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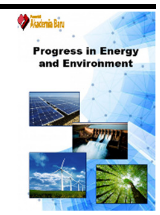

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Deterministic Safety Analysis for High Level Waste (Spent Fuel): Management of NPP, A Review

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ABSTRACT

The main purpose of this review paper is to identify, determine and analyze the possible hazards and risks during high level waste spent fuel management. The process consists of analyzing the safety issues and possible risks during waste management according to IAEA safety standard series. The analysis will revolve around four possible major accidents and hazards during high level waste (spent fuel) management. From the analysis, we will be able to identify the most suitable methodology and safety regulations in coherent with IAEA standards during high level waste management which assures the safety of plant personnel, public community and environment for clean, green and safe energy supply. A total of 64 paper have been review.

1. Introduction

Safety analysis is an important factor in for safety assessment in which it is used to show how safety requirement follow the international standard during operational conditions and several of initiating events [1]. According to IAEA, safety analyses are evaluation that uses analytical method where it overlook the physical phenomena occurring in the nuclear power plant [2]. Deterministic safety analysis is to demonstrate that a facility is tolerant to identified hazards that present in the design basis where it will define the limits of safe operations [3-4]. Deterministic safety analysis also can be defined through IAEA standards, where it says deterministic safety analysis for NPP predict the response to postulated events that initiated. There must be specific set of rules and criteria needed to be applied. It uses mathematical models that utilizes all keys of system in a plant to predict how much the hazards/radiation will spread [5-7].

There are objectives for deterministic safety analysis:

1. The design of a NPP must meet the design and safety requirements
2. Operational limits and conditions must be confirmed to be consistent with the design and safety requirement for NPP.

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3. Establishing and validating accident management procedures and guidelines are assisted.
4. The demonstrating is assisted for safety goals, which it can be established to limit the risk posed by the NPP are met [8].

Waste is any material that have no more further use. Still not all waste is useless, where some are being reused for different purpose. Example is used paper can be recycle or reused for different purpose. When come to the content of NPP, it will produce radioactive waste that emits radiation [9-10]. Radioactive waste is not only present in the nuclear fuel cycle but also can be obtained from medicine, agriculture, research and industry sectors also. The waste is classified into low level waste (LLW), intermediate level waste (ILW) and high-level waste (HLW). These classifications are based on the level of radioactive content where it is measured in activity [11-14].

When the uranium fuel used in the NPP is no longer efficient in splitting its atoms and produced heat for electricity generations, it will be called as spent fuel. This spent fuel is high level radioactive waste [15]. High level waste is a byproduct of the burning of uranium fuels that is located inside a nuclear reactor. It has high decay heat which is more than 2kW/m3 in results it requires cooling and shielding. HLW have two distinct kind which is used fuel that has been designated as waste and separated waste from reprocessing of used fuel. HLW required special attention for its disposal because it may bring hazardous effect to the environment [16].

In the management of radioactive waste, there are three general principal which are “concentrate and contain”, “dilute and disperse” and also “delay and decay”. The first two is used for non-radioactive wastes. The delay and decay is a special principal where it is used mostly in the management of radioactive waste, it meant the waste will be kept and allowed to reduce naturally its decay of radioisotopes [17].

High level waste management is important because it will ensure the isolation of HLW from biosphere and will avoid any release of hazardous radionuclide. The HLW management can be based on the following sequence of operations. First is interim storage in the liquid form, followed by solidifications and packaging of the waste, then is the engineered storage of the solid waste and finally disposal of the solid waste into geological formations.

Spent Fuel Pool is a water pool that use as a place to keep the used or spent fuel of nuclear power plant after their burn up process. It is at least 20 feet of water which will have adequate shielding from radiation [18–20].

2. Possible Hazard and Accident

It was undeniable that every power plant come with a risk and there are variety of possible accidents that could happen in the spent fuel pool due to some causes like weather, seismic or heavy load. In this paper, we will review the possible accident could happen to Spent Fuel Pool.

2.1 Loss of Coolant Inventory

Due to some reasons such as malfunctioning of the pool cooling system and loss of the pool water inventory, the adequate cooling of the spent fuel in the Spent Fuel Pool (SFP) can principally be lost. It is known that the Spent Fuel Pool (SFP) is used mainly for cooling the assemblies discharged from the reactor core [21]. There are so many examples of past events for both cases [22]. The explained events are obviously not the common either the most significant ones, but they do present some different possible scenarios that could lead to loss of spent fuel cooling especially in Spent Fuel Pool (SFP).

There is absolute considerable potential to uncover the fuel during the loss-of-water inventory accident. As a result, access to the Spent Fuel Pool (SFP) is prevented by the radiation fields and cause the heat-up of the uncovered fuel assemblies. There are many main ways for loss of Spent Fuel Pool (SFP) coolant inventory which are the connected systems that can be caused by the leakage through pumps seals, fail welds, heat exchanger cracks and the piping cracks or breaks [23-25,9–11]. Next is the leakage through the Spent Fuel Pool (SFP) liner or structure which often linked to liner defects, accidents or severe seismic events. The other main way is the leakage through temporary gates or seals during re-fuelling which often happens while the Spent Fuel Pool (SFP) is connected to the reactor cavity for re-fuelling. A fast and limited loss of inventory often allowed by the failure of the seals which may be an exceptional when the configuration of the plant is unfavourable.

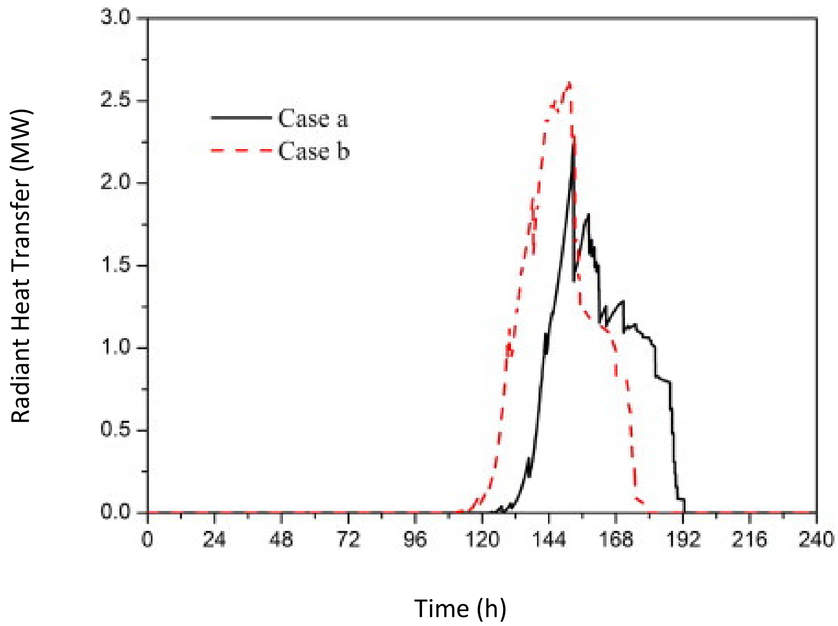

Fig. 1. Analysis of the loss of pool cooling accident in a PWR spent fuel pool with MAAP5 [26]

The losses in Spent Fuel Pool (SFP) coolant may cause environmental problems in other areas of the plant and also flooding, especially if the Spent Fuel Pool (SFP) is located at high elevation [13-14]. Careful installation of gates and seals, the monitoring of the Spent Fuel Pool (SFP) water level by adequate instruments and alarms and the adequate procedures and training are some of the preventive and corrective actions to do in order to avoid the loss in Spent Fuel Pool (SFP) coolant or loss of inventory. Besides, the consistency of planned core off-load evolutions and decay heat removal with the licensing basis must be assured. This should also include the appropriate reviewing of all relevant procedures associated with the core off-loads together with the special design for the sensors and the transmitter which should be able to withstand all types of environment to operate. There are so many other basics causes for the loss of Spent Fuel Pool (SFP) coolant that can be summarised which are insufficient attention to alarm signals, loss of electricity supply, human error, poor task programming, alarm failure, equipment failure, incorrect system operation, inadequate training, inadequate management control, and many other reasons which can be minimized.

Based on Safety analysis of CPR1000 spent fuel pool in case of loss of heat sink, it is reported that on April 10, 2003, 30 spent fuel assemblies were being cleaned in a special container in the fuel manipulation pit of the Spent Fuel Pool (SFP) during the re-fuelling outage in the Paks unit 2, Hungary. The fuel however was left in the container with reduced cooling after completion of the cleaning.

This incident resulted in severe cladding oxidation and fuel damage [15-16]. Even though this incident does not contribute to a significant accident, it gave useful insights for understanding Spent Fuel Pool (SFP) loss of cooling/coolant accidents phenomena. Also, it gave some studies to make a research about such accidents.

There are some places that had been dealing with the loss in Spent Fuel Pool (SFP) coolant [26] such as in Korea in Kori 1, the event is actually regarding the loss of shutdown cooling due to station blackout during the re-fuelling outage in a Pressurized Water Reactor (PWR) and caused the loss of off-site power and making the Spent Fuel Pool (SFP) temperature to slightly increased [25]. The next chosen accident happens in Sweden's Boiling Water Reactor (BWR) named Forsmark 3 where the event of their emergency diesel generators failed to start after undetected loss of two phases on 400kV incoming off-site supply. It caused the loss of Spent Fuel Pool (SFP) cooling capability with no increase in Spent Fuel Pool (SFP) temperature[12–14 , 16–18].

With this, it could be concluded that there are many lessons can be learned from events and there are so many recommendations done from some major studies of the Spent Fuel Pool (SFP) loss of cooling scenarios itself.

2.2 Loss of Spent Fuel Pool Water

The cooling water in a spent fuel pool could be lost in a few number of ways either through accidents or malicious acts. The drain of water is usually happened due to the decay heat produced by the fuel assemblies.

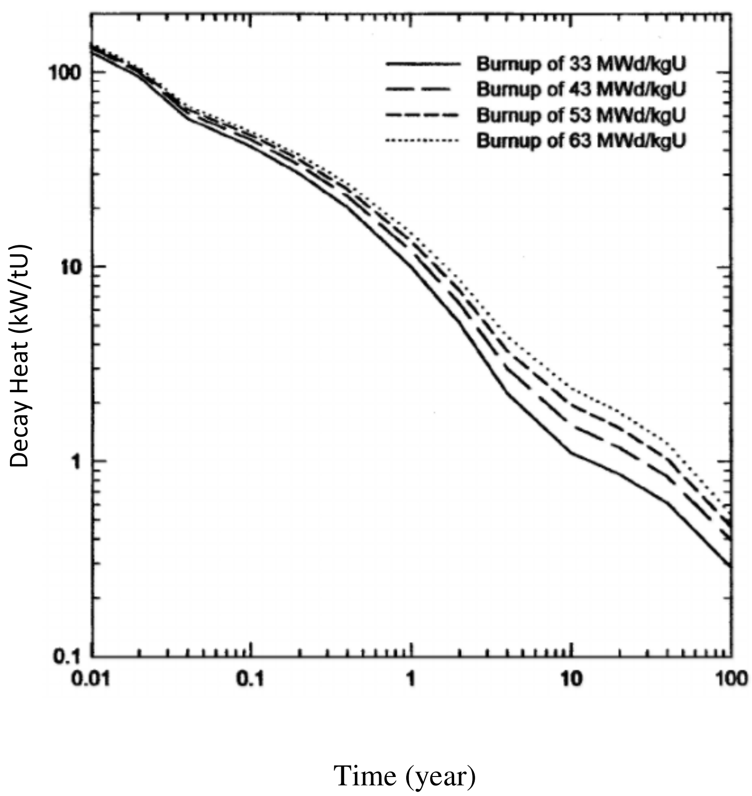

Fig. 2. Decay heat as a function of time from 0.1 years to 100 years

Keeping the spent fuel pool cool down is less needed as in the core since the time that it would take to heat the top of spent fuel would be more than 10 days if the most recent spent fuel discharge is only a year after shutdown, in case of accident occur or some terrorist attack it could lead to the rapidly drainage of pool to be below than the top of fuel [19,20].

The spent fuel pool has an opening at normal water level called scuppers. The water enters from scuppers and flows into the spent fuel pool cooling system which cool down the water before returning it to the spent fuel pool. To reduce the risk of accidentally draining water, the wall and floor spent fuel pool have no penetrations below the normal water level.

The decay heat released from spent fuel assemblies heat up the water filling the racks and the water rises due to convection. As the water rises, it pulls in cooler water from bottom of the racks to replace it which allow the natural circulation to cool down the spent fuels.

When the water was to rapidly drain from a spent fuel pool, this will stop the pool cooling system but the chimney effect will take over [35]. The decay heat released from spent fuel assemblies heat up the air filling the racks and air rises due to convection where the rising air pulls in cooler air from bottom of the racks to replace it which have the similar flow as the water but the air cooling can only be done on spent fuel that being remove from reactor core more than 2 months.

Meanwhile when a spent fuel pool only partially drains. It will stop the spent fuel pool cooling system and chimney effect. Even when water drop below than the upper racks, the spent fuel can continue to be cooled. The decay heat release from spent fuel assemblies heats the water filling the racks to the boiling point and water vapor flowing through the exposed upper section of the fuel assemblies. This can prevent spent fuel from overheating.

At some point, the water level in a partially drained spent fuel pool can drop low enough which prevent cooling. The decay heat release from the uncovered section of the spent fuel is not carried away by the water vapor past through and instead from getting removed, the heat increases the temperature of the metal rods containing the fuel pellets which can damage the spent fuel assemblies similar to overheating damages of fuel assemblies inside the reactor core [36].

The loss of water on spent fuel could lead to several major events and by assuming the loss of water was caused by the station blackout accident where during the accident all electric power was cutoff and the cooling system fail to work. A research has been done where the case is set into two. The case a will be the condition where water is at normal full amount on 12.2m meanwhile case b will be the condition where water is loss and the amount of water is at 10.7m from bottom of the cask [11 , 22-24].

Table 1
Major events during the loss of pool cooling accident

Events	Timing (h)	
	Case a (H = 12.2m)	Case b (H = 10.7m)
SFP water was saturated	9.98	9.04
Spent fuel assemblies began to expose	95.79	82.25
Hydrogen combustion happened	141.59	127.74
Corium pool presented	142.96	132.39
MCCI happened	201.06	182.77

From figure 3, the water level increase at the beginning of the transient due to the pool water expansion along the increase in temperature. Before saturated, the pool water absorbed decay heat from the spent fuel which made the water pool boiling and the decay heat is removed by evaporation of heat transfer. From figure 4, it shown that the water level decrease slowly by water evaporating on the top of water surface. Since there is no water being supplied back and this has cause the water level to drop significantly until it completely dries up [27].

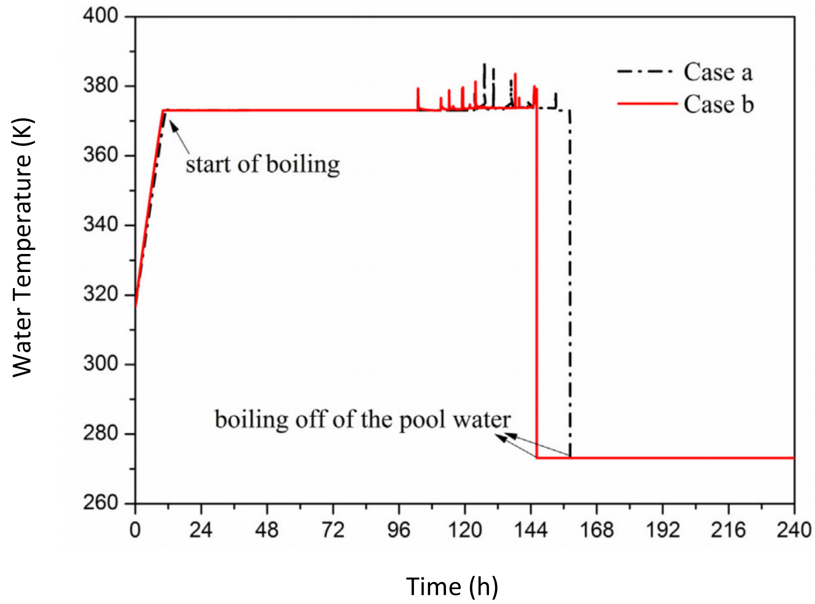

Fig. 3. Water temperature in SFP under the condition of different initial water levels

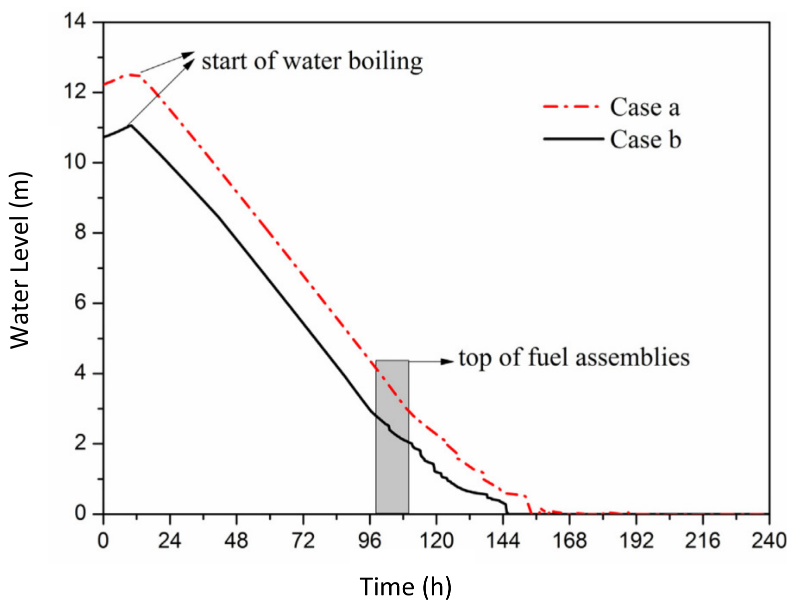

Fig. 4. Water level in SFP under the condition of different initial water levels

The event that involve on the loss of pool water occur during December 1998 at Browns Ferry Unit 3 where the temperature increases approximately to 25 ^{o}F for 2 days. The accident occurs due to the short cycling of water through an open check valve and the control room did not detect the decrease in water due to the flaw in design. Therefore, an approach how to prevent this event has been discuss and the approach include constant check of temperature and water level on control room, performed a regular basis which is once per shift and make document in the observations inside a logbook [40].

2.3 Seismic Events

Seismic events are the events which energy is released in the earth crust and producing seismic waves, then the energy is transferred in wave form and move through the earth crust [37]. Sometimes, the energy would be strong enough, causing earthquake [23-24,27].

Spent fuel pool structures in a nuclear power plant must be seismically robust. It must not be affected by either strong or weak seismic events. This is because the spent fuel pool is the place where the used fuel that are very radioactive is stored [37]. If the spent fuel pool faced any faulty or cracking of structures due to seismic events, there are high possibility that intense radiation will be released to the atmosphere. Spent fuel pool is constructed of thick, reinforced concrete walls and slabs lined with stainless steel. These materials that constructed the spent fuel pool must be strong enough to withstand vigorous movement or vibration and have the ability to resist intense and continuous radiation [23,28-29].

In boiling water reactor power plant, the spent fuel pool is constructed in the reactor building and at a height of a few stories from the ground level. While in pressurized water reactor power plant, the spent fuel pool is built outside of the containment structure and partially underground [30-31]. The design of the spent fuel pool such as the location and supporting arrangement of the structures will affect the pool's capability to seismic events. However, the dimensions of the spent fuel pool do not design to fulfil the seismic demand, but to consider the aspect of radiation shielding [32-33]. Anyway, the ability of the spent fuel pool to withstand external events in term of seismic demand is beyond the limit of the pool designed.

2.4 Aircraft Crashes

Aircraft crashes on nuclear power plant is possible when there is a terrorist attack or sabotage of aircraft [38]. The damage of aircraft crashes to a nuclear power plant is fatal especially the damage of spent fuel pool. Aircraft damage will not only affect the structures of the spent fuel pool, but also the support system that operating around the pool such as power supplies, heat exchanger, water supply system and may also affect the recovery system for emergency events[24,33-35].

The recovery system is an important and necessary system to be installed in a nuclear power plant. The aim is to provide immediate recovery plans when there are any emergency events occurred such as earthquake, tsunami or fire. The recovery system is also important for accidents such as loss of coolant accident and loss of operating power system [37-38]. When there is a large aircraft crashes to the power plant, the blast and heat generated might be so strong that will cause serious damage to the structures of the plant and even the recovery system. Once the recovery system is malfunctioning, more serious circumstances would occur such as core meltdown and release of high amount of radiation from spent fuel pool.

However, research shows that the probability of an aircraft crashes event to occur on current nuclear power plant is very low. This is because the design of power plant which is Generation 3+ nowadays, has high level of safety features [39–41]. The secondary containment which contained the reactor core will not allow the penetration of external force. When there is an aircraft crashes on a nuclear power plant, the aircraft will crash on other structures first, which will reduce the crash impact. The safety structures designed will absorb the impact and thus reduce the likelihood of an aircraft crashes event which will cause catastrophic damage to occur[42–44]. This is the same goes to the spent fuel pool, where the pool is located inside the containment building too.

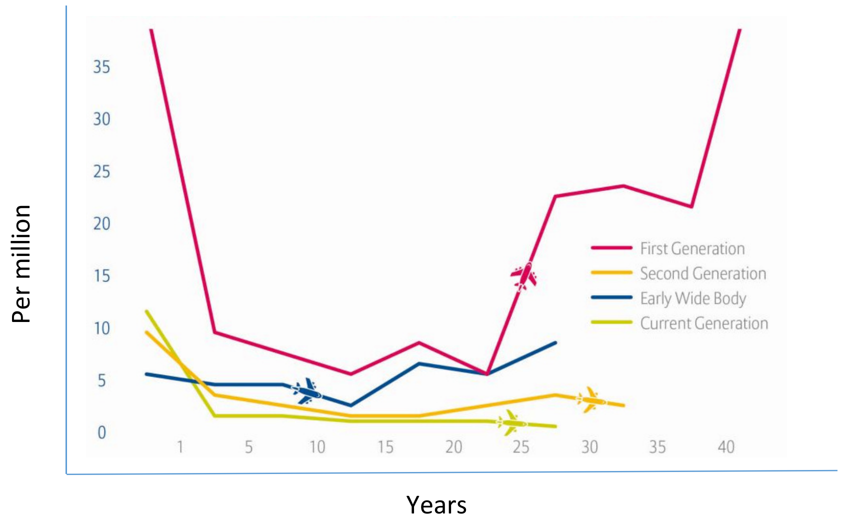

Fig. 5. Accident Rates Jet Aircraft by Generation per 1 million departures [50]

In conclusion, an aircraft crashes events which will cause damage on spent fuel pool is almost impossible to be occurred. Catastrophic damage on spent fuel pool is more likely to be occurred due to other event such as loss of cooling accidents.

2.5 Loss of Offsite Power from Plant-Centered, Grid Related Events

When there are some failure of hardware or design or even the human errors, it can lead to power shortage where it will have a chain reaction until effect the pump in the coolant or spent fuel pool not working [40]. Plant centered power loss is events that happens because of the NPP had some damage and should shut down in which there is not power supply to its own systems [59]. Example for the category plant-to-grid disturbance, a turbine trip/reactor trip at the Virgil C. Summer Nuclear Power Plant affected three other plants and the grid [60]. This is a possible event because it has happened before, although it did not affect the spent fuel pool still there are some possibility of it to happen. Even when diesel driven pump failed, and no offside power or plant centered power, the possible accident can be avoided with having extra back up power.

The bad weather like hurricanes, snow and wind, ice, wind and salt, wind, and one tornado event, the are possibility for the power loss to happen. The electrical pumps are unavailable and the diesel-driven fire pump is available only for makeup until the offside power can be bring back. Recovery of offsite power after severe weather events is can be hard because it will be difficult for help to reach due to bad weather.

2.6 Heavy Load Drops

According to NUREG 4982, the frequency of a heavy load drop near spent fuel pool can damage the pool. The heaviness of the load is given in the table.

Table 2
Weight of Material Near or on Spent Fuel Pool [61]

Area	Loads Handled	Weight.	Frequency Handle
PWR Refueling	Spent Fuel Shipping Cask	15-110 Tons	2 per refuel
	Pool Divider Gates	2 Tons	2-4 per refuel
	Fuel Transfer Canal Door	2 Tons	2 – 4 per refuel
	Spent fuel pool gates	2-6 tons	2 per refuel

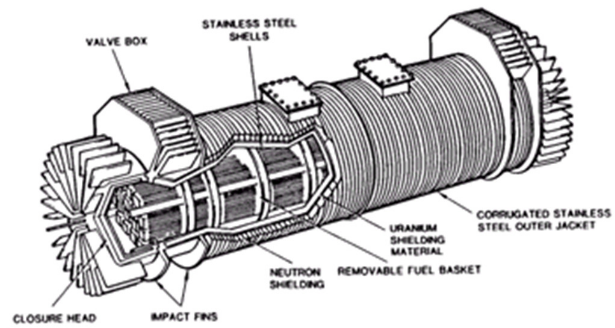

Fig. 6. Spent Fuel Shipping Cask [62]

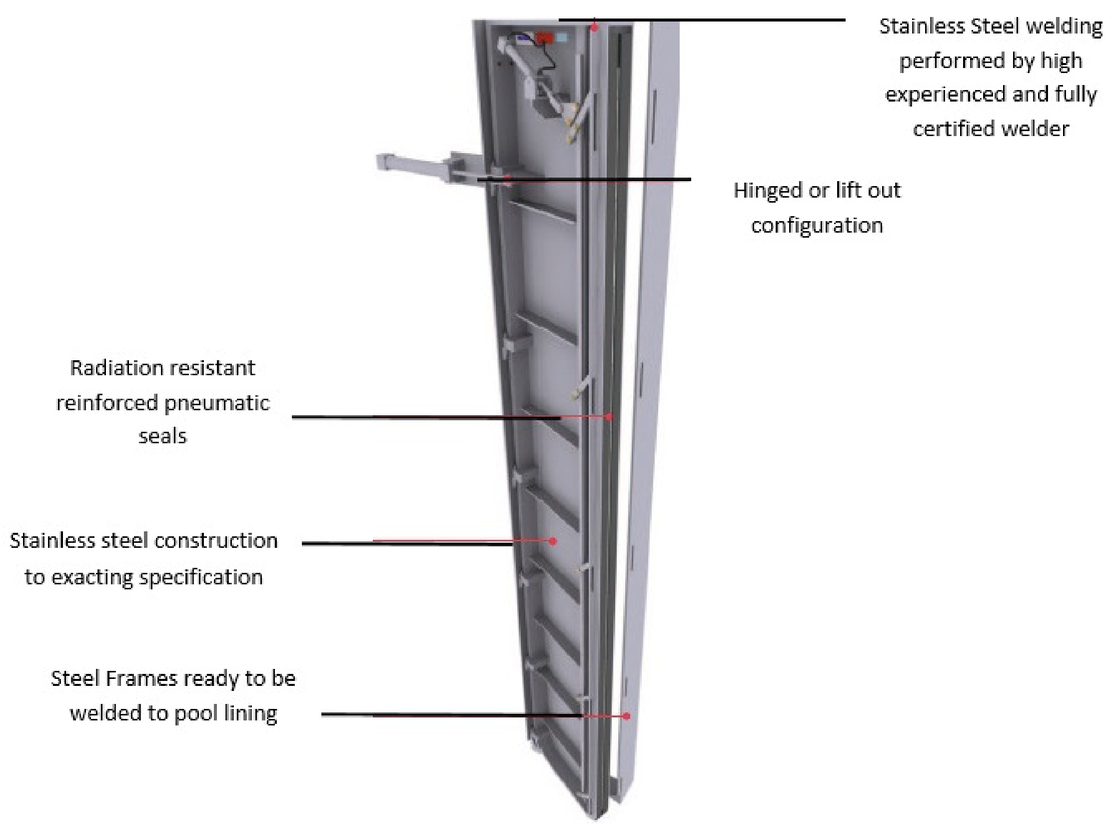

Fig. 7. Spent fuel pool gates [63]

The table shows the amount of weight the material present in the spent fuel pool have. This shows that the effect of the drop is higher. The heaver the material, more effect it will have when it drops into the floor of the pool.

The collapse of this material into the spent fuel pool floor, it can damage and it will be lead to the loss of coolant and release of hazards.

Mean value of $3.4\text{x}10^{4}$ per year is given for the drop frequency of a heavy load drop, and this is for the non-single failure proof load handling system. Meanwhile for single load handling system, the drop frequency is $9.6\text{x}10^{-6}$ per year.

The estimated rate of probability for a drop resulting in pool failure was $4.5\text{x}10^{-7}$/Ry. A crane that present in the spent fuel pool have failure probability of $3\text{x}10^{-6}$per operating hour if it assumed that each lift was of have a duration of 10 minutes if it wants cause gross structural damage to the pool wall if a crane failure occurred. Human error was not considered.

On August 21, 1984, the Haddam Neck Plant had a failure of the refueling cavity water seal, during the refueling cavity was flooded. In 20 minutes, the water level in the refueling cavity dropped by about 23 feet to the top of the reactor vessel. Still it does not release any radioactive hazards to the environment, still we can consider it is a possibility for it to undergoes damage that will have an effect to the environment.

Table 3
Accidents Happen in Spent Fuel due to heavy load failure [64]

Date	Plant	Seal Locations	Cause	Total Leakage
9/72	Pt.Beach	Transfer gate	Failure of Air supply	11,689 gal
10/76	Brunswick	Inner Pool Gate	Air leak in seal and power supply for the compressor failed	Pool level drop until 5m
5/81	Arkansas Nuclear 1	Transfer gate	Human Error	1000gal/min
8/84	Haddam Neck	Cavity Seal	Design Weakness	200,000 gal in 20 minutes

The table 3 shows the past accidents that happened in the spent fuel pool due to some heavy material. This show there are possibility of failure in the heavy material that present in the spent fuel pool.

3. Conclusion

In conclusion, high level waste management in nuclear power plants should not be taken for granted. This review pertains on high level nuclear waste which centred on the management of spent fuel of the plant. The processes should and must comply with IAEA safety standards. The possible hazards and accidents related discussed and analysed in this paper review showcase the scenarios that should be avoided at all cost in managing and handling high level nuclear waste. The analysis of these hazards and accidents ensures the safety of plant personnel, public community and environment. Hence, through the deterministic safety analysis, the safety aspects of nuclear power plants and the high-level waste management would be assured for clean, green and safe energy supply.

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