DIPLOMARBEIT

Development of an Assessment Tool for Spent Fuel Pool Accident Scenarios

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Stefan Ecker
Matrikelnummer 01126618

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der Technischen Universität Wien

Betreuung
Betreuer: Ao.Univ.Prof.i.R. Dipl.-Ing. Dr.techn. Helmuth Böck
Mitwirkung: Senior Scientist Dipl.-Ing. Dr.techn. Mario Villa

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Abstract

Recently spent nuclear fuel generated during the operation of nuclear power plants is typically stored in large water pools near the reactor or in adjacent buildings which are referred to as spent fuel pools (SFPs). In the SFPs the activity contained in the fuel elements is reduced according to the half-life, and the fuel elements are also cooled through several years. Although the large water mass in the pool provides a significant time window for mitigation in case of an emergency, the stored radionuclide inventory remains a potential for a release of activity to the environment if cooling is lost for a significant period of time.
During the Fukushima Daiichi accident in March 2011 a loss of cooling water in one of the SFPs occurred, resulting in partially damaged fuel elements and radionuclide release. Numerous extraordinary actions were required to ensure sufficient cooling of the spent fuel until an alternative cooling system could be installed.
This thesis work proposes to develop a tool that could help authorities who are trying to assess an emergency situation, focus on the crucial unanswered questions concerning the safety of any involved SFP(s) in an emergency. The goal is to create a tool to support a trained user to perform a high level assessment of SFP safety functions during an emergency in order to evaluate the optimal protective and response actions that need to be taken.
A prototype of the tool has been created as part of this thesis. The project, including the source code is available at:
`https://drive.google.com/open?id=14NX61XXs6uiYDxHyNet4xSOm4TCnf85R`

Zusammenfassung

Typischerweise werden die verbrauchten Brennelemente, die während des Betriebs von Kernkraftwerken erzeugt werden, in großen Wasserbecken in der Nähe des Reaktors oder in benachbarten Gebäuden gelagert die als Abklingbecken(eng. Spent Fuel Pools, SFPs) bezeichnet werden. Diese Abklingbecken kühlen die Brennelemente. Obwohl die große Wassermasse des Pools im Notfall ein signifikantes Zeitfenster für Gegenmaßnahmen bietet, besteht aufgrund des gespeicherten Radionuklidinventars ein Potential für die Freisetzung radioaktiven Materials in die Umwelt, wenn die Kühlung für eine erhebliche Zeitdauer verloren geht. Während des Fukushima Daiichi Unfalls in 2011 entstand die Sorge dass die SFPs trocken liegen, und es zu Brennstoffschäden und Freisetzung von Radionukliden kommen könnte. Es wurden zahlreiche außerordentliche Maßnahmen ergriffen, um eine ausreichende Kühlung des verbrauchten Brennstoffs zu gewährleisten, bis ein alternatives Kühlsystem installiert werden konnte.

Diese Arbeit schlägt vor, eine Methode zu entwickeln die verantwortlichen Behörden, die Zugang zu begrenzten Informationen aus der Einrichtung haben, dabei helfen könnte die Situation zu verstehen und sich auf die entscheidenden unbeantworteten Fragen zur Sicherheit jeglicher involvierter SFP(s) in einem Notfall zu konzentrieren . Das Ziel ist es eine Methode zu entwickeln, um einen ausgebildeten Benutzer dabei zu unterstützen, eine hochrangige Bewertung der SFP Sicherheitsfunktionen während eines Notfalls durchzuführen, um zu bewerten wo und welche Schutz- und / oder andere Antwortaktionen ergriffen werden müssen.

Im Zuge dieser Arbeit wurde ein Softwaretool-Konzept entwickelt. Das Projekt und der Programmcode stehen unter folgendem Link zur Verfügung:

`https://drive.google.com/open?id=14NX61XXs6uiYDxHyNet4xSOm4TCnf85R`

Contents

1. Introduction

In the global effort to confront climate change and meet the objectives of reducing greenhouse gas emissions, nuclear power generation continues to be an important aspect in developing sustainable energy solutions for the future. When it can no longer be used, fuel from reactors needs to be stored for several years before they can safely be stored in a final depository. The safe and efficient management of spent nuclear fuel is therefore a crucial aspect of utilizing nuclear power.

1.1. The Nuclear Fuel Cycle

1.2. Background and Global Spent Fuel Inventory

The process of producing and managing nuclear fuel is referred to as the nuclear fuel cycle. The main steps include [1]:

- Uranium mining and milling
- Conversion of uranium oxide to uranium hexafluoride UF_6
- Enrichment
- Fuel fabrication
- Reactor operation
- Spent fuel storage
- Reprocessing and/or final disposal

Focus of this thesis is the spent fuel storage, also often referred to as interim storage. After some time in the reactor the concentration of the isotopes responsible for maintaining the chain reaction drops to the point where it is not longer efficiently usable. At this point the fuel is considered “spent” and has to be replaced with fresh fuel. Spent fuel is highly radioactive and emits a significant amount of heat, thus it requires safe storage to prevent

fuel damage and radioactive releases. The typical approach is to transfer the spent fuel into a pool at the reactor for initial cooling and then further into intermediate storage where it can be kept for several years or decades until the next steps.
An overview of the current nuclear power technologies in operation is given in Table 1 and Table 2.

Table 1.: Number of NPPs in operation as of January 2018 (including 6 reactors in Taiwan, China) [2].

Country	Number Of Reactors In Operation	Total Net Electrical Capacity [MW]
ARGENTINA	3	1632
ARMENIA	1	375
BELGIUM	7	5913
BRAZIL	2	1884
BULGARIA	2	1926
CANADA	19	13554
CHINA	38	33384
CZECH REPUBLIC	6	3930
FINLAND	4	2764
FRANCE	58	63130
GERMANY	8	10799
HUNGARY	4	1889
INDIA	22	6240
IRAN, ISLAMIC REPUBLIC OF	1	915
JAPAN	42	39752
KOREA, REPUBLIC OF	24	22501
MEXICO	2	1552
NETHERLANDS	1	482
PAKISTAN	5	1320
ROMANIA	2	1300
RUSSIA	35	26111
SLOVAKIA	4	1814
SLOVENIA	1	688
SOUTH AFRICA	2	1860
SPAIN	7	7121
SWEDEN	8	8629
SWITZERLAND	5	3333
UKRAINE	15	13107
UNITED KINGDOM	15	8918
UNITED STATES OF AMERICA	99	99869
Total	**448**	**391744**

Regardless of reactor type, the spent fuel is transferred into a reactor storage pool right after being discharged. However, what happens next with it is strongly dependent on the adopted fuel management strategy by the state or relevant authority. Strategies for spent fuel management can be generally categorized into three approaches:

Table 2.: Different types of reactors in operation as of January 2018 [2]. Pressurized Water Reactors (PWR and VVER), Boiling Water Reactors (BWR), Pressurized Heavy Water Reactors (PHWR), Graphite Moderated Light Water Cooled Reactors (RBMK), Gas Cooled Reactors (GCR), and Fast Reactors (FR).

Reactor Type	PWR/VVER	BWR	PHWR	RBMK	GCR	FR
Number Of Reactors In Operation	291	76	49	15	14	3
Moderator	H_2O	H_2O	D_2O	Graphite	Graphite	none
Coolant	H_2O	H_2O	D_2O	H_2O	CO_2	Na
Fuel Type	UO_2 or MOX	UO_2 or MOX	UO_2	UO_2	UO_2	UO_2
Fuel Enrichment	Up to 5%	Up to 5%	Natural Uranium	Up to 3%	2.5-3.8%	17-26%
Cladding	Zr Alloy	Zr Alloy	Zr Alloy	Zr Alloy	Stainless Steel	Stainless Steel

The open fuel cycle approach considers spent fuel as waste. The current strategy is to keep spent fuel in interim storage until it can be disposed in deep geological repositories for an indefinite period of time. Other disposal options like disposal between tectonic plates, in polar ice caps or in space have been considered in the past but are currently not pursued. The concept of geological disposal facilities is to excavate underground galleries several hundred meters below the surface, and fill them with spent fuel storage casks before backfilling and sealing them. [3].

The closed fuel cycle approach reprocesses spent fuel for future use. During reprocessing the fissile material which is still contained in the spent fuel is separated from radioactive fission products and actinides.

The wait-and-see approach defers from a decision and keeps spent fuel in interim storage for an unspecified amount of time. This strategy provides the flexibility to store the spent fuel while evaluating other approaches, but also keep the ability to continuously monitor and retrieve the spent fuel.

Fig. 1 illustrates the planned disposal strategies for the global inventory of spent fuel that has been discharged. This estimate is based on reports published by relevant countries. Estimations of the globally discharged spent fuel indicate that approximately 11 000 tons of heavy metal per year ($\frac{tHM}{y}$) of spent fuel are generated. $8000\frac{tHM}{y}$ of which are being placed in interim storage facilities. The cumulative amount of spent fuel generated worldwide is estimated to be near 250 000 tHM in the early years of 2000, and is projected to increase above 440 000 tHM by 2030. Approximately one third of the discharged fuel is reprocessed while the rest is being placed in interim storage facilities [5, 6].

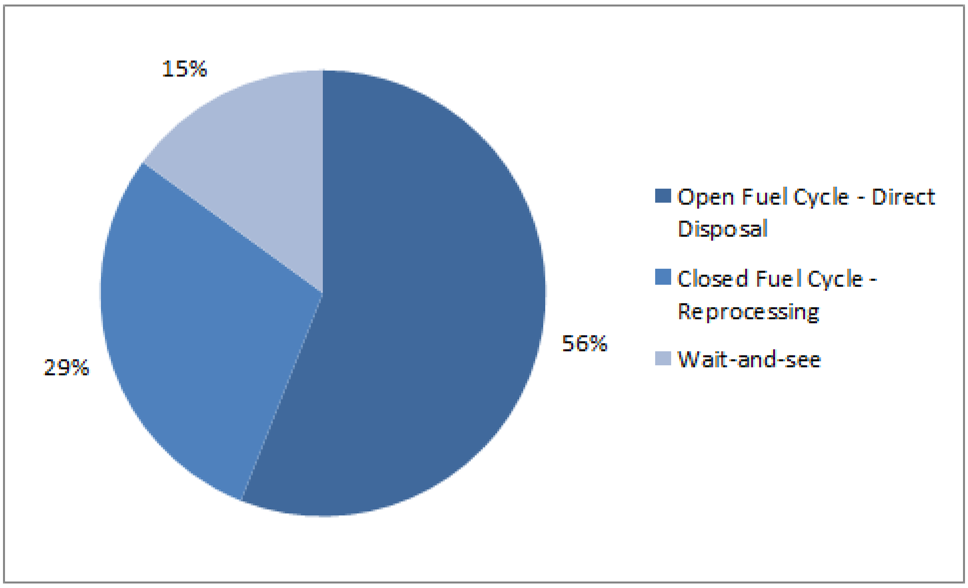


Figure 1.: Planned disposal strategies for the global spent fuel inventory as of 2013. Countries may pursue more than one strategy e.g. for different reactor types [4].

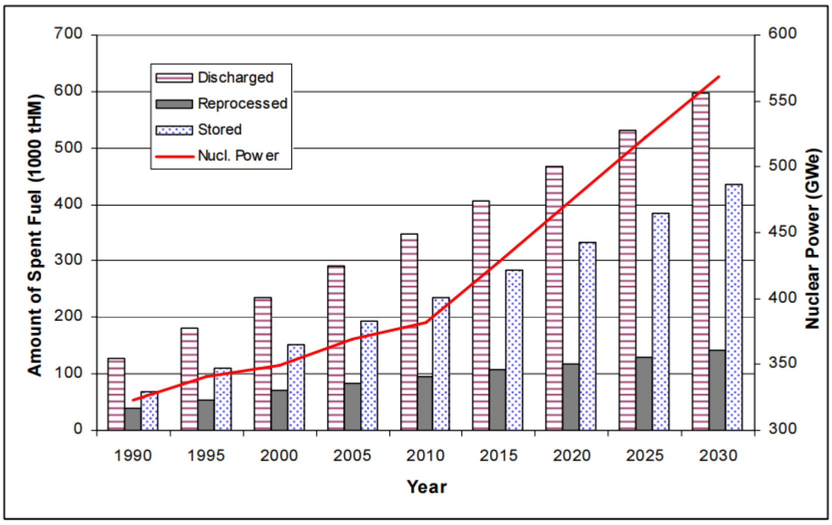


Figure 2.: Estimation of cumulative spent fuel discharged, stored and reprocessed from 1990 to 2030. From [7] (2009)

When it comes to a decision about how the spent fuel can be stored, the established technologies regarding interim storage of spent fuel can be divided into two categories; wet and dry storage.

Wet storage refers to storage pools in which the spent fuel assemblies are placed. The pools are filled with demineralized or borated water, and are cooled via a dedicated cooling system. Dry storage on the other hand is a concept where the spent fuel is placed into a cask which is passively cooled by natural air circulation. Various cask designs exist and they can be stored either inside a building or outside. Both technologies are used around the world and each one has its advantages and disadvantages over the other.

At present, wet storage is the predominant technology in use. About 80% of the global spent fuel inventory is being held in spent fuel pools (SFPs) [4]. As mentioned above, these storage pools are necessary in every nuclear power plant for initial cooling after the fuel is removed from the reactor. More detailed information on different wet storage facilities can be found in section 2.1.
There are several advantages in using wet storage. The usage of water provides not only excellent heat absorption capabilities but the placement of fuel elements below a large water mass also adds an effective and inexpensive radiation shield. This keeps dose rates for workers in the pool area low without the need for additional barriers. The pool design further allows for easy accessibility of the fuel assemblies, and allows for the movement of fuel under water. Fuel conditions can easily be monitored via visual inspection when good water quality is maintained. In addition experience has shown that the fuel cladding integrity is not significantly challenged by extended storage under water. All of these factors and the good operational experience are reason why wet storage has been the interim's storage working horse for decades. There are however some drawbacks in using the wet storage option. Cooling system and water quality need to be maintained, and the open pool configuration requires a protecting building to shield it from external hazards. Most importantly, since the cooling system relies on electrical power, there is a potential for a loss-of-cooling accident where fuel could overheat and release radioactive material to the environment.

For dry storage fuel is loaded into robust, cylindrical casks made out of steel and/or concrete. The big advantage of it is that the cooling mechanism is passive and requires no electricity. Once loaded they require little maintenance and since the casks itself are designed to withstand extreme external hazards like airplane crashes, a surrounding building may not necessarily be needed. Even if a cask would break the radioactive release would be small in comparison to a SFP accident. However there are additional challenges associated with it as well. It is more expensive than wet storage. Special equipment is needed to transfer the fuel into the cask, and the loading process is time

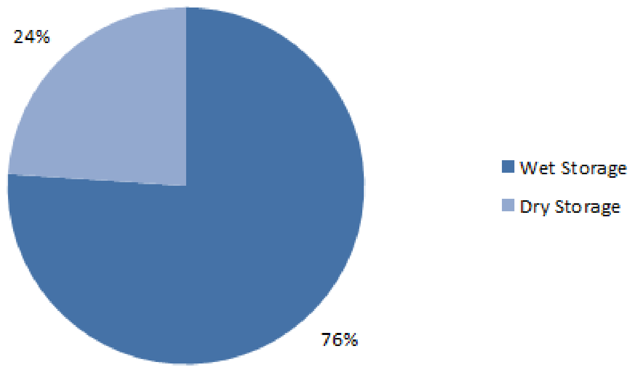


Figure 3.: Distribution between storage technologies in use for the global spent fuel inventory discharged from NPPs until 2013.

consuming. Furthermore the fuel needs to be dried as much as possible in order to avoid residual water which may react with fuel cladding. There is also no direct way of visually inspecting the condition of the fuel. This would require a complicated opening of the bolted and welded cask.

Which of the storage technologies and management strategies is being used in a country depends on many factors like national policies and regulations, existing infrastructure, geographical factors or size of spent fuel inventory. Fig. 3 shows the global distribution between wet and dry storage of spent fuel discharged from NPPs until the year 2013.

1.3. The Spent Fuel Pool Dilemma

As can be seen from Fig. 2 the amount of spent fuel stored in interim storage has been increasing steadily over the past decades and is projected to continue growing in the future. During the early stages of commercial nuclear power production in the 1950s and 60s it was assumed that spent fuel would stay in interim storage between one and five years before being reprocessed or transferred into a final depository. Hence the name interim storage. However two main factors have led to the need to extend storage periods for spent fuel and to store greater quantities of it. The first is the slow progress in the development of final depositories, not only because of technical problems but also political reasons. Only few countries including Sweden and Finland are in the process of actively constructing a deep geological repository as of now. The second factor is the reduced usage of reprocessing partly due to proliferation concerns [8, 9].

As a result NPPs have mostly been storing their accumulating inventory on-site, until a more fitting storage option is available. The most direct way to accommodate the need for additional storage was to pack the storage pools more densely by reducing the space between fuel assemblies. This in course required the installation of neutron absorbing materials to prevent criticality. Storage periods increased from years to decades, and the construction of new SFPs away from the reactor (AFR) provided a straightforward solution for additional storage capacity. As demand for storage capacity continued to increase alternative methods like dry storage were also picked up by several countries. Dry storage and its superior safety potential became increasingly attractive because of security concerns raised after 9/11 and the events at Fukushima Daiichi. While the number of spent fuel stored in casks increased over the past years, SFPs still hold the majority of inventory [10].

2. Design of Spent Fuel Pools

2.1. Design Basis

Just like reactors, SFPs come in all shapes and sizes but posses common design features. The basic requirements for any spent fuel storage facility are [11]:

- Maintaining **subcriticality** in operational states and accident conditions
- **Heat removal** to ensure that no temperature limits are exceeded in operational states and accident conditions.
- Prevent or limit the **release of radioactive material** to the environment
- Provide **radiation shielding** for the protection of workers and the public
- Maintain **structural** integrity of the storage pool and other components in operational states and accident conditions. This includes prevention of fuel degradation.
- Maintain safe **handling and retrievability** of spent fuel in operational states and accident conditions

There are three major types of NPPs in use today. Together they account for more than 90% of operating reactors, and therefore will be the focus of this thesis. The most popular type are light water reactors (LWRs) who use water as moderator and coolant. The two versions are the pressurized water reactors (PWRs) where the water is kept under high pressure to prevent boiling, and boiling water reactor (BWRs) where it is allowed to boil. The third most common reactor type is the pressurized heavy water reactor (PHWR or CANDU) who uses deuterium instead of regular water.
Regardless of reactor type every NPP requires some form of wet storage. Immediately after being discharged spent fuel is transferred into a pool adjacent to the reactor. These at-reactor (AR) pools are part of every NPP design and essential for operation. While there are some exceptions the majority of these pools are located outside the primary reactor containment [12]. As the name suggests they are connected to the reactor building and located either in the reactor building itself or a dedicated fuel handling building.
Away-from-reactor (AFR) pools on the other hand encompass wet storage facilities that

are constructed independent of the reactor building. When AR storage capacities are not sufficient the construction of additional storage pools provides a straightforward solution. These facilities often serve as central storage for multiple reactor units and can be located on-, or off-site a NPP. Consequently they are dimensioned accordingly and can posses multiple pools. Different to AR SFPs they usually include a shipping and receiving are for fuel casks [13].

The core concept is the same for every SFP. The storage pools are large reinforced concrete structures lined with stainless steel. They are usually around 12 m deep and filled with water which is cooled by a dedicated cooling system. The water is not only a reliable heat removal medium but also provides an effective radiation shield. Additives like boron may be added to the water in order to ensure subcriticality. During operation water temperature is usually kept around 50° C [13]. The cooling system pumps take suction from the SFP through a skimmer surge tank or strainer. The water is pumped through a heat exchanger and eventually transferred to the ultimate heat sink of the NPP (sea, river, ...). In- and outlets of the cooling system typically penetrate the pool wall near the water surface, to prevent inadvertent loss of water in case of a break in the piping. In addition the cooling piping is typically equipped with anti-siphon devices against unintended flow paths. For long term operation it is important to keep the water clean in order to maintain visual inspection capabilities and avoid fuel degradation. Hence SFPs are equipped with a water purification system that monitors and manages the water chemistry. A set of operational parameters is continuously monitored in SFPs, although different configurations are possible and instrumentation may vary between facilities. These parameters include water level, temperature or flow rate. SFPs that rely on soluble neutron poisons for criticality control usually measure the boron concentration. Information about these parameters are either fed to the main control room or a local panel. In the building itself radiation monitors are located around the pool to measure any elevated radiation levels. In the event of an accident several safety systems exist to prevent fuel uncovery. Emergency diesel generators (EDGs) can be connected to the cooling system if external power is lost. Many NPPs also have the ability to use the residual heat removal (RHR) system of the reactor to cool the pool. Losses of pool water are typically compensated via the operational water storage tanks. During an emergency alternative equipment like the fire protections system, portable pumps or external sources can be used to compensate losses.
The fuel assemblies are stored in storage racks, which provide additional criticality control by spacing and/or usage of neutron absorbing materials. [13, 12].

2.2. Spent Fuel Pools in Light Water Reactors

2.2.1. BWR

Typical characteristics for BWR SFPs are that they are located next to the reactor on the operating floor above ground level. During refueling the reactor is shut down, opened and filled with water. In normal operation the reactor and SFP are separated by a leak tight gate. When the pools are filled with water the gate can be removed to allow the transfer of fuel and equipment. In addition a second pool is located next to the reactor to store reactor components during refueling. A refueling platform above the pools is used to transfer fuel between the reactor and SFP. Fig. 4 shows the layout for a generic BWR SFP.

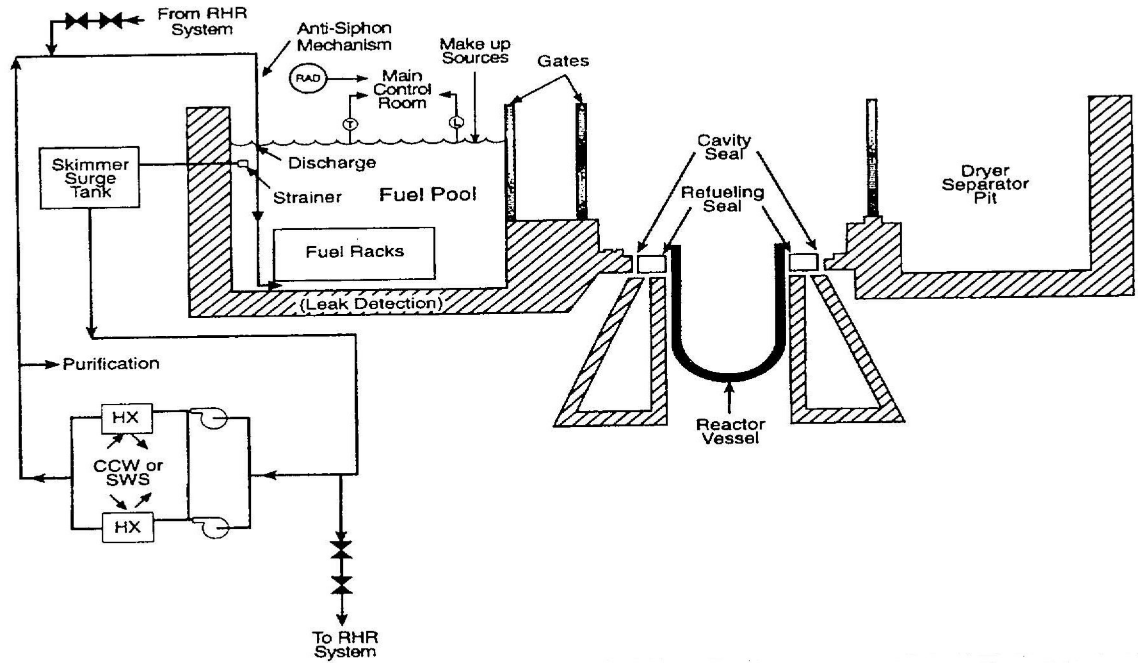


Figure 4.: Generic BWR spent fuel pool and cooling system [14].

2.2.2. PWR

Fig. 5 shows the layout for a generic PWR SFP. The distinct design feature is that the fuel handling area is split into two parts. The SFP is located in designated building adjacent to the reactor building. During refueling operations the reactor is opened and the reactor cavity filled with water. Removed fuel assemblies are moved horizontally through a transfer tube into the fuel handling building, where it is again raised into a vertical position and stored in the SFP.

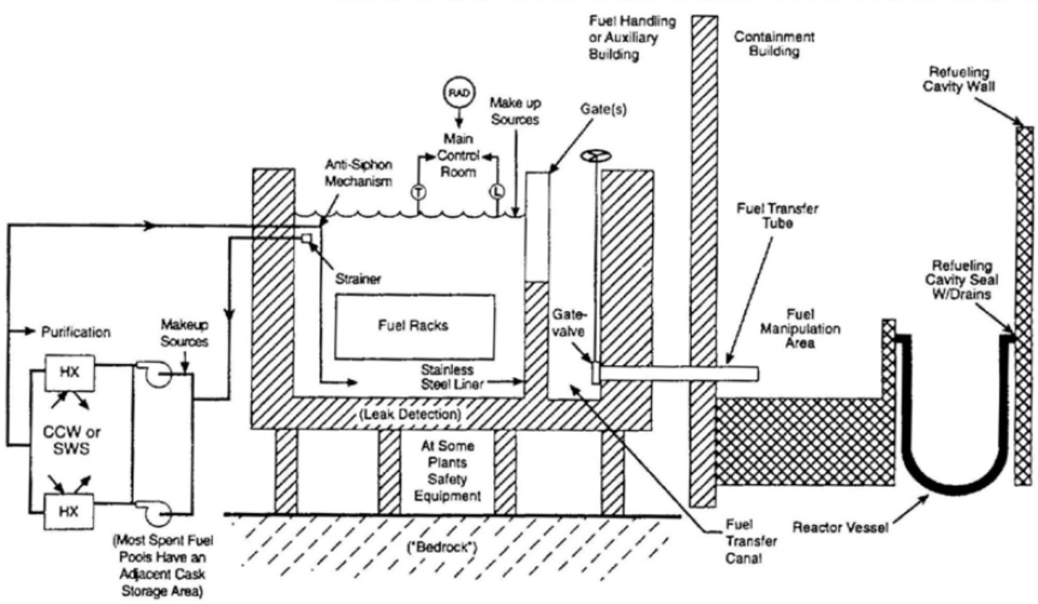
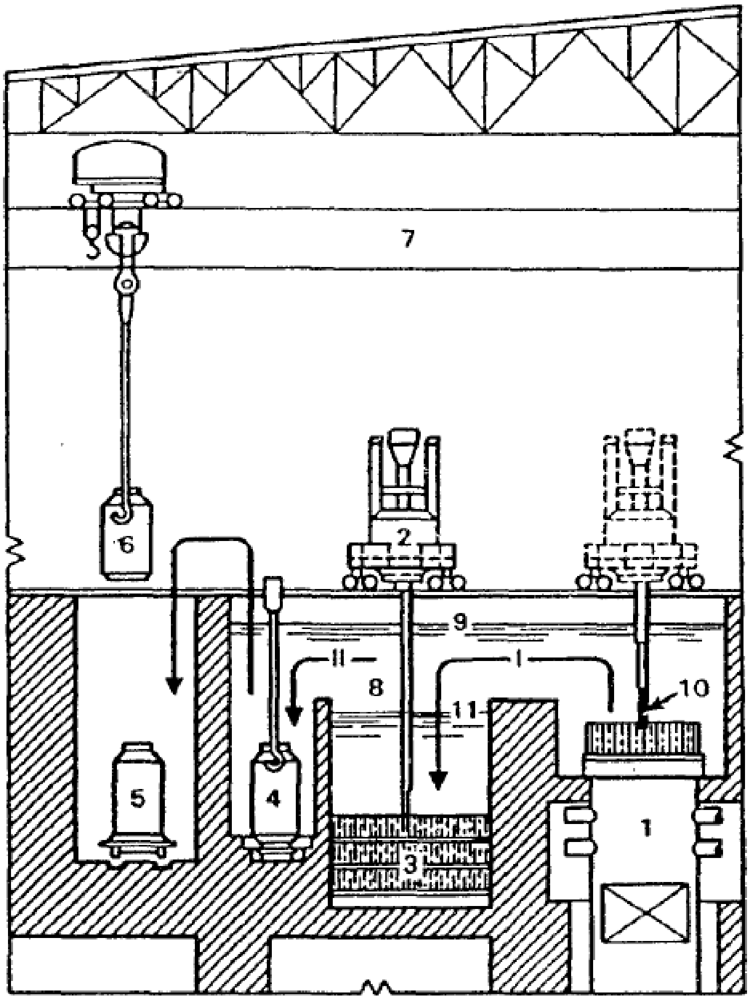


Figure 5.: Generic PWR spent fuel pool and cooling system [14].

2.2.3. VVER

While they also fall into the category of PWRs, the spent fuel storage concept for VVER type reactors differs from its western counterparts. The older VVER 440/213 and 440/230 models have the storage pool next to the reactor in the reactor hall. (Fig.6).



1- reactor pressure vessel, 2 - refueling machine, 3 - racks for spent fuel, 4 - receiving container, 5 - railroad transport, 6 - transport cask, 7 - reactor building bridge crane, 8 - spent fuel storage pool (I - reloading of spent fuel from reactor to storage pool and II - reloading of "cooled" spent fuel to transport container), 9 - water level during refueling, 10 - spent fuel element, 11 - water level during storage.

Figure 6.: Schematic VVER 440 spent fuel storage and refueling operation [15].

The same concept is used for newer models like the VVER 1000, however its revised design makes it one of the few models where the SFP is actually inside the primary reactor containment.

2.3. Spent Fuel Pools for Pressurized Heavy Water Reactors

The dominant type of PHWR is the heavy water cooled, heavy water moderated CANDU. This type of reactor uses natural uranium as fuel and typically the reactor core is contained in a cylindrical calandria which holds the heavy water moderator. The ends of the calandria are closed with two parallel end shields which are perforated with holes for the fuel channels. Each fuel channel is fuelled with multiple fuel bundles. The pressurized heavy water coolant is circulated through the fuel channels and eventually to the steam generators.

The refueling process uses two remotely controlled fuelling machines, one operating at each end of a fuel channel. New fuel bundles from one fuelling machine are pushed into a fuel channel and the displaced irradiated fuel bundles are received into the second fuelling machine at the other end of the fuel channel. This means that, opposed to LWRs, refueling can be done without the need to shut down the reactor. About 10 fuel channels are refuelled each week. Hence this so called on-power refueling produces a steady stream of spent fuel. For CANDUs the SFP is also referred to as Irradiated Fuel Bay (IFB). The IFB consists of multiple sections. First, the irradiated fuel bundle is transferred into a discharge bay filled with light water. It is then transferred through a transfer canal into a reception bay, where it is loaded onto storage trays or baskets. Once the trays are full they are transferred to the storage bay. As with LWRs the SFPs for CANDUs are large reinforced concrete structures, located at or slightly above ground level. The walls of the fuel pool are typically lined with steel. The size and shape of the pools varies depending on the station. Generally receptions bays are about half the size of the main storage pool [16, 17]. Reception bay and storage bay usually have independent cooling and purification systems and can be sealed off from another. The design principle for the cooling circuit is the same as for LWRs.

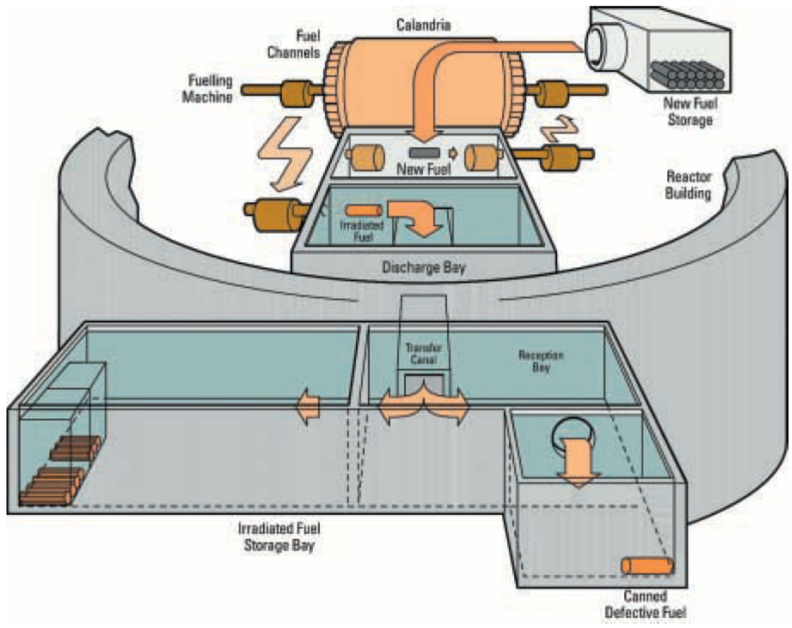


Figure 7.: Schematic process of the fuel handeling operations in a CANDU type reactor [16].

2.4. Storage Rack Configurations

After being transferred from the reactor the spent fuel assemblies are inserted into storage racks in the SFP to keep them in position. There are various rack designs in operation today. During an accident the rack configuration could be an important factor to consider regarding coolability and criticality control. Early designs for LWR storage racks use open rack configurations that rely on large spacing between fuel assemblies. This design also ensures open flowpaths for water circulation and allows crossflow between fuel assemblies. However as discussed in section 1.3 the general spent fuel storage strategy in pools shifted to high density storage. In practice this means that the open storage racks have mostly been replaced with high density racks. Aside from the closer spacing they also require holder walls to provide the neutron shielding. The walls prevent water access from the side, and holes in the baseplate allow for vertical water circulation. Most storage racks maintain around 20 - 40 cm of space between the baseplate and the bottom of the pool to allow water access from below. The design of a storage rack would become increasingly important when the fuel is uncovered. Studies have found that the effectiveness of air cooling after a complete loss of water is greatly influenced by the rack design (see Fig. 9).

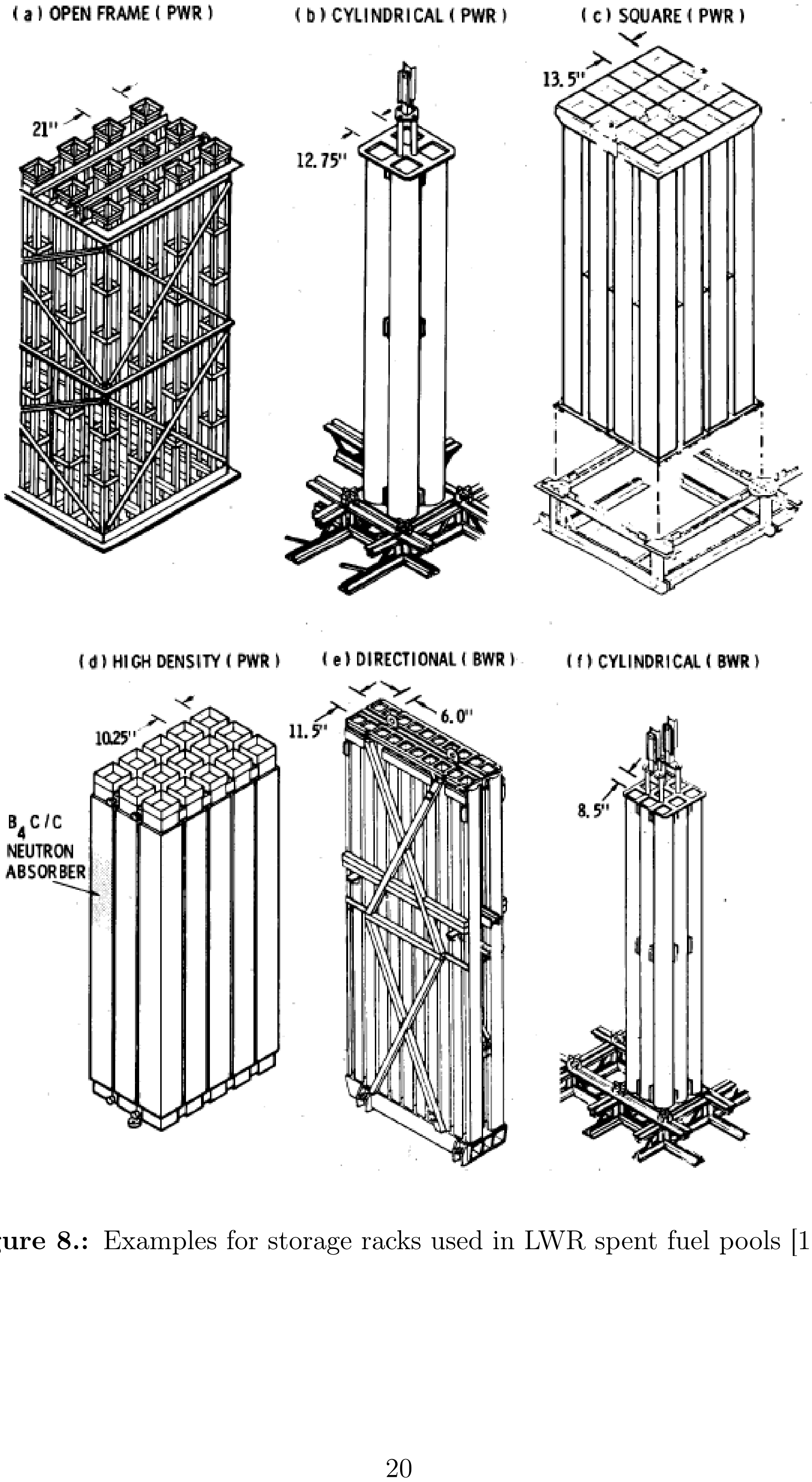


Figure 8.: Examples for storage racks used in LWR spent fuel pools [18].

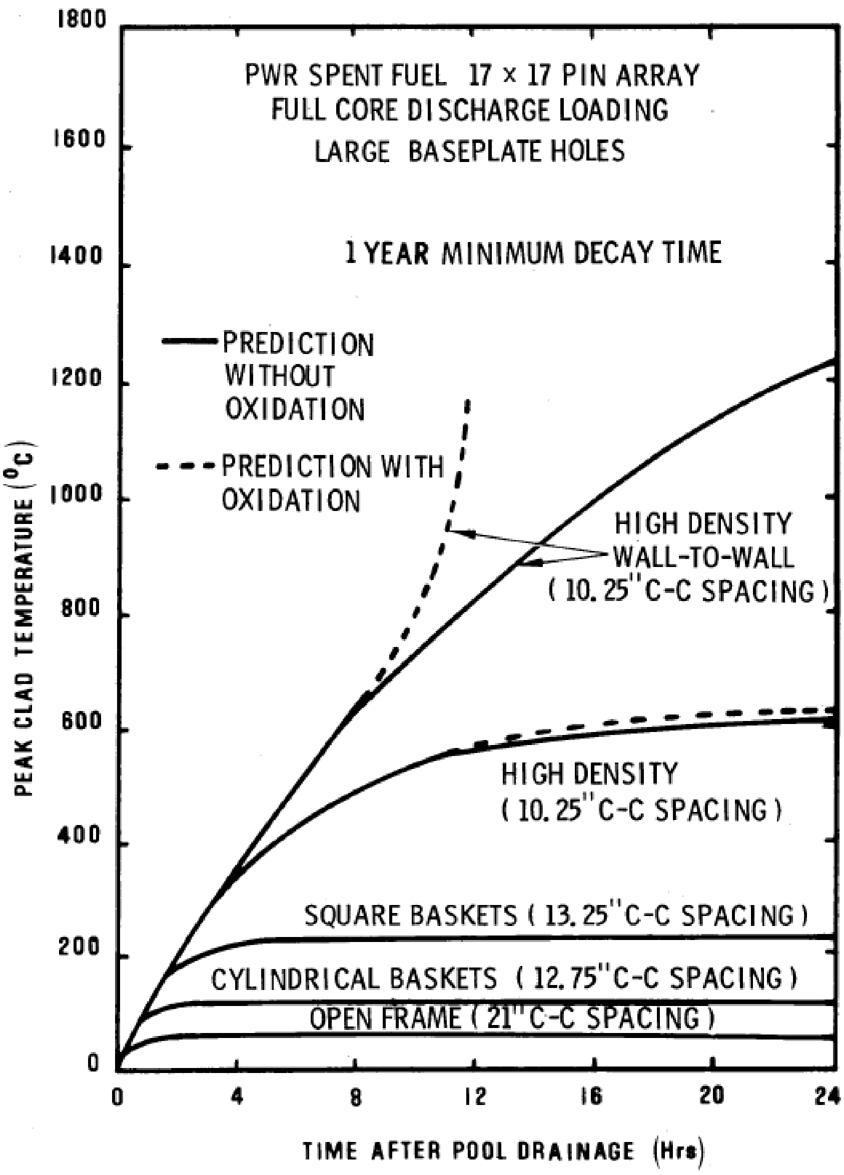


Figure 9.: Effect of the storage rack configuration on the coolability of PWR spent fuel following a complete loss of water [18].

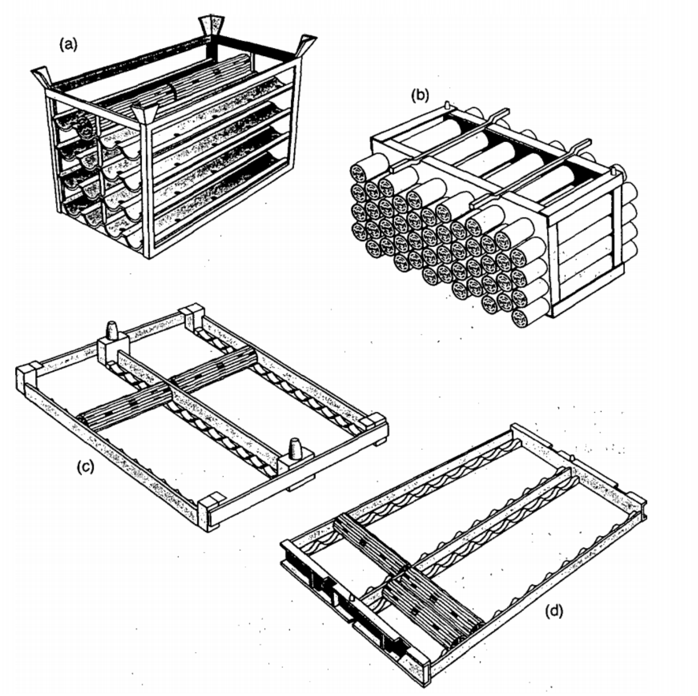


Figure 10.: Examples for CANDU spent fuel storage (a) baskets, (b) module and (c)-(d) trays [19].

Since CANDU reactors use natural uranium there is no criticality risk when they are stored in light water or air. Therefor there is no concern for bundle spacing. Spent fuel from CANDUs is either loaded into baskets, modules or trays. All of these racks have an open storage configuration.

3. Accident Potential

As discussed in chapter 1 there are some safety concerns regarding wet storage. The stored fuel could be damaged by external events, system failures or human errors. This chapter discusses potential accident scenarios regarding SFPs, their consequences and gives examples of past accidents.

3.1. Hazards

Because of their low decay heat and simple design compared to reactors, SFPs are generally regarded as safe [20, 14]. Studies estimate the risk of a severe SFP accident to be very low (see Table 3). However the possibility for accidents, even when they are highly unlikely, can evidently never be excluded. Events like the 2011 Great East Japan Earthquake can be hard to predict, and consequences like fuel damage, hydrogen explosions, zirconium fire or radioactive releases could still occur.

Table 3.: Initiating events and the estimated frequency that they lead to fuel uncovery in SFPs [20].

Initiating Event	Frequency of Fuel Uncovery per year
Seismic event	$2 \cdot 10^{-06}$
Cask drop	$2 \cdot 10^{-07}$
Loss of offsite power	$2.9 \cdot 10^{-08}$ - $1.1 \cdot 10^{-07}$
Fire	$2.3 \cdot 10^{-08}$
Loss of pool cooling	$1.4 \cdot 10^{-08}$
Loss of coolant inventory	$3 \cdot 10^{-09}$
Aircraft crash	$2.9 \cdot 10^{-09}$

3.1.1. Loss of pool cooling

A loss of the dedicated SFP cooling system can be attributed to either the loss of cooling flow or loss of the ultimate heat sink. Both would result in rising pool temperatures and eventually lead to a loss of water inventory. Since the integral components of the cooling system are dependent on electricity, a loss of offsite power would restrain their functionality. Because of the large water mass of the pool, fuel heat-up would be rather slow. Thus short power breaks are not as dangerous as for reactors and a significant time window for mitigation methods would be available. Furthermore alternative electrical on-site power sources like emergency diesel generators or emergency batteries would likely be available to supply power for a certain amount of time. Complications arise when the duration of the power loss exceeds several days as was the case during Fukushima. The cooling flow could be impaired by a loss of SFP coolant inventory with following loss of suction of the pump as well as mechanical issues like foreign material clogging a filter or pipe in the system. For facilities that use sea water as an ultimate heat sink sand, mud or organisms could clog the intake pipes. A special feature of SFPs is that in case of a loss of ultimate heat sink the surrounding atmosphere would naturally take over the role as a new heat sink as long as water is evaporating from the pool. In general SFPs should be designed to have redundant and independent cooling circuits, and usually a single line should be able to provide sufficient cooling.

3.1.2. Loss of pool inventory

The main pathways for a loss of SFP coolant are the connected systems, the leakage through temporary gates or seals during refuelling or other activities and leakage through the SFP liner or structure. Loss through connected systems could include pipe breaks or leaks in the SFP cooling and purification system. For certain reactor types like BWRs a flow path to the reactor vessel could exist during refueling or maintenance activities. This would open up additional pathways through the reactor piping systems or drainage into the reactor cavity. Usually a loss of inventory through the SFP cooling system piping would be limited by anti-siphon devices. In addition openings in the SFP structure are usually designed to be above the top of fuel elements in order to limit losses through that pathway. This applies for example to gates, transfer tubes or openings for the pumps. Inventory could also be lost by leakage through the SFP liner or failure of the SFP structure. Such losses could be caused by severe seismic events or the drop of heavy loads onto the structure of the SFP. The important difference to a loss of cooling accident is that in this case the water level could decrease significantly faster. This could be the result of major leak. In addition water could also be lost due to sloshing during an earthquake.

3.1.3. Other events

As mentioned before a heavy load drop into the SFP could affect the structural integrity of the SFP, resulting in a loss-of-inventory or damaged fuel assemblies. This is why lifting heavy loads over the spent fuel pool is usually restricted.

Faults in the electrical system could lead to an internal fire. In general a fire suppression system and compartmentalization of the building would limit the spread of the fire. A prolonged fire in the SFP building could damage electrical systems, the structure itself or lead to a loss of power.

As most nuclear installations SFP structures are designed to be seismically robust and can often withstand loads beyond their design basis. However as can be seen from the events in Fukushima, the surrounding circumstances following an earthquake may be more challenging to the SFP safety than the earthquake itself.

3.2. Consequences

This section discusses the main consequences of the postulated events in section 3.1. Even though very unlikely, the consequences of a SFP accident with fuel uncovery and subsequent radiological release could be severe. An overview of the accident phenomena is given in Fig.11.

3.2.1. Loss of pool cooling

Following the loss of the SFP cooling system the decay heat will begin to heat up the water until an equilibrium temperature or the boiling point is reached (see 4.2 for more details). The water level will start to decrease until the fuel elements are partially or fully uncovered. Because of the large water mass this uncovering process is relatively slow for NPP accident standards. Assuming that no mitigation measures are taken it can take weeks before the water level reaches the top of the fuel. The uncovery process can be categorized into three stages depending on the water level.

As long as the fuel is fully covered with water, natural convection and evaporation provide sufficient cooling for the fuel. The temperature of the fuel assemblies would increase but no fuel damage is expected. After the water level reaches the top of the fuel, thermo-hydaulic phenomena become more complex. It should be noted that detailed effects after this point strongly depend on fuel rack design and fuel characteristics, and a comprehensive analysis is not within the scope of this thesis. If the fuel is partly uncovered the rising steam may still provide some cooling to the top parts of the fuel. The

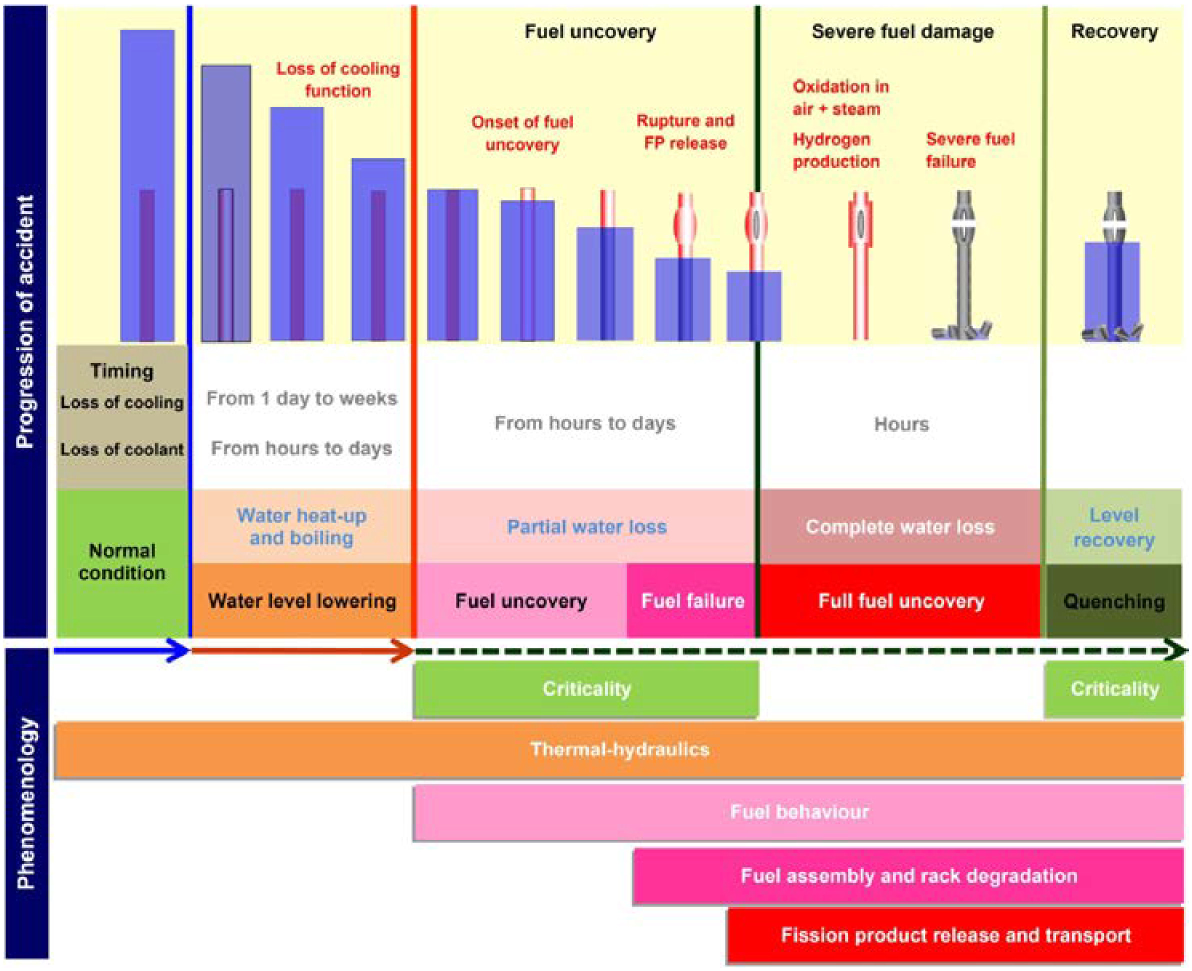


Figure 11.: Overview of accident phenomena regarding SFPs. The accident progression and estimated timings are given for a loss of cooling and loss of coolant event [12].

effectiveness of this is dependent on the steam production rate, and thus decreases with dropping water levels. When fuel racks are completely uncovered natural circulation of air becomes the main cooling mechanism. Depending on the decay heat and fuel rack design this may be sufficient to prevent severe damage to the fuel elements. The effectiveness of air cooling can be enhanced if a ventilation system is available where hot air exits the SFP building and is replaced with cool air entering at lower elevation. In addition it is crucial for the natural airflow that it can enter the fuel racks from below. Hence a shallow water layer may obstruct downward flow paths. Regarding emergency response it is important to consider that the considerable steam production inside the SFP building may impair working conditions. Additionally electrical equipment could fail or visual inspections may not be possible. Furthermore as the water level decreases, so will the with it associated shielding and radiation levels will increase. If the water is contaminated, for example as a result of fuel damage, the steam would spread the contamination inside the building. Eventually access to the SFP building will be restricted.

3.2.2. Loss of pool inventory

The consequences of an inventory loss with decreasing water level are similar to the ones described in 3.2.1. The important difference is that the dropping of the water level could happen much faster. In this case not all stages necessarily need to be reached. Furthermore a rapid draindown would typically not be associated with major steam production. With decreasing water levels, the pumps would eventually lose suction and cooling systems would be lost as well.

3.2.3. Fuel behaviour

Since the decay heat of spent fuel is relatively low, significant fuel damage due to overheating is not expected as long as it is covered with water. Uncovered fuel however can reach high temperatures and experience severe damages. Rising temperatures would increase the internal pressure in the fuel rods and weaken the cladding material, leading to ballooning. Eventually the fuel cladding would fail and release the volatile fission products that were kept in the gap between fuel and cladding. Deformation of the fuel elements could increase flow resistance within the fuel assembly and impair cooling even further.

An important phenomenon regarding fuel degradation in SFPs is the oxidation of zirconium. Because of its favorable mechanical properties, most nuclear fuels use a zirconium alloy (Zircaloy, see Table 2) as their cladding material. Zirconium can react with oxygen in water, steam or air to form zirconium oxide. The formation of oxides weakens the material and contributes to the failure of the cladding. While also present at low temperatures, the oxidation rates become significant at high temperatures above 900° C. Several zirconium oxidation reactions are possible, all of which are exothermic and result in a temperature dependent energy release (ΔH). In the scenario of a complete water loss the oxidation reaction of the zirconium cladding is:

$$Zr + O_2 \rightarrow ZrO_2 + \Delta H \tag{1}$$

Partially uncovered fuel elements will react in a steam environment:

$$Zr + 2H_2O_{steam} \rightarrow ZrO_2 + 2H_2 + \Delta H \quad (2)$$

It is important to note that this reaction in a steam environment produces hydrogen. In the event of a SFP accident the hydrogen production rate could be high enough to lead to explosions inside the SFP building. The ensuing damage to the structure could provide pathways for radioactive material releases into the environment [12].
Conditions for the exposed fuel could deteriorate if temperatures continue to rise even further. After reaching about 1200° C the oxidation reaction could become rapid and self-sustaining. This so called zirconium fire would consume the fuel cladding and potentially cross over to neighbouring fuel assemblies. The runaway temperature increase could produce enough heat to melt fuel racks and assemblies, resulting in the release of fission products. As with most SFP related phenomena the behaviour of a zirconium fire is dependent on complex circumstances, e.g. storage configuration. It is estimated that the probability of reaching the ignition temperature for a zirconium fire is greater when high density storage racks and fresh fuel are used.

3.2.4. Criticality

Criticality accidents involving SFPs are generally viewed as highly unlikely. SFP designs are required to ensure subcriticality (usually $k_{eff} < 0.95$) during all credible operational and accident scenarios. Only few credible accident scenarios have been described. One possible scenario would be the drop of a heavy load on a fuel rack that does not use any neutron absorbing materials. This could lead to a more ideal geometry for criticality. Due to their lower melting point, neutron absorbing materials in fuel racks could be lost before the fuel melts. In cases where subcriticality relies on their use, such an event could theoretically also lead to recriticality. Reflooding an empty SFP could result in a positive reactivity insertion.

3.2.5. Radiological releases

Releases of fission products in case of a SFP accident would occur if the fuel has been damaged, for example because of cladding failure. As long as the fuel is covered with water releases would usually be limited since particles would stay underwater. The pool purification system would filter these contaminants. In case of exposed fuel elements however fission products would be released to the environment, driven by steam and air flow. The extent of the release would therefore be proportional to the fuel damage and temperature. The composition of released radionuclides depends on multiple factors like type of fuel, burn-up and storage duration. Some SFP are located inside the reactor containment. For these the consequences of a release in case of an accident would be the same as for reactor accidents. SFP outside the containment on the other hand are usually in a non-hermetic building.

3.3. Release of ^{137}Cs in case of a SFP fire

The radiological inventory of spent fuel consists of various radionuclides. The exact source term depends on initial conditions like fuel type or initial enrichment, but also on irradiation history and time since discharge from the core. One of the major contributors to the environmental contamination from releases of damaged spent fuel is ^{137}Cs which accounts for almost half of the fission-product activity in 10-year old spent fuel. ^{137}Cs is a fission product with a half-life of 30-years and emits a high-energy gamma ray when it decays. These two properties make it one of the most difficult radioactive contaminants in the event of a release.

Studies have shown that in case of a loss of water in a SFP the spent fuel would heat up and catch fire, resulting in the release of considerable amounts of fission products [20, 18]. Accompanying the heat up process would also be the production of hydrogen which can lead to explosions inside the SFP building, thus creating pathways for environmental releases. In combination with the enormous amounts of fuel that could be in storage, as discussed in the section above, such an event could have far more severe consequences than a 'traditional' reactor accident.

It has been estimated that a typical SFP in the US contains around 400 tons of spent fuel. In case of an accident models project that this could lead to a release of 1600 PBq of ^{137}Cs [21]. In contrast, during the 1986 Chernobyl event, which is regarded as one of the most severe accidents in nuclear power plant history, approximately 80 PBq of ^{137}Cs have been released. Fig. 12 and Fig. 13 illustrate the different consequences between those two magnitudes.

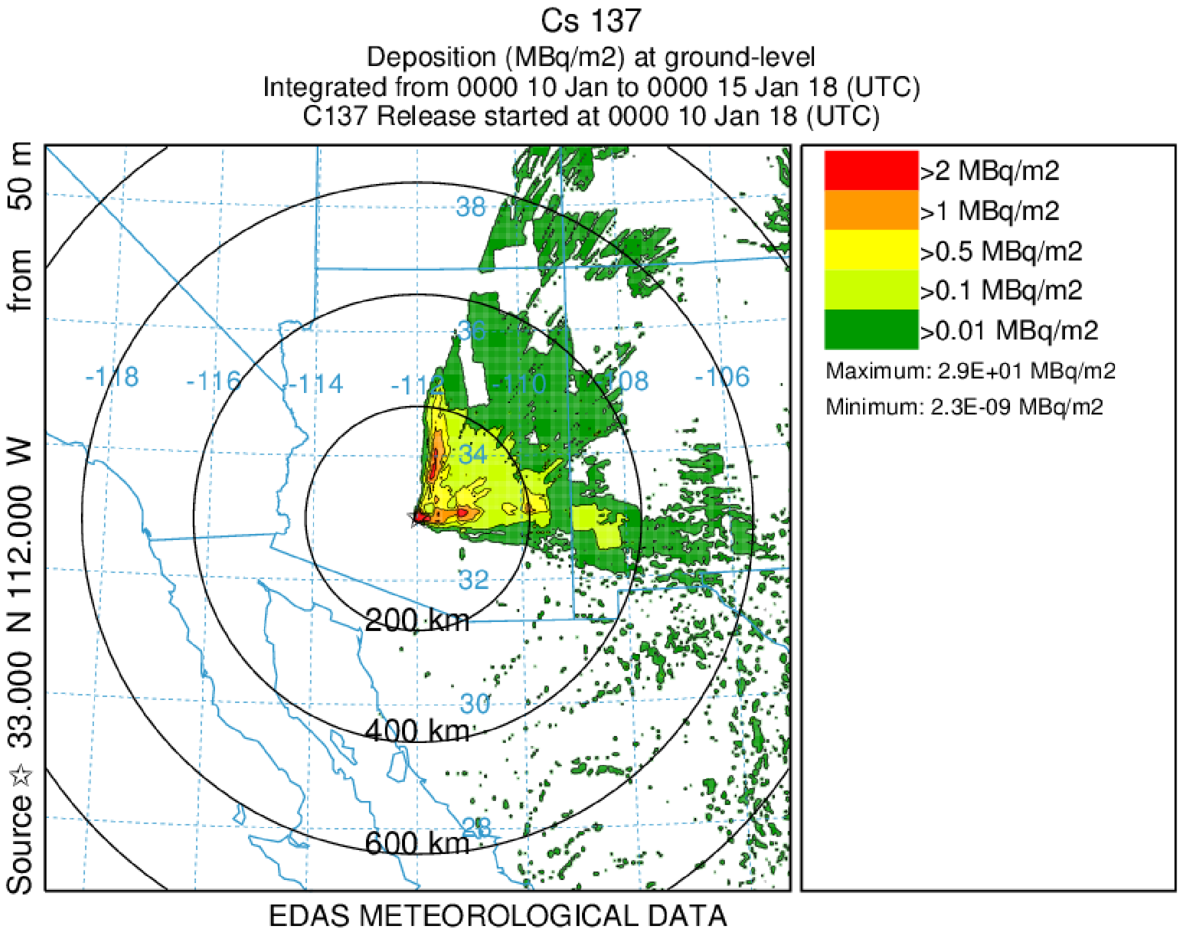


Figure 12.: Contaminated areas from a hypothetical SFP fire releasing 74 PBq of ^{137}Cs to the environment. This activity corresponds to the amount of ^{137}Cs released during the Chernobyl accident. Colors represent areas of ground deposition (in MBq/m2) according to their severity. Areas in orange and red would in general be subject to compulsory relocation. Affected areas were calculated using the HYSPLIT model together with real meteorological data. This image has illustration purposes only, thus location and dates have been chosen arbitrarily.

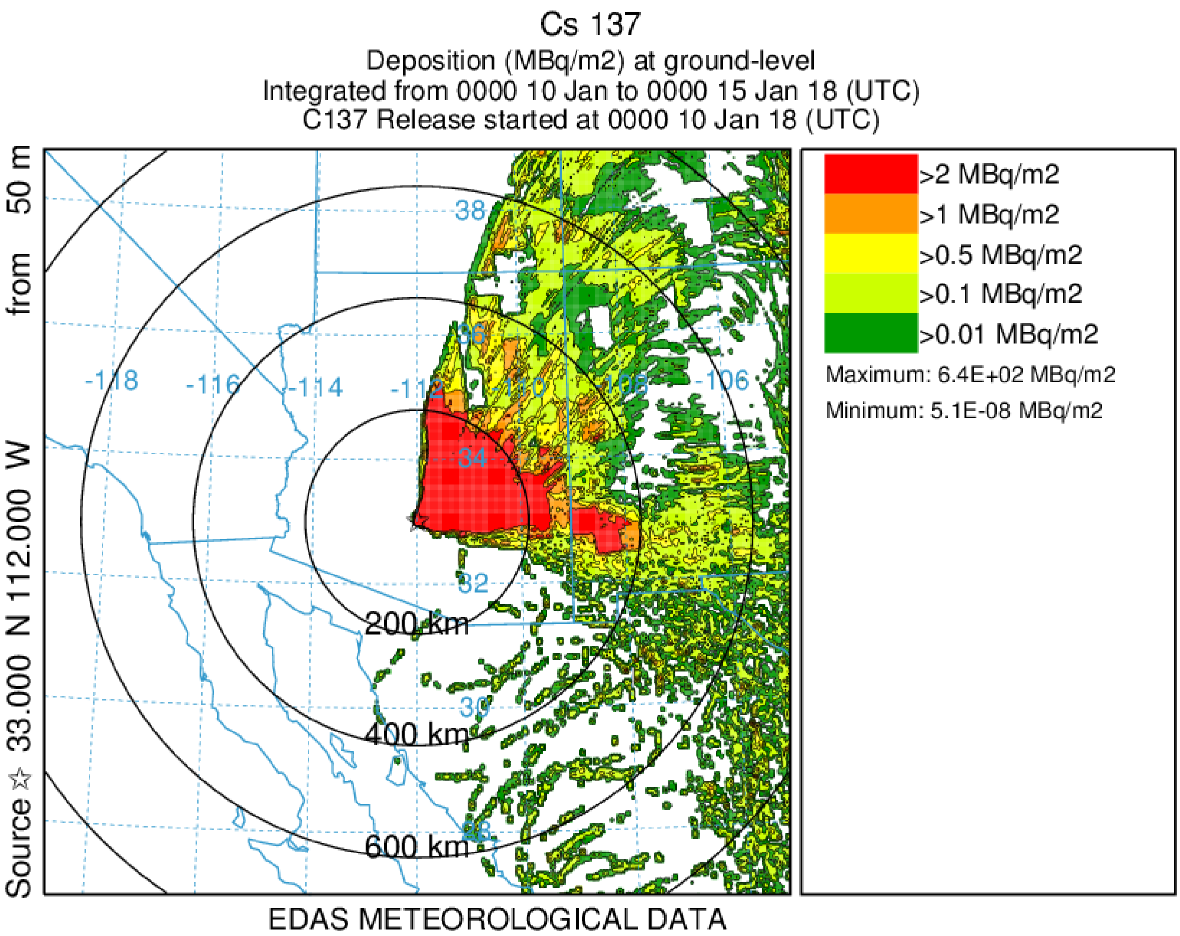


Figure 13.: Contaminated areas from a hypothetical SFP fire releasing 1600 PBq of ^{137}Cs to the environment. This activity is based on the inventory stored in a typical US SFP. Colors represent areas of ground deposition (in MBq/m2) according to their severity. Areas in orange and red would in general be subject to compulsory relocation. Affected areas were calculated using the HYSPLIT model together with real meteorological data. This image has illustration purposes only, thus location and dates have been chosen arbitrarily.

There have been attempts to quantify the consequences of a SFP fire. Studies estimate that 31 000 km^2 and millions of people would be affected by relocation, resulting in costs upward of 500 billion $.

3.4. Fukushima Daiichi Unit 4

The events that developed at the Fukushima Daiichi Nuclear Power Plant following the Great East Japan Earthquake on March 11^{th} 2011 are considered as one of the most severe accidents triggered by external events in nuclear power plant history. It further serves as a reminder that spent fuel pools are an important aspect to consider in the response to such an event. Even though all six units of the Fukushima Daiichi NPP were impacted by the earthquake and following tsunami, this section especially focuses on the events that occurred within reactor Unit 4 since it provides a unique aspect regarding the safety of SFPs.

At the time of the earthquake Unit 4 had been shut down for a planned refuelling outage since the 30^{th} November 2010. The reactor was disassembled with the head cover removed and the cavity gates were installed, isolating the SFP from the upper pools. Most importantly all fuel assemblies had been transferred from the core to the SFP. At the time of the accident a total of 1331 spent fuel assemblies and 204 new fuel assemblies were stored inside the SFP. The decay heat of all fuel assemblies was estimated to be 2.26 MW by 11 March. The SFP temperature was 27°C [22].

Following the earthquake and tsunami Unit 4 entered Station Blackout (SBO) conditions i.e. the loss of all AC power. Consequently the SFP lost its cooling and make-up capabilities. Unable to remove the decay heat the water temperature began to rise. In addition a loss of DC power prohibited the direct measurement of water levels and water temperature in the SFP. During the first days of the accident the SFPs were not considered a priority because it was assumed that the large water volume would provide sufficient time before fuel uncovery. This was also confirmed by initial visual inspection of the water level via helicopter. However on March 15^{th} a hydrogen explosion in Unit 4 raised concerns among operators since the production of hydrogen in Unit 4 would have implied at least partial fuel uncovery. Aware of the potential consequences a visual inspection via helicopter was initiated to assess the status of the SFP (see Fig.14). It was concluded that there was sufficient water in the Unit 4 SFP to cover the top of the fuel racks. Nevertheless the visible damage to the structure and knowledge about the amount of stored inventory caused concerns. Hence beginning with March, 20^{th} a series of water injections from external sources started. This included fire truck sprays, water cannons and concrete pump trucks until eventually a cooling system was installed [23]. Estimated water levels and temperatures of the Unit 4 SFP between March, 11^{th} and May 30^{th}, 2011 are shown in Fig.19. Later analysis found no significant fuel damage for the assemblies stored in Unit 4. Nevertheless the lessons learned form this sequence of events is that the

Figure 14.: Image of the Fukushima Daiichi Unit 4 taken during the helicopter overflight on March, 16^{th} 2011. The flight was undertaken to inspect the damage following a hydrogen explosion the day before. Visible is the refueling deck region and green fuel handling machine [25].

insufficient information about the state of the SFP made it difficult to assess the situation (Fig.14). It took over three weeks before first reliable water measurements could be taken. Further investigations of the accident point out two important events.
First, the hydrogen that caused the explosion in Unit 4 was probably transported through a pathway from Unit 3.
Second, it is thought that as water levels in the pool dropped because of evaporation, the pressure difference on the gate to the reactor well caused leakage around the gate seals. This lead to additional water filling the pool. Some studies estimate that without this inadvertent flow the water level would have dropped below the top of the fuel racks [24].

4. Theory

4.1. Decay Heat Generation

The major part of the total energy released during neutron induced fission of nuclear fuel is contributed by the kinetic energy of the fission fragments. However about 6 % of the resulting energy arises from gamma and beta radiation released by the natural decay of the various radioactive fission products and actinides in irradiated fuel. Their combined radioactivity is the reason why spent fuel needs to be safely stored for thousands of years. The radioactive decay also produces heat. Hence this so called decay heat will continue to heat up the fuel even after the reactor is shutdown and fission stops. The amount of heat produced at a point in time after shutdown can be approximated with the Wigner-Way Formula [26].

$$P_d(t) = 0.0662\, P_0\, [t^{-0.2} - (t_0 + t)^{-0.2}]$$

where:
$P_d(t)$ = Decay heat power at time t
P_0 = Thermal power before shutdown
t_0 = Time of power operation before shutdown
t = time elapsed since shutdown

Unattended the remaining decay heat could produce enough heat to damage the fuel elements. Hence spent fuel requires continuous cooling in order to prevent overheating of the fuel elements.
It is possible to calculate the cumulative decay heat produced by a spent fuel pool, using codes like ORIGEN [27]. They require however detailed knowledge of the fuel inventory and their irradiation history. This information may not be readily available to emergency response organizations during an accident. Thus it remains a factor of uncertainty. Nevertheless standards for the decay heat are available [28], and predetermined graphs (Fig.: 16) together with operational experience could be used to produce reasonable estimates.

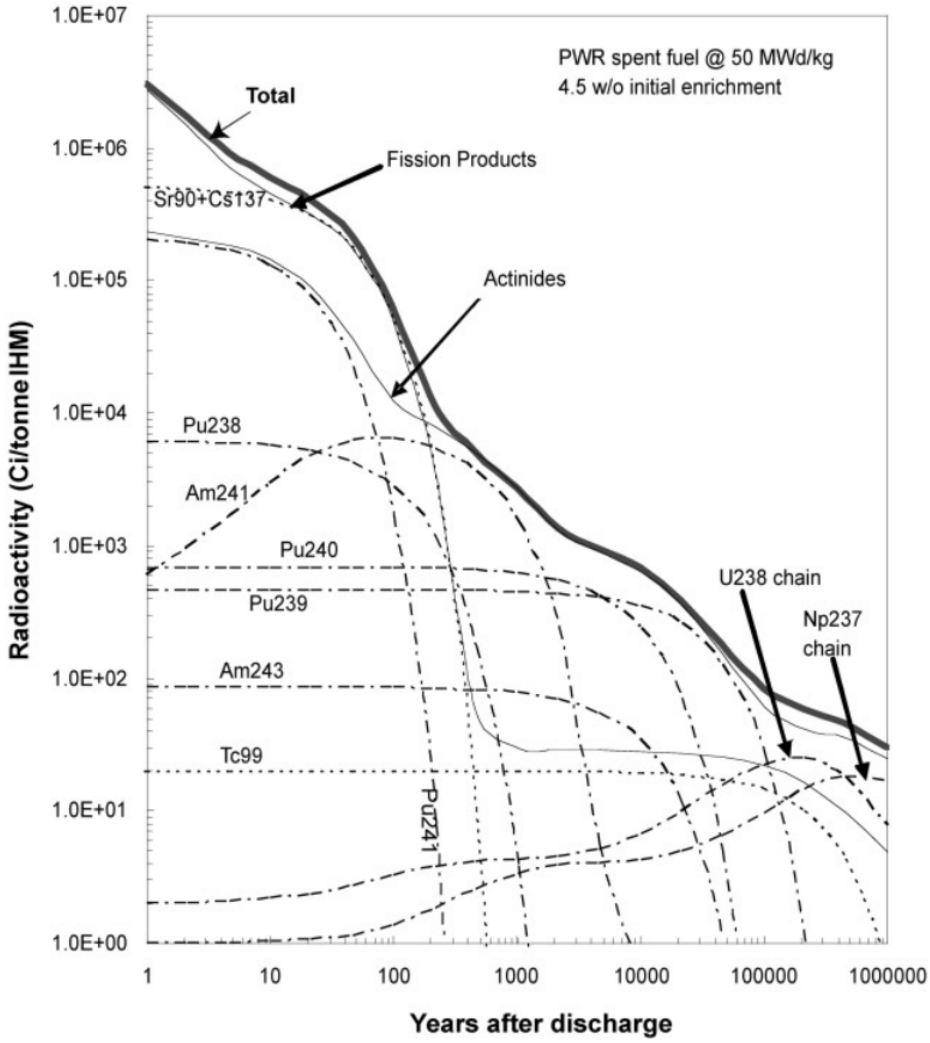


Figure 15.: Radioactivity of typical PWR fuel after years of discharge [29].

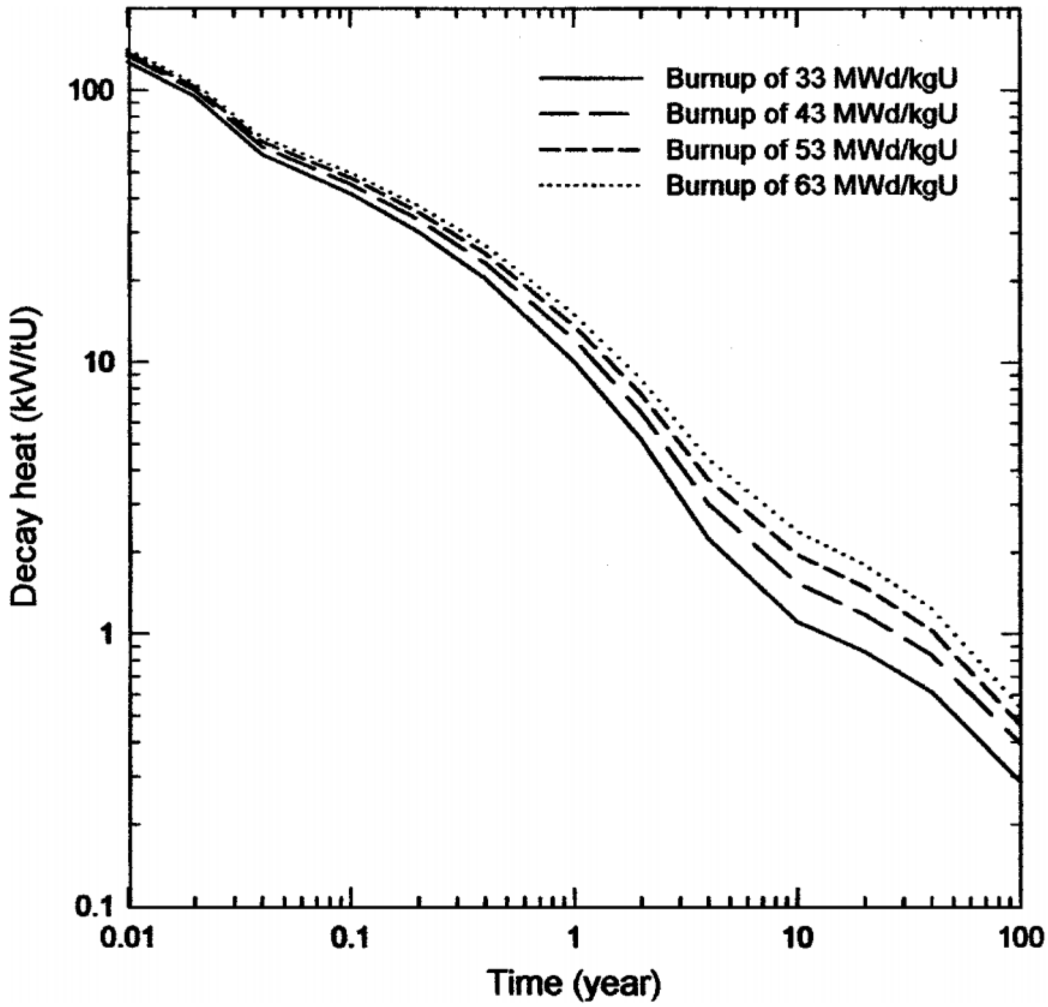


Figure 16.: Decay heat of typical PWR fuel with different burnup in relation to years after discharge [21].

4.2. Evaporation and Cooling

After a loss of SFP cooling the decay heat of the stored spent fuel will heat up the water in the SFP. Heat is able to leave the pool via conduction through the pool walls, water surface thermal radiation, natural air convection or evaporation. However previous studies have shown that the major part of the energy is lost through evaporation, while the remaining losses via radiation, convection and conduction can be combined into a single loss value of ~5% [30].
Thus good estimations for evaporative losses are not only useful for designing, maintaining and operating the SFP, but can provide critical information such as how much time is available before the fuel is uncovered, or the water temperature in case of a severe accident. During an accident competing needs between the SFP and other reactor systems can arise, considering that limited make-up capabilities may only be available. For example, diverting coolant from the RPV to the SFP prematurely can lead to unnecessary damage to the core or containment, but waiting too long to provide SFP coolant make-up may result in fuel uncovery. Using basic thermodynamics it is possible to create a simple model to predict SFP water levels. Some simplifying assumptions of this model are:

- The pool water has a uniform temperature
- Density, specific heat and specific latent heat of vaporization for water are constant
- Spent fuel is modeled as a thermal energy source
- Thermal energy losses due to radiation, convection, and conduction are combined into a single loss value of ~5%
- Effects after fuel uncovery are not considered, hence the model is only valid for water levels above the top of the fuel
- Once evaporated, water does not condense and flow back into the pool

Considering conservation of mass, the amount of water in the pool at a time t after the loss of SFP cooling can be described as:

$$M(t) = M_0 + \int_0^t \dot{m}_a(t)\,dt - \int_0^t \dot{m}_e(t)\,dt - \int_0^t \dot{m}_l(t)\,dt$$

where:
t = time since the loss of SFP cooling [s]
$M(t)$ = SFP water mass at time t [kg]
M_0 = initial SFP water mass [kg]
$\dot{m}_a(t)$ = rate of water being added to the SFP [$\frac{kg}{s}$]
$\dot{m}_e(t)$ = evaporation rate [$\frac{kg}{s}$]
$\dot{m}_l(t)$ = leak rate [$\frac{kg}{s}$]

And conservation of energy in the pool can be modeled as:

$$M(t)\,c_p\,\Delta T = \int_0^t \dot{q_{dh}}(t)\,dt - \int_0^t \dot{q_{loss}}\,dt - \int_0^t \underbrace{L_v\,\dot{m}_e(t)}_{\dot{q_e}(t)}\,dt - \int_0^t \dot{m}_a(t)\,dt\,c_p\,\Delta T_a$$

where:
t = time since loss of SFP cooling [s]
$M(t)$ = SFP water mass at time t [kg]
c_p = isobaric specific heat capacity of water [$\frac{J}{kg\,K}$]
ΔT = change of SFP water temperature [K]
ΔT_a = temperature difference between SFP water and make-up water [K]
$\dot{q_{dh}}(t)$ = thermal energy of the decay heat [W]
$\dot{q_{loss}}(t)$ = thermal energy lost by radiation, convection or conduction [W]
$\dot{q_e}(t)$ = thermal energy lost through evaporation [W]
L_v = specific latent heat of vaporization for water [$\frac{J}{kg}$]
$\dot{m}_e(t)$ = evaporation rate [$\frac{kg}{s}$]
$\dot{m}_a(t)$ = rate of water being added to the SFP [$\frac{kg}{s}$]

A schematic view of the mass-energy balance is shown in Fig 17.

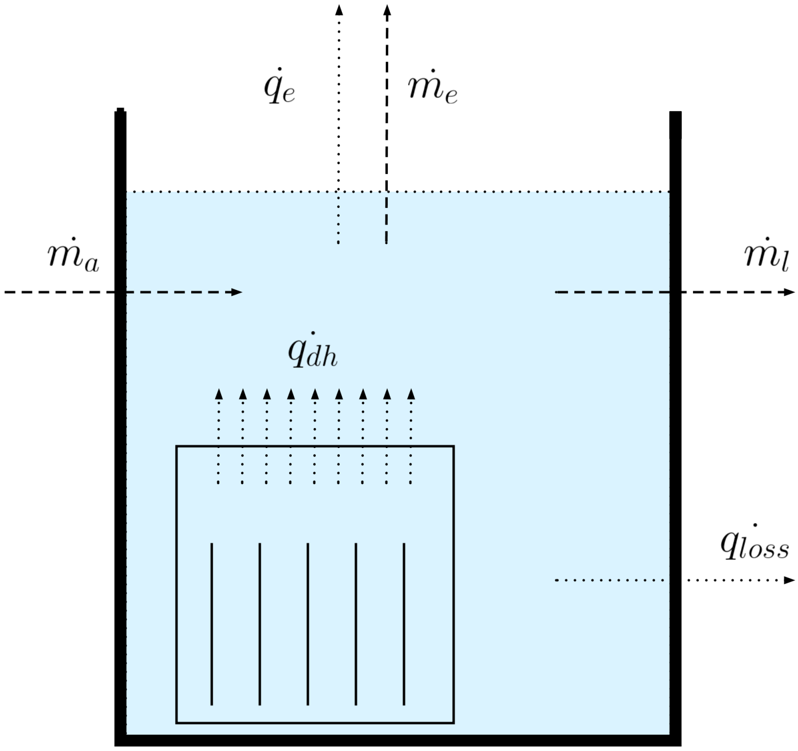


Figure 17.: Schematic illustration of the heat-mass balance in the event of lost SFP cooling capabilities.

It is evident that the amount of energy that can be carried off by evaporation is proportional to the evaporation rate. When cooling systems are lost, the temperature of the water will start to rise until it reaches the boiling point or the so called equilibrium temperature. At equilibrium temperature the rate of energy lost due to evaporation is equal to the rate of energy added to the system. Hence it is the maximum temperature a SFP can reach with a certain decay heat load. After reaching the equilibrium temperature all available decay heat is used for vaporization. In addition, the evaporation rate can easily be calculated based on the energy balance:

$$\dot{m}_e = \frac{\dot{q}_{dh} - \dot{q}_{loss}}{L_v} = \frac{\dot{q}_e}{L_v} \tag{3}$$

However during the heat-up phase, the evaporation rate is most easily derived from empirical models. Established methods therefore often use experimental data to fit their model. Multiple empirical equations have been proposed and they generally follow the format, or variations of:

$$\dot{m}_e = C\,A\,(p_w - p_a)$$

where:
C = numerical constants and transport coefficients
A = water surface area
$p_{w,a}$ = partial pressure of water vapor in air. For water (w) or room air (a) temperature

Fig.18 illustrates and compares three of these models from previous studies for a specific pool configuration.

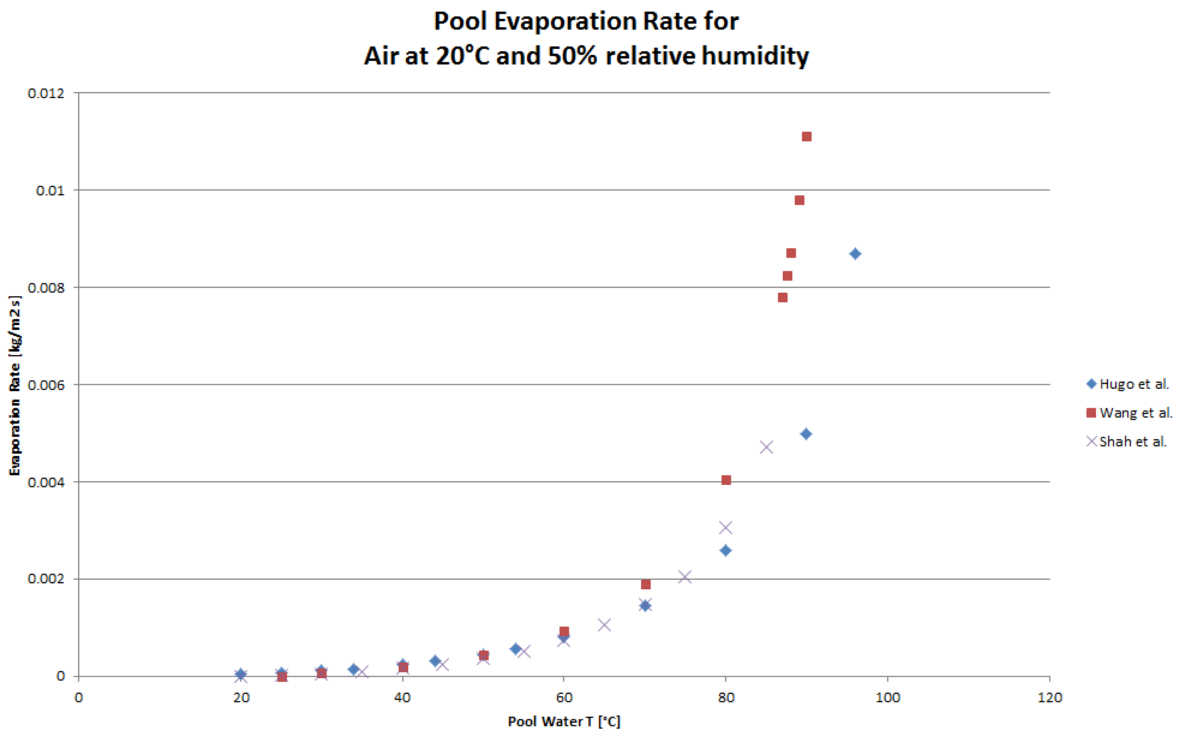


Figure 18.: Different models for the specific evaporation rate (in $\frac{kg}{sm^2}$) for a given SFP temperature, with surrounding air at 20°C and 50% relative humidity. Wang et al. [27]. Hugo et al. [31]. Shah et al. [32]

These models can be used to estimate the evaporative losses during the heat-up phase of the pool. In order to achieve conservative estimates, the model with the highest predicted evaporation rate was chosen for calculations.
Using these relations, and if the central initial conditions of the SFP are known, it is then possible to predict the evolution of the SFP water level and derive other parameters. Required initial inputs are pool dimensions, water temperature, top-of-fuel height and decay heat.

4.2.1. Evaluation of the model

In order to test the feasibility of the model, its results can be compared to measurements and other models for the Fukushima Daiichi Unit 4 SFP. The official measurements and predictions as released by TEPCO [33], can be seen in Fig.19. The TEPCO-calculated decay heat of Unit 4 on March 11 was **2.26 MW**. According to the proposed model, this would correspond to an equilibrium temperature of ∼90°C as can be seen from Fig.20, which is in accordance with the measured values in Fig.19.

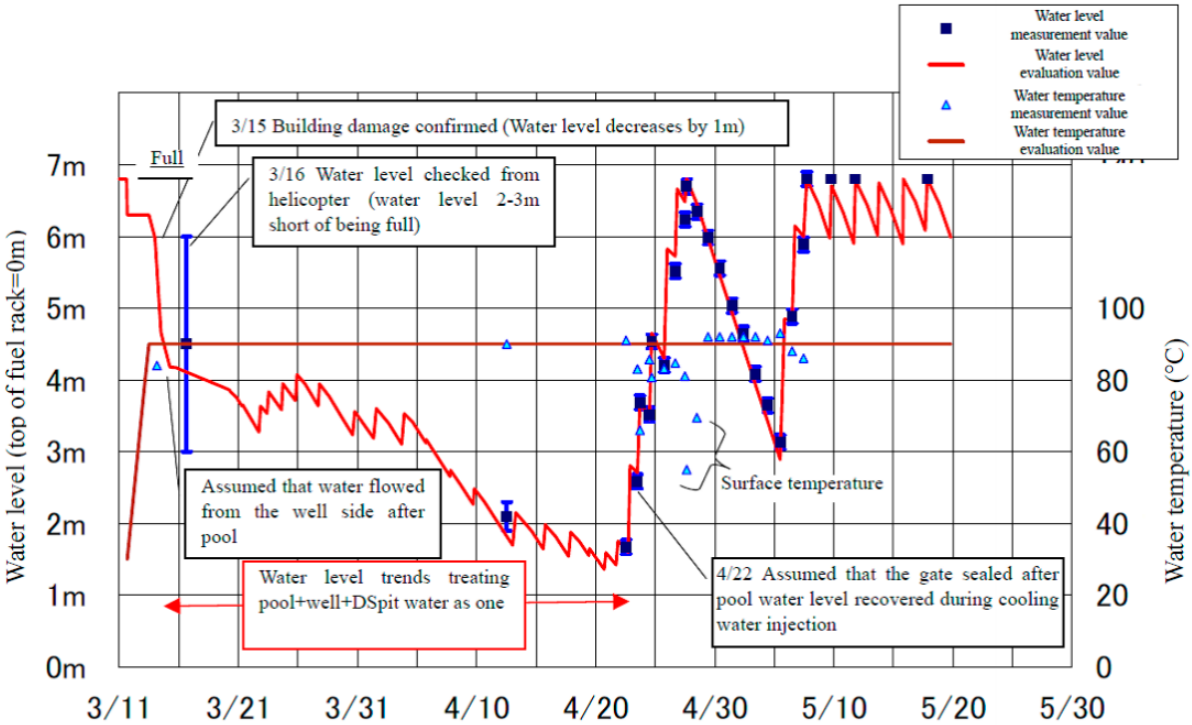


Figure 19.: Water levels and temperatures in the Unit 4 spent fuel pool at the Fukushima Daiichi plant from March 11 to May 20, 2011 as estimated by TEPCO [33].

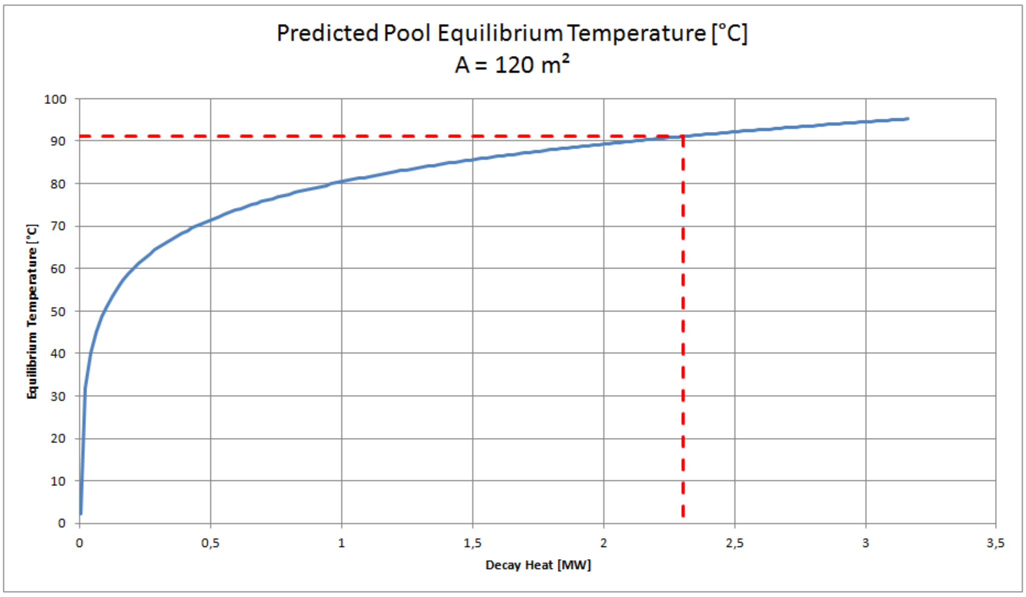


Figure 20.: Predicted equilibrium temperature for a SFP with an surface area of 120m^2. This surface area corresponds to the Fukushima Daiichi Unit 4 SFP.

5. Assessment Tool

5.1. Objective and Scope

When it comes to the management of emergencies one of the most critical aspects is the capability to quickly and competently respond to, and estimate the consequences of an accident. Especially in events involving nuclear facilities it is important that response actions, like evacuation or sheltering, are initiated promptly in order to be effective. Evidently the overarching objective for emergency response to nuclear or radiological emergencies is to prevent or reduce deterministic or stochastic health effects.
In many cases the amount of information available during the early stages of an accident may be limited or unreliable. In addition, response actions generally need to be implemented before detailed calculations or measurements can be made. Therefore the assessment process should be **predetermined, simple and effective**.
In order to help with the assessment process this thesis proposes a tool that provides guidance, and the information needed to evaluate the consequences of an accident involving a SFP. It is intended to be used by emergency organizations tasked with the assessment of the accident, and aims to help the decision making process. When using this tool a trained professional can create an assessment report of the current situation. The goal of the generated status report is to help high-level authorities, who may not be experts in nuclear engineering, to understand the situation and thus make informed decisions. However only the technical aspect of SFP accident assessment is within the scope of this tool and it does not recommend emergency procedures such as the implementation of public protective actions or activation of response units.

5.2. Assessment Tool Concept

The assessment tool will guide users through a form with the intention that they focus on the important safety aspects regarding SFPs. Central aspect for the assessment is the status of fission product barriers and critical safety functions. The high-level structure of the form follows the format of:

- General Information
  - Name of the facility
  - Description of the event
  - Date
- Step 1: Water Inventory Control
  - Water Inventory
  - SFP Make-Up Sources
- Step 2: Critical Safety Functions
  - Decay Heat Removal
  - Fuel Integrity
  - Radiological Protection
  - Subcriticality
- Step 3: Additional Information
  - Electrical Systems
  - Access to the SFP

Users will be tasked with determining the status of the relevant function, which can either be normal, degraded or failed. To help the decision making process detailed instructions with relevant information to the technical aspects and impacts are provided. Instructions for each section follow the general format of:

Instructions

Function Normal
Condition for normal function
Function Degraded
Condition for degraded function
Function Failure
Condition for failed function

Technical Background *A brief description of the system and basic technical information needed to understand its function and potential consequences.*
Simple Questions to Consider *A list of questions that may be helpful in determining the status of the function.*

Step 1: Water Inventory Control

During an emergency at a Spent Fuel Pool (SFP), being able to keep the fuel racks covered with water is the central aspect for the safety of the SFP and practically all other safety functions depend on this. As long as the spent fuel is sufficiently covered with water there should be no risk of overheating or significant radiological releases to the environment. It is therefore the essential objective in responding to accidents involving SFPs.

Water Inventory

Evaluate the current situation and determine the status of the water inventory. The characteristic parameters are the water level and temperature. A degraded/failed function of any of these would draw an overall degraded/failed status.

Function Normal
Water level and temperature are within operational limits and are able to be maintained.
Function Degraded
Water level and/or temperature have not exceeded any limits, however they may be challenged in the future.

Function Failure
The water level and/or temperature are not controlled. Fuel uncovery has occurred or is expected to take place in the near future.

Technical Background The water inventory is the essential element in evaluating the safety of a SFP and water levels should always be maintained above the top of the spent fuel. A significant loss of water inventory leading to fuel uncovery could lead to severe fuel damage and radiological releases. Possible events which could cause a loss of water inventory include a seismic events leading to leakage through the SFP structure or connected systems. In case a break in the piping of the SFP occurs, consider that most SFPs are equipped with design features like siphon breakers which help to to prevent significant draining of the pool. Also consider that water losses could lead to flooding of the surrounding area and impair access or equipment. At high water temperatures evaporative losses could become significant. In this case consider estimating the time until fuel uncover if the loss rate can be determined.
Simple Questions to Consider:

- What is the water level in the SFP?
- Are there any leaks in the SFP structure or connected systems?
- What is the water temperature?
- Is visual inspection possible? Are there any signs of significant evaporation?
- Is access to the SFP restricted in any way?

SFP Make-Up Sources

Evaluate the capability to maintain the water inventory through water supplement.

Function Normal
Make-Up sources of water are available to maintain the water inventory.
Function Degraded
Make-Up sources of water are available, however maintaining water inventory in the future is not ensured.
Function Failure
Make-Up sources of water are not available and/or loss rate of water inventory cannot

be compensated with the available Make-Up sources of water.

Technical Background In case of an accident sufficient coolant must be provided to remove the residual decay heat from the spent fuel. Make-Up sources which might be available include:

- Operational water storage tanks
- Fire protection system
- Sprays
- Condensate service water
- Refueling water storage tank
- External water sources (Firetruck sprays, portable pumps connected to seawater...)
- Passive Make-Up systems

Potential failure of these systems could include:

- Inadequate access to the Make-Up system
- Insufficient time to connect system
- Failure to start pumps

Even if make-up sources are available the impact of water addition will also depend on the amount of water that is lost due to leakage or evaporation. Consider that in general the large water mass of the SFP provides an ample time buffer for mitigation measures.

Simple Questions to Consider

- Are additional Make-Up systems required?
- Can Make-Up systems be connected?

Step 2: Critical Safety Functions

The objective of this section is to determine the status of the critical safety functions for a SFP. Failure of any of these functions represents a considerable threat to the safety of the SFP.

Decay Heat Removal

Evaluate the current situation and determine if decay heat can adequately be removed from the SFP.

Function Normal

Decay heat can be transferred at a sufficient rate from the fuel to the coolant and the ultimate heat sink.

Function Degraded

Decay heat can be transferred from the fuel, but extended adequate decay heat removal is not ensured.

Function Failure

Decay heat cannot be sufficiently removed from the fuel. Fuel damage is possible.

Technical Background Adequate decay heat removal has the capability to:

- Transfer decay heat from the fuel to the coolant
- Transfer decay heat from the coolant to a ultimate heat sink
- Maintain the coolant at stable temperature and volume
- Prevent fuel damage

During normal operation the decay heat is discharged via the SFP cooling circuit to an ultimate heat sink. Main components of the cooling system are circulation pumps and heat exchanges. If cooling circuits are lost alternative decay heat removal mechanisms would be available:

- Evaporation of the water inventory
- Steam cooling of partially uncovered fuel elements

- Natural air convection in case of complete drainage of the pool
- Some NPPs have the capability to align the residual heat removal (RHR) system

The effectiveness of these mechanisms depends on the storage configuration and fuel characteristics. Elevated pool temperatures, rising pressure in the SFP building and steam production indicate inadequate decay heat removal.

Simple Questions to Consider

- Is decay heat transferred from the spent fuel to the coolant?
- Is decay heat transferred from the coolant to an ultimate heat sink?
- Is the coolant volume increasing, decreasing or stable?
- What is the pool temperature?
- Are there indications of boiling?
- Can alternative cooling systems be aligned?
- How much fuel is stored in the SFP?

Fuel Integrity

Evaluate the current situation and determine the status of the stored fuel.
Function Normal
Fuel is not damaged.
Function Degraded
Fuel is not damaged, but maintaining fuel integrity is not ensured. This is also appropriate for a situation where fuel may have experienced physical mechanical damage from falling debris but is not at risk of further damage from overheating.
Function Failure
Fuel damage is imminent or confirmed.

Technical Background Damage to the stored fuel could occur due to heavy load drops, corrosion or other mechanical failures. This type of fuel damage is not considered to be complete fuel failure as the damage and potential release should still be very limited. Severe fuel damage is possible after the onset of fuel uncover due to overheating. Phenomena related to fuel overheating after the water level drops below the top of the fuel include:

- Fuel swell/burst
- Gap release
- Zirconium Oxidation
- Zirconium fire
- Fission product release
- Dislocation from initial geometry
- Damage to fuel racks

Oxidation of the fuel cladding could lead to increasing hydrogen levels in the building with the potential for hydrogen combustion. Potential symptoms for fuel damage are:

- Increased radiation levels in the SFP building
- Measurement of hydrogen in the SFP building
- Uncovered fuel elements

It is also important to consider that it is possible for spent fuel to be completely uncovered and still not overheat. Cooling may be provided via natural convection of air in this situation which would prevent fuel damage. This is dependent on the age of the fuel, air flow rate and the physical geometry of the spent fuel arrangement in the pool.

Simple Questions to Consider

- Are there indications of elevated radiation levels in the SFP building?
- Are there signs of evaporation or boiling?
- What is the water level in the SFP?
- What is the temperature/pressure in the SFP building?

- Are inspection methods available?
- Is it possible to measure hydrogen levels in the SFP building?

Radiological Protection

Evaluate the current situation and determine the capability of the SFP to contain radioactive material and shield from radiation.

Function Normal

Radiological protection is ensured.

Function Degraded

Extended radiological protection is not ensured.

Function Failure

A release is taking place and /or radiation shielding is not provided.

Technical Background In SFPs radiological protection is provided by the water volume above the stored fuel. Decreasing water levels would impair the radiation shielding function of the SFP. In most cases the fuel cladding is the only fission product barrier. Failure of the fuel cladding would likely lead to radioactive releases to the environment. The isotopic composition and extent of the release would thereby depend on the characteristics of the fuel stored in the SFP. Consider that in general SFPs are not located inside a containment. While ventilation systems with filtering capabilities may be available, SFP buildings are usually not leak tight and offer pathways for radiological releases into the surrounding areas. Releases under water are usually contained in the pool water and could be handled by the SFP water purification system.

Simple Questions to Consider

- What fuel inventory is stored (burnup, storage history)?
- Is the SFP inside a containment?
- What is the water level?
- Can radiation levels be measured? Are filtration systems available?

Subcriticality

Evaluate the current situation and determine if subcriticality of the stored fuel is ensured.

Function Normal

Subcriticality of the stored spent fuel is ensured.

Function Degraded

Subcriticality of the stored spent fuel is provided, however criticality safety functions are challenged.

Function Failure

Subcriticality cannot be ensured.

Technical Background Note that conservative safety margins (usually $k_{eff} < 0.95$) make SFP criticality events unlikely even during accident conditions. Criticality control could be lost because of:

- Damage to the spent fuel geometries necessary to ensure subcriticality, e.g. heavy load drop.
- Damage to neutron absorbers where subcriticality depends on them, e.g. melting of absorber plates.

In the event that critically of spent fuel is achieved, fuel would get severely damaged resulting in release and dispersion of fission products.

Simple Questions to Consider

- What type of fuel is stored?
- What is the safety margin for k_{eff}?
- Spent fuel parameters (e.g. initial enrichment, final enrichment, burnup)?
- What storage configuration is used (high density/low density)?
- Are additional neutron poisons required?
- Is the fuel rack geometry intact?
- Is the fuel covered with water?
- Are neutron monitoring devices providing any measurements?

Step 3: Additional Information

Electrical Systems

Evaluate the current situation and determine the status of the available AC and DC electrical power sources for SFP related systems. This includes all backup and emergency power supplies that may be available.

Function Normal

AC and DC power is available.

Function Degraded

AC and/or DC power is available, but continuous adequate power supply is not ensured.

Function Failure

AC and DC power has been lost.

Technical Background During normal operation off-site AC power is used to run safety equipment and DC power provides instrumentation and control of that equipment. If off-site power is lost multiple alternative power sources are usually available. This includes:

- Power generated from other units
- Emergency Diesel Generators
- Mobile Diesel Generators
- Batteries

Consider that emergency power sources may be available, but not connected to SFP related systems. In the event that power to the SFP cooling system is lost, the water inventory can provide an ample time-window for mitigation methods to restore power.

Simple Questions to Consider

- What are the available AC power sources?
- What are the available DC power sources?
- What mobile power sources are available?

- How much fuel for emergency generators is available?
- What is the expected lifetime of the station batteries?
- Are backup/emergency AC or DC power supplies available to the SFP systems?

Access To The SFP

Evaluate the current situation and determine if access to the SFP is possible.
Function Normal
Access to the SFP is possible.
Function Degraded
Access to the SFP is currently available but prolonged access cannot be ensured.
Function Failure
Access to the SFP is unavailable

Technical Background During an accident adverse conditions may limit the accessibility to the SFP and prevent fuel handling operations or mitigation measures. Such conditions include:

- Structural damage to the SFP building
- Heavy steam production
- Increased hydrogen levels
- Increased radiation levels
- Flooding

Simple Questions to Consider

- Is visual inspection of the building possible?
- Are there any signs of fuel damage?
- Is monitoring data available (radiation, hydrogen, water level,...)?

5.3. Prototype and Demonstration

As part of this work a prototype of the assessment tool has been created. The goal of this project is to demonstrate the desired functionalities, and serve as a basis for future developments. Technical details on the prototype and development process, as well as instructions on how to obtain the code can be found in Appendix B. This section provides a number of representative screenshots to illustrate the functions of the tool.

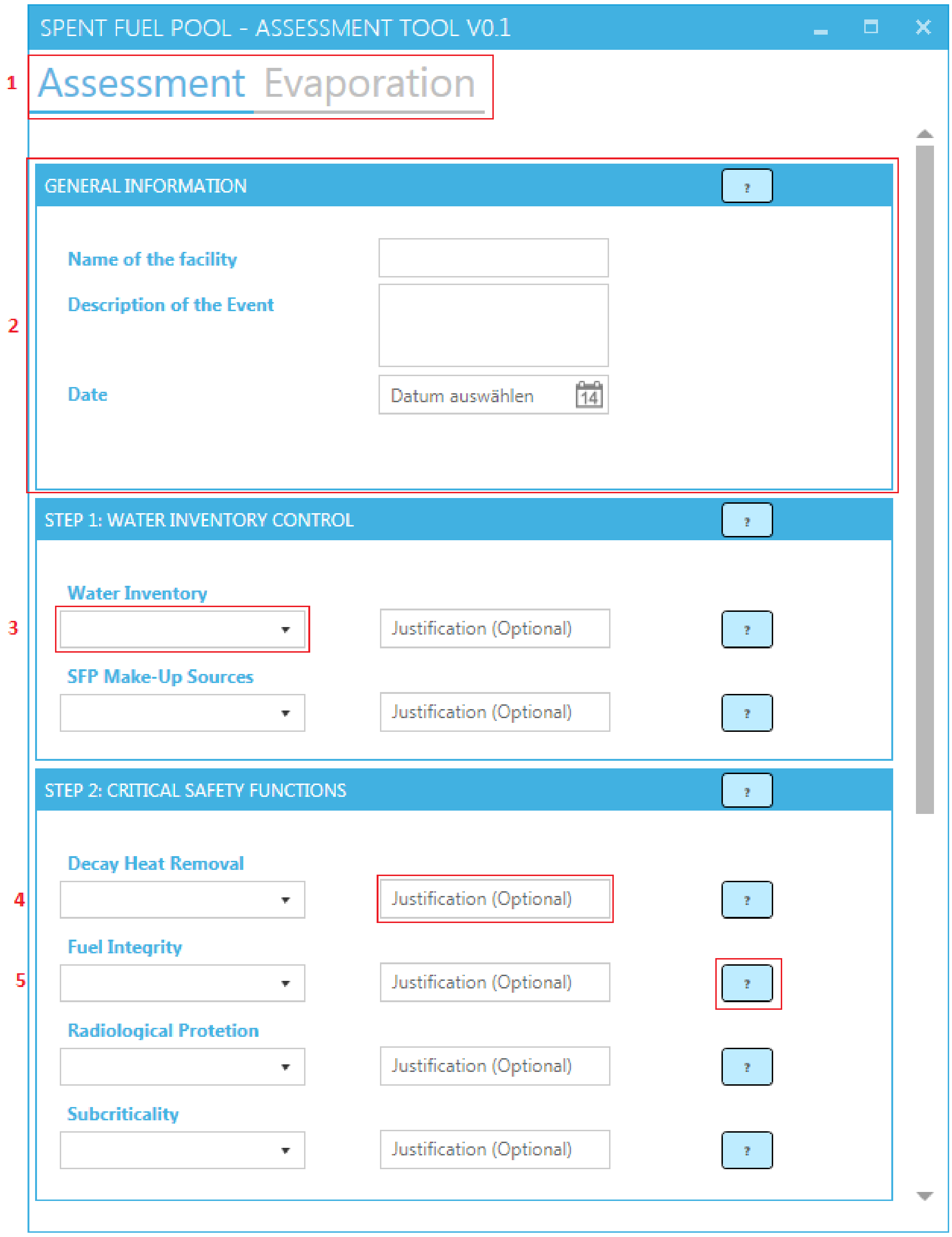


Figure 21.: General layout of the assessment tool. [1] The tab at the top lets the user switch between the functions of generating an assessment report ("Assessment"), and predicting the time available until the fuel is uncovered ("Evaporation"). [2] The tool follows the structure which is outlined in section 5.2, and expects the user to enter the relevant information. [3] Using the Drop-Down boxes, the user can select the status of the relevant safety function. [4] If possible a justification for the status can be provided in the adjacent text box. [5] Pressing the "?" button displays the instructions for the relevant section.

Figure 22.: By pressing the "?" button, the detailed instructions for the relevant section are displayed. The complete set of instruction is described in section 5.2. Pressing the arrow button on the top closes the instruction box.

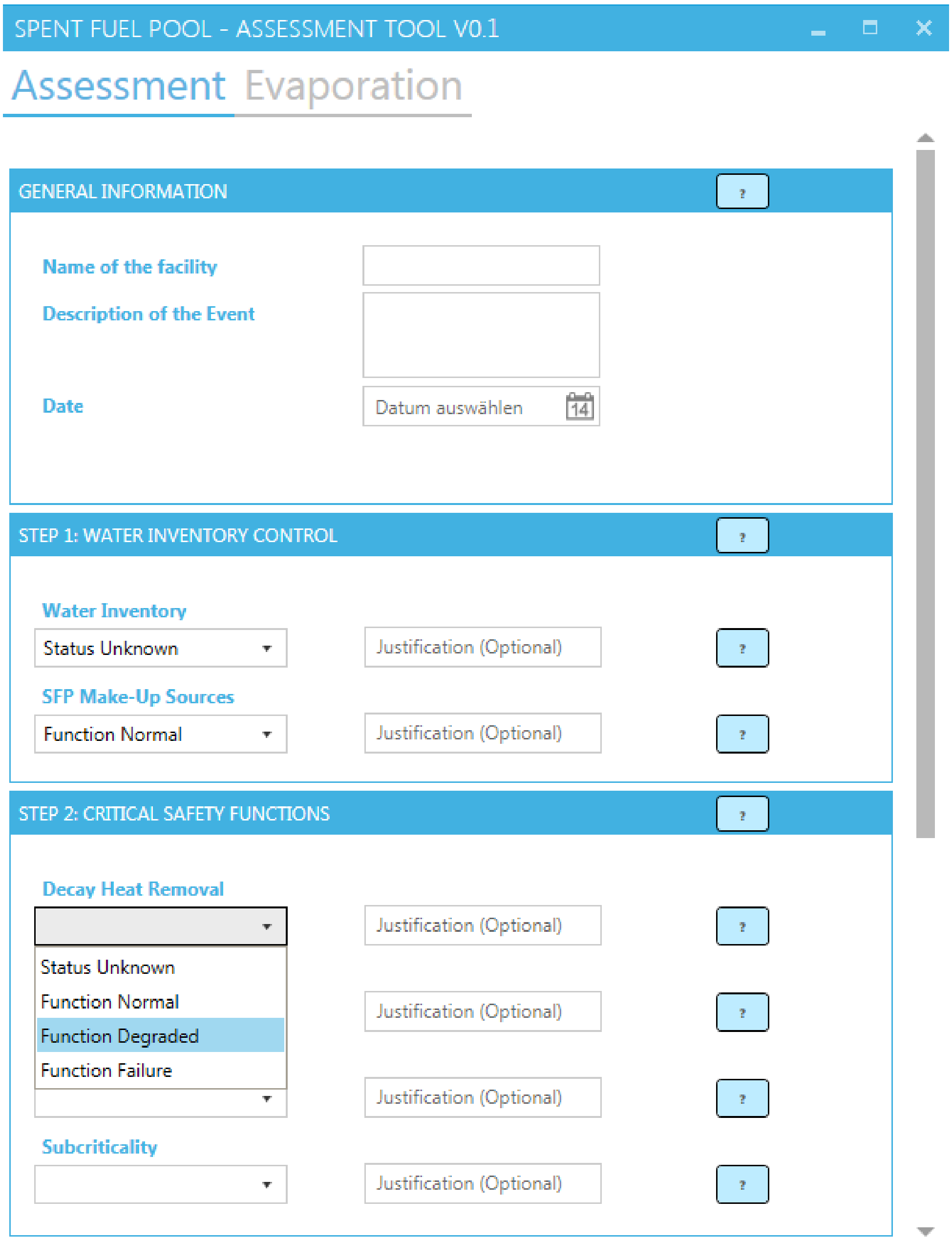


Figure 23.: The status of each safety function can be selected from a Drop-Down box.

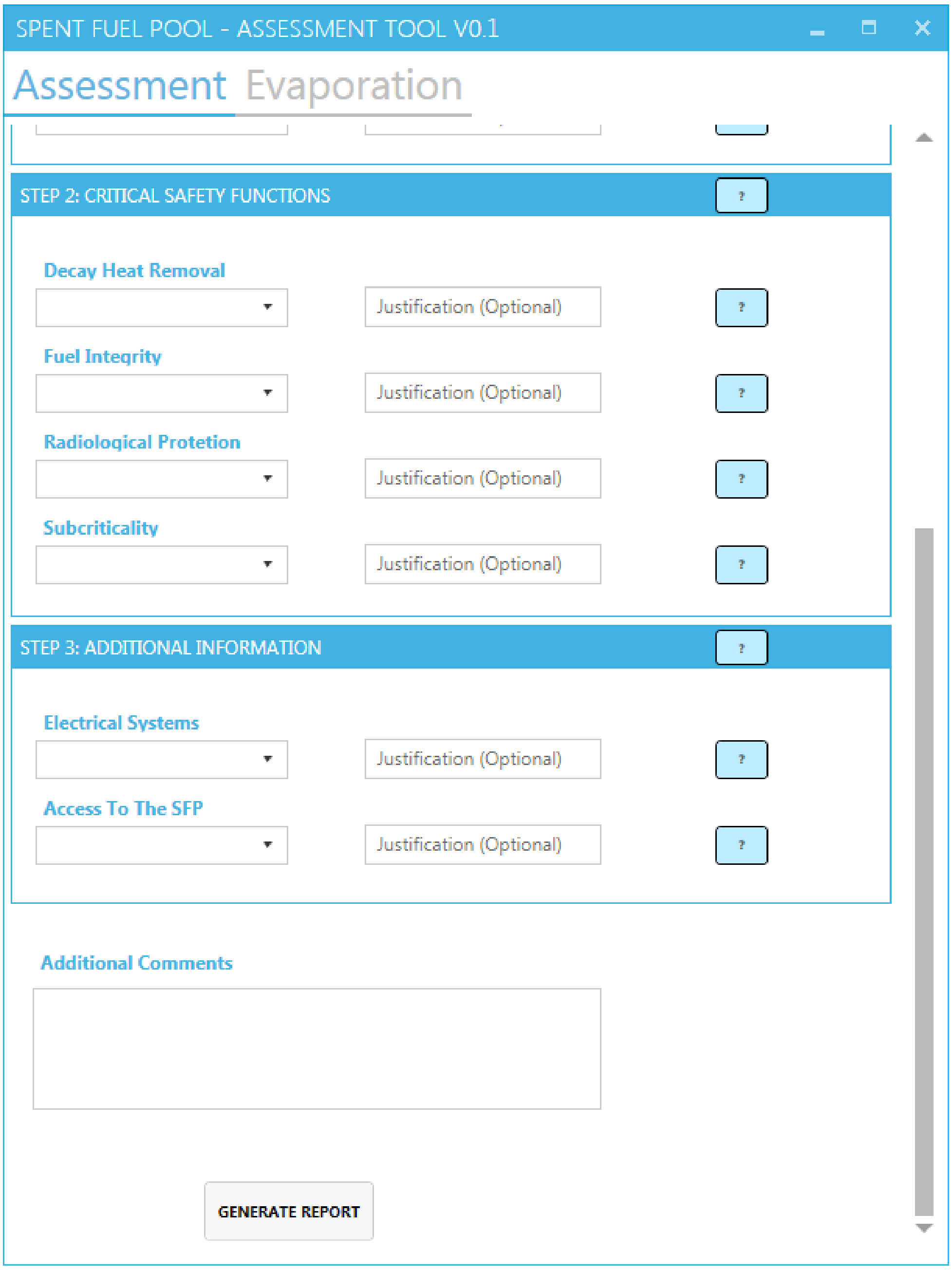


Figure 24.: At the end of the form the user is able to provide additional information about the event. Pressing the "Generate Report" button will open a Microsoft Word document that includes all the information provided by the user.

Spent Fuel Pool Assessment Report

Name of the facility: Lorem ipsum

Description of the Event: Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua.

Date: 01.01.2018

Function	*Status*	*Justification*
Water Inventory	Function Normal	Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua.
SFP Make-Up Sources	Function Failure	Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua
Decay Heat Removal	Function Normal	Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua.
Fuel Integrity	Status Unknown	
Radiological Protection	Function Normal	Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua.
Subcriticality	Function Normal	Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua.
Electrical Systems	Function Degraded	Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua.
Access To The SFP	Status Unknown	

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat.

Figure 25.: Exemplary report produced by the assessment tool. After filling out the form in the assessment tool, it is possible to generate a report in Microsoft Word that summarizes the information that was provided. The image above shows a screenshot of the generated Word document. The text that was chosen for this example is an arbitrary placeholder text.

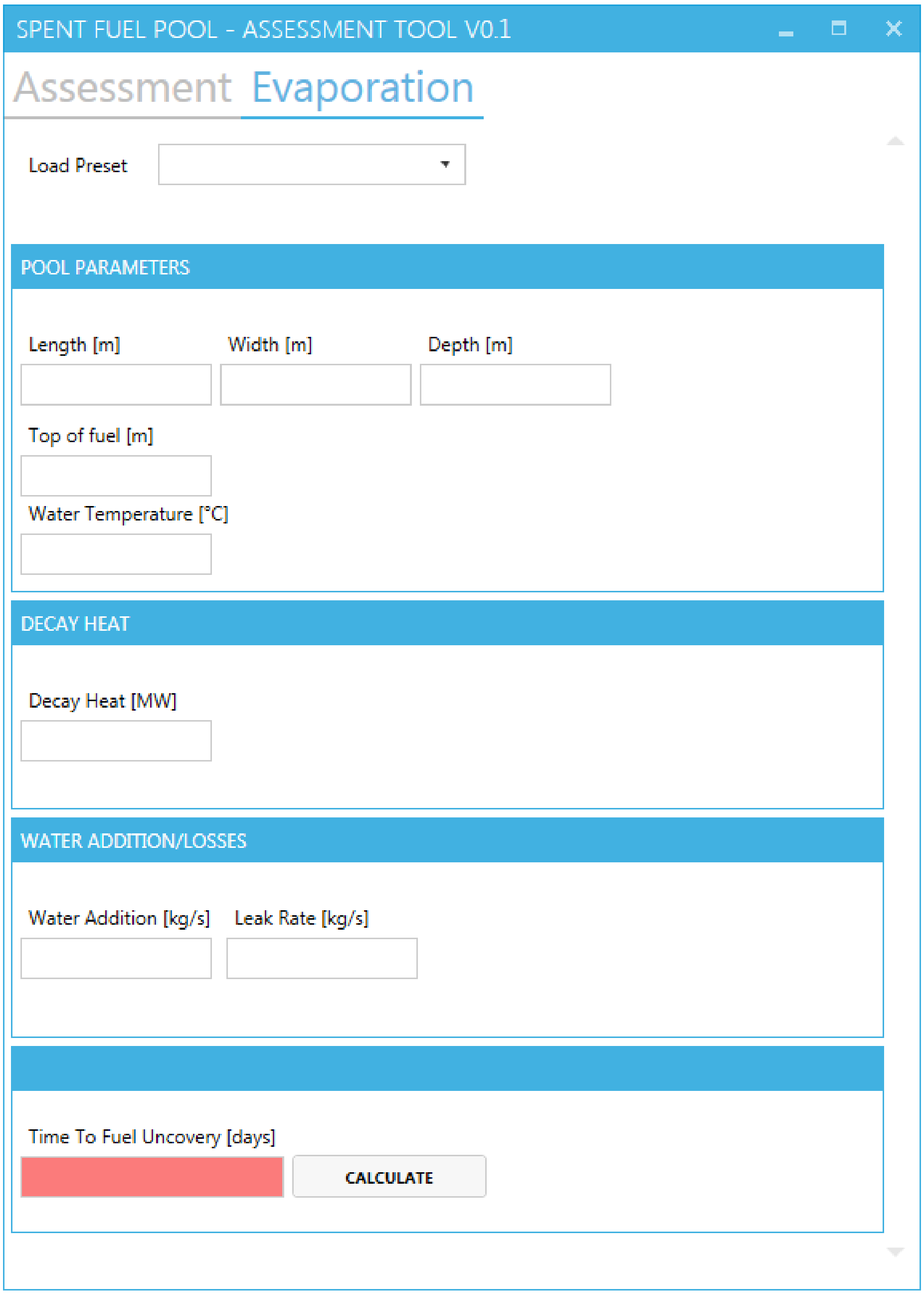


Figure 26.: In the evaporation tab, the user has the possibility to estimate the amount of time available before the fuel elements are uncovered.

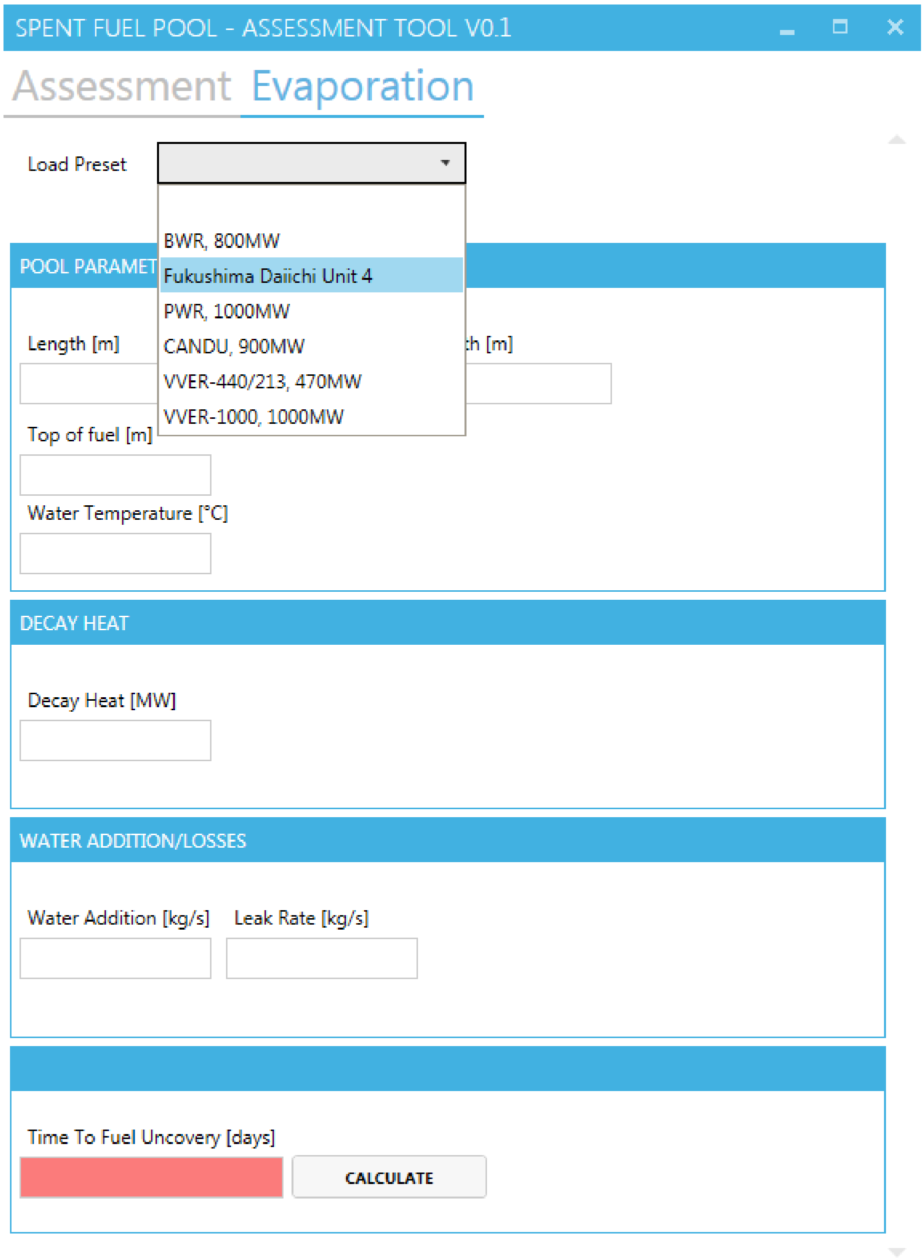


Figure 27.: From the Drop-Down box it is possible to select predetermined data-sets for common nuclear power plants. This can include average pool dimensions and decay heat output for a filled SFP.

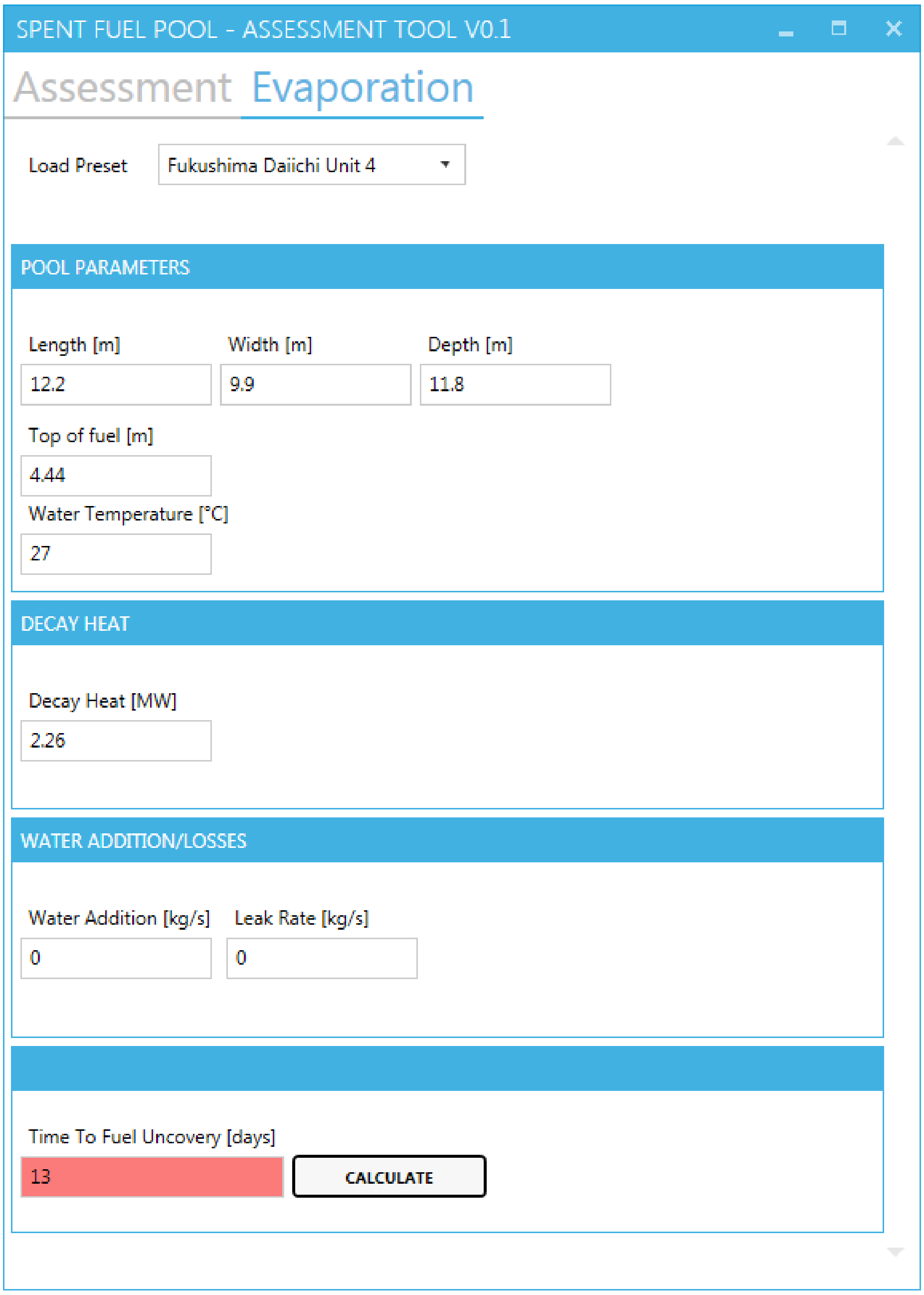


Figure 28.: Pressing the "Calculate" button, the tool provides an estimated time frame for the water level to drop below the top of the fuel elements.

6. Conclusion

In this thesis a method to assist the high-level assessment of accidents involving Spent Fuel Pools was proposed. A concept for a computer-based software tool was presented, which aims to guide trained professionals of emergency response organizations through the process of creating an assessment report of the situation. In many cases the amount of information available during the early stages of an accident may be limited or unreliable. In addition, response actions generally need to be implemented before detailed calculations or measurements can be made. Therefore the assessment process was designed to be predetermined, simple and effective. Thus the functionality of the most important safety functions are the focus of the assessment process. The generated report is supposed to help decision makers, who may not be experts in the field of nuclear engineering, to make informed decisions about further steps that may be required. The thesis provides an overview of the current status of wet-storage technologies for spent nuclear fuel. Storage designs for different reactor types are discussed, and critical safety functions identified. In addition, the reasons behind the increasing amount of spent fuel stored in intermediate storage are outlined. It is discussed how the significant amount of radioactive inventory has the potential for severe accidents. The phenomenology of SFP accidents is presented, with consequences reaching from an increase in water temperature to a spent fuel fire. A case study of the Fukushima Daiichi Unit 4 SFP, illustrates that this accident potential should not be neglected. Furthermore it was shown that a simplistic model, based on conservation of mass and energy, can be used to make reasonable predictions on SFP-related parameters such as water temperature, water level and time until fuel uncovery. The prototype of the assessment tool which is presented in this thesis could be expanded upon to produce more elaborate tools. Access to operational parameters, which are often not accessible to the public, could increase the effectiveness of this method.

As of 2018, the challenge of a final repository for spent nuclear fuel is still unanswered for many countries. Thus the safety of intermediate stored spent fuel elements in SFPs will continue to be a topic for discussion and research for the years to come. Overall the operation of SFPs is well understood, and their use is generally regarded as inherently safe. However history has shown that natural disasters, or even malicious acts by humans, can be unpredictable. In building a strong safety culture for nuclear power it is therefore never wrong to be well prepared.

A. Spent Fuel Pool Data

This appendix provides a brief overview of technical data for SFPs in operation in different countries. The data is based on a report from the Nuclear Energy Agency (NEA) [12].

Figure 29.: Overview of representative SFP data for CANDUs [12].

GENERAL INFORMATION	CANADA	KOREA
REACTOR TYPE	PHWR (CANDU) (515 to 880 MWe)	PHWR (CANDU6) (660 MWe)
CONTAINMENT TYPE	Single and multi-unit/Vacuum building	Single and multi-unit/Vacuum building
POOL LOCATION RELATIVE TO CONTAINMENT	Inside confinement / Spent fuel building, adjacent to containment	Spent fuel building, adjacent to containment
FUEL STORAGE POOL CAPACITY (Approximate Number of Fuel Assemblies)	50 000 - 200 000	44 688
POOL BOTTOM LOCATION RELATIVE TO PLANT GRADE	At or below grade	Below grade
NUMBER OF FUEL RODS PER ASSEMBLY	28 or 37	37
GEOMETRIC DIMENSIONS OF THE FUEL POOL		
LENGTH (m)	40	20
WIDTH (m)	10	12
DEPTH (m)	8	10
GEOMETRIC DIMENSIONS OF THE STORAGE RACKS		
MATERIAL	Stainless steel	Stainless steel
FRAME	Open	Open
CROSS FLOW BETWEEN RACK CELLS	Yes	Yes
CRITICALITY CONTROL	Fuel element spacing only	Fuel element spacing only

Figure 30.: Overview of representative SFP data for PWRs and VVERs [12].

GENERAL INFORMATION	BELGIUM	CZECH REPUBLIC		FRANCE		GERMANY	HUNGARY	JAPAN	KOREA		USA
REACTOR TYPE	PWR (440 to 1050 MWe)	VVER-1000 (1000 MWe)	VVER-440/213 (470 MWe)	PWR (900 to 1450 MWe)	EPR (1650 MWe)	PWR (1170 to 1410 MWe)	VVER-440 (470 MWe)	PWR	OPR-1000 (1000 MWe)	APR-1400 (1340 MWe)	PWR (480 to 1310 MWe)
CONTAINMENT TYPE	Large dry		Bubble condenser	-	-	Large dry	Bubble condenser	Large dry	Large dry	Large dry	Large dry
POOL LOCATION RELATIVE TO CONTAINMENT	Outside primary containment, adjacent	Inside primary containment	Outside primary containment, adjacent	Outside primary containment, adjacent	Inside primary containment	Inside primary containment	Outside primary containment, adjacent	Outside primary containme nt, adjacent	Outside primary containme nt, adjacent	Outside primary containme nt, adjacent	Outside primary containment, adjacent
FUEL STORAGE POOL CAPACITY (Approximate Number of Fuel Assemblies)	373 to 820	705	950	310 to 630	1100	800	1056	-	1500	1700	544 to 2363
POOL BOTTOM LOCATION RELATIVE TO PLANT GRADE	-	Above grade	Above grade	Above grade	Above grade	Above grade	Above grade	-	Above grade	Above grade	At or below grade
NUMBER OF FUEL RODS PER ASSEMBLY	179 to 264	312	126	264	264	300	126	179 to 264	236	236	208 to 264
GEOMETRIC DIMENSIONS OF THE FUEL POOL											
LENGTH (m)	-	13.05	6	12	12	9	6	-	8.6	12.8	6.7
WIDTH (m)	-	6.21	3.76	5.5	9	11.5	3.7	-	10.4	10.8	12.2
DEPTH (m)	-	8.1	15.07	12.5 to 14.2	14.4	13.5	15	-	12.6	12.8	13.1
GEOMETRIC DIMENSIONS OF THE STORAGE RACKS											
MATERIAL	-	Borated stainless steel	Borated stainless steel	Borated stainless steel/Stainless steel	Borated stainless steel	Stainless steel	Borated stainless steel	Borated stainless steel/ Stainless steel	Stainless Steel	Stainless Steel	Stainless Steel
FRAME	Square	Hexagonal	Hexagonal	Square	Square	Square	Hexagonal	Square	Square	Square	Square
CROSS FLOW BETWEEN RACK CELLS	-	No	No	No	No	No	No	No	No	No	No
CRITICALITY CONTROL	-	Solid neutron absorbers and borated water	Solid neutron absorbers and borated water	Solid neutron absorbers and borated water/Fuel element spacing	Solid neutron absorbers and borated water	Solid neutron absorbers and burn-up credit	Solid neutron absorbers and borated water	Solid neutron absorbers and borated water	Solid neutron absorbers and borated water	Solid neutron absorbers and borated water	Solid neutron absorbers and borated water

Figure 31.: Overview of representative SFP data for BWRs [12].

GENERAL INFORMATION	GERMANY	JAPAN	SPAIN	SWITZERLAND	USA	
REACTOR TYPE	BWR (1280 MWe)	BWR (460 to 1100 MWe)	BWR-6 (G.E.) (1096 MWe)	BWR (370 to 1220 MWe)	BWR (600 to 900 MWe)	BWR (1000 to 1400 MWe)
CONTAINMENT TYPE	Reinforced Concrete with Inner Steel Liner	Mark I/II	Mark III	Mark I/II	Mark I/II	Mark III
POOL LOCATION RELATIVE TO CONTAINMENT	Outside primary containment, inside reactor building	Outside primary containment, inside reactor building	Outside primary and secondary containment, in separate building	Outside primary containment, inside reactor building / In separate building	Outside primary containment, inside reactor building	Outside primary containment, in separate building
FUEL STORAGE POOL CAPACITY (Approximate Number of Fuel Assemblies)	3230	900 to 1770	5404 (in 2 SFPs)	-	2301 to 4117	3104 to 4348
POOL BOTTOM LOCATION RELATIVE TO PLANT GRADE	Above grade	Above grade	Below grade	Above grade	Above grade	At or below grade
NUMBER OF FUEL RODS PER ASSEMBLY	Up to 91	60 to 74	60 to 92	-	49 to 92	49 to 92
GEOMETRIC DIMENSIONS OF THE FUEL POOL						
LENGTH (m)	13	7.16 to 10.37	12	-	10.8	7.9
WIDTH (m)	11.5	12.04 to 12.20	11	-	12.2	12.2
DEPTH (m)	11.5	11.8 to 11.91	13.1	-	11.8	12.2
GEOMETRIC DIMENSIONS OF THE STORAGE RACKS						
MATERIAL	Stainless steel	Aluminum Borated aluminum Stainless steel	Stainless steel	Borated stainless steel	Stainless steel	Stainless steel
FRAME	Square	Square	Square	-	Square	Square
CROSS FLOW BETWEEN RACK CELLS	No	No	No	-	No	No
CRITICALITY CONTROL	Solid neutron absorber and burnup-credit	Fuel element spacing and solid neutron absorber	Fuel element spacing and solid neutron absorber	Solid neutron absorber	Solid neutron absorber	Solid neutron absorber

B. Assessment Tool Prototype

A functional prototype of the tool has been created with a free version of Microsoft Visual Studio 2017, which is an integrated development environment (IDE) from Microsoft. Development and testing was carried out on a 64-bit Windows 7 operating system, as well as on Windows 10 machines. Providing the full source code on paper would not be feasible. In order to obtain the project the author proposes two options. The entire project is documented and freely available under the following link (as of 2018):

`https://drive.google.com/open?id=14NX61XXs6uiYDxHyNet4xSOm4TCnf85R`

Should the link not suffice, requests can be directed to the author directly as well. The folder contains an exemplary executable, as well as the project folder that can be opened with Visual Studio. It requires a Windows operating system with a version of Microsoft Word 2007 or later. Though it should be noted that this is a prototype version, and full functionality on different computers is not guaranteed.

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