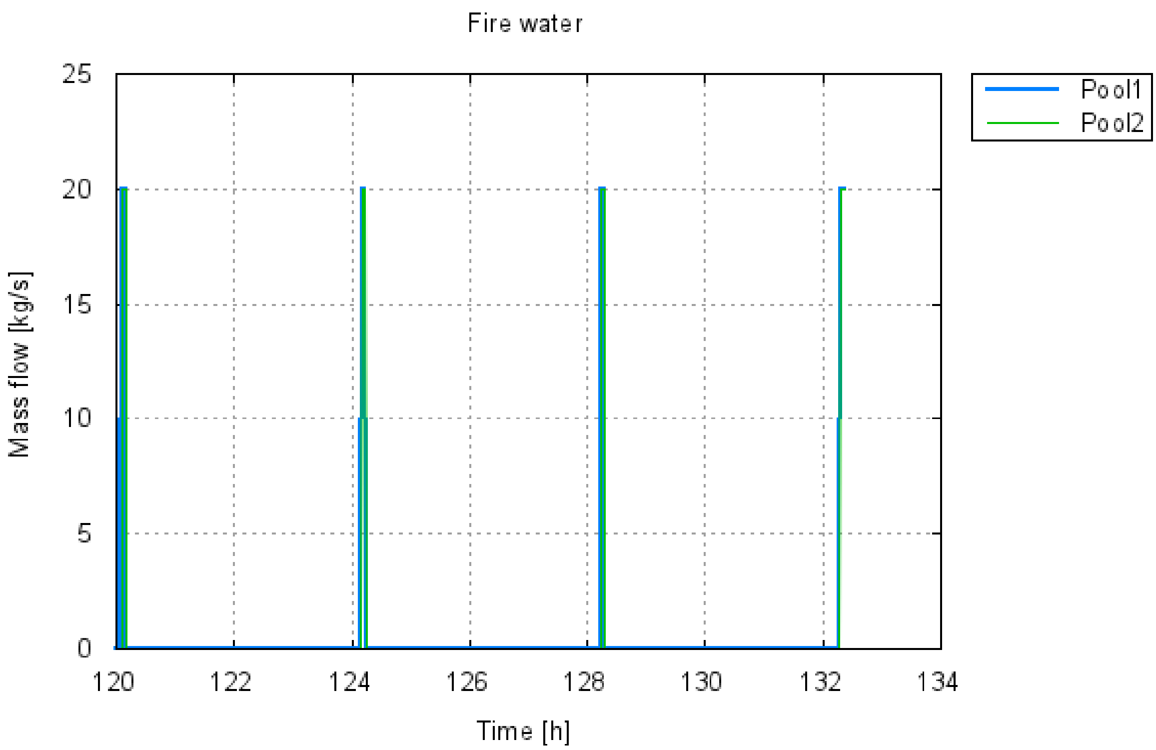

Figure 26. Mass flow of fire water injected to pools. Equal amount is injected to pools 1 and 2.