BNPP Spent Fuel Pool Fire Protection

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Abstract

This paper is reviewing the causes and risks of initiating a fire in the spent fuel pool of Nuclear Power Plants (NPPs) and the current capabilities to extinguish or prevent spent fuel fires from occurring to propose new applications supporting preventing or mitigating spent fuel fires to ensure the safety of the people, assets, and environment. This paper addresses many lessons from the Fukushima Daiichi accident and other research experiments done on spent fuel pools. Furthermore, risk assessments such as HAZOP and FTA were developed to come up with recommendations and new preventive measures that can be implemented in BNNP and other nuclear power plants around the world.

Keywords
BNNP, Spent Fuel Pool, Spent Fuel Fire, Zirconium Fire, Fire Protection.

Introduction
These concerns are related to safety & security risks, environmental impacts, and the potential for nuclear weapons proliferation. According to IAEA, the Chernobyl accident in 1986 and Fukushima Daiichi accident in 2011 are the main contributors to public concerns especially when it is related to safety and security risks. These two disasterswere associated with the release of massive amounts of radioactive materials into the environment, which is eventually getting to the food chain or getting directly to the body by exposure to the radioactive materials. For example, according to the World Health Organization, more than 4,000 cases of thyroid cancers among children and adults have resulted from the Chernobyl accident only by the inhalation of radioactive iodine. Not mentioning the destructive effects on the public of the nuclear bombs on Hiroshima and Nagasaki, according to Nagata in 2019 that the number of people affected by the bombs reached up to 140,000 deaths by 1945 and more than the number of the deaths, people have been suffering from long-term health issues including cancer.

However, the Fukushima Daiichi accident introduced diverse types of concern, as due to the 9.0 magnitude earthquake and the tsunami, caused power loss. This power loss caused a failure of the cooling system in the power plant. As a result of losing the cooling system, a series of explosions and meltdowns occurred. There was another concern with Fukushima Daiichi, which is the usage of seawater to cool down the reactors and spent fuels as seawater or salty water are producing another challenge as salt accumulates and creates corrosion, which if the right circumstances occurred can lead to further damage and fires.

Objectives

Running nuclear power plants, there is a risk of initiating fire from the spent fuel pools that are used to store the fuel after use. This paper aims to investigate the triggers and risks associated with fires of the spent fuel based on the literature review. Also, to review the currently available ways to mitigate or prevent such fires from occurring. Finally, this paper aims to suggest designing innovative ways to prevent or mitigate spent fuel fires by applying maximum safety to the public and to the power plant and its employees.

In other words, the focus point is the occurrence of spent fuel fires and how they are triggered. Based on the findings of the literature review, the paper will propose innovative ways to prevent or mitigate spent fuel fires. In addition, the paper's focus will be to ensure the protection of people, assets, and the environment as the main priority. Other main aims will be to explore new methods and technologies available or to be developed to extinguish fires in nuclear power plants, to lower the risk of fire as low as reasonably achievable or practicable, and to ensure that any proposed solution or innovative solution is practicable and feasible for implementation.

Literature Review

As spent fuel fires are the focus of the paper the most relevant case study to this incident is the Fukushima Daiichi in 2011 as there was a loss of cooling in the spent fuel pools in some of the operating reactors. So, a literature review will be covering this case study to highlight the important findings that will support the goal of this paper. In addition, there will be a focus on Zirconium fires and the current application of fire extinguishment or prevention literature review to support the suggestion and proposed innovative ideas.

Fukushima Daiichi Accident Case Study

Based on the executive summary of The Fukushima Daiichi Accident (2015), the tsunami caused by the 9.0 magnitude earthquake resulted in the loss of power in the nuclear power plant in Fukushima. As a result, there was a loss of cooling in three reactors in addition to the loss of cooling of the spent fuel pools.

Another result of losing the cooling of the reactors is a meltdown of the fuel has occurred in addition to the breach from the three containment vessels. This released Hydrogen from the reactor pressure vessels creating an explosion inside units 1, 3, and 4. These explosions damaged the structures, assets, and people. In addition to the release of radioactive materials into the atmosphere or the environment. There was a national and international emergency response to control the disaster. The main aim is to investigate the situation of the spent fuel pools. To emphasize, one of the three fundamentals of safety functions is to remove the heat from the spent fuel pool. However, the emergency response could not fulfill this since all means of control were lost due to the loss of the AC and DC electricalsystem, which resulted in the failure to initiate the other water injection path to remove the heat. Nevertheless, there wasanother plan to manage the spent fuel, by removing the fuel from the pools.

For example, the removal of fuel from Unit 4 was not completed until December 2014, as it is a challenging process. The spent fuel pool in unit 4 contained at that time more than 1,300 spent fuel assemblies with the biggest decay heat to be removed among all spent fuel pools in Fukushima NPPs.

Decay heat is basically the heat energy produced by the decay of radioactive isotopes of nuclear fuel, and this heat must be removed or cooled to prevent any damage to the fuel or the surroundings. Especially, since nuclear fuel cannot be stopped from reacting like gasoline or other heat producing fuels. Therefore, the loss of cooling led to an increase in the temperature of the pool due to the decay heat of the fuel. However, there was another countermeasureto support the prevention of electricity loss but when the water entered and flooded the building, including diesel generator buildings as they were in lower ground, which contained this countermeasure, the situation did not change and there was no cooling.

Nevertheless, there was a stabilization effort, which replaced the spent fuel pools of Unit 3 and Unit 4. With the inspection done by a helicopter over the two units, the initial inspection stated that unit 4 spent fuel pools were covered with enough water to cover the fuel assemblies, but this was not the case for unit 3 pools. As a result, the emergency response team has started to cover unit 3 spent fuel pool with water to prevent overheating and these included airdrops of water. But how is this related to fire?

Basically, the first assumption of the explosion in Unit 4 was that the explosion started because of hydrogen and the overheated fuel in the pools as it has lost its cooling systems. On 16 March 2011, the inspectors confirmed the assumption stating that the explosion in Unit 4 but not the hydrogen from the same unit rather than the migrated hydrogen from Unit 3 to Unit 4 was caused by the common ventilation systems.
Based on the case study the loss of cooling of the spent fuel pools has resulted in overheating of the fuel due to the decay heat because of failure to provide other measures of power to cool the fuel. In addition to the migration of Hydrogen from Unit 3 to Unit 4 an explosion has occurred. This releases a question to investigate why such an explosion happened. The answer to this question is zirconium cladding on the fuel rods.

Zirconium (Zr) Fire

In this section, first, we will describe and explain what Zirconium (Zr) is, then talk about its application, then briefly explain how it is related to spent fuel pools, and lastly how fires or explosions can be ignited in the presence of Zr. These three steps will support the understanding of the hazard of overheating of spent fuel pools.

Zirconium (Zr) chemically is a transition metal and reactive element with other elements to produce stable compounds that's why it is found naturally as a silicate or oxide compound. Zirconium has an atomic number of 40 with an atomic mass of 91.224. Zr has four stable isotopes $_{90}$Zr, $_{91}$Zr, $_{92}$Zr, and $_{94}$Zr, which are all naturally occurringisotopes. In addition, there are $_{93}$Zr and $_{96}$Zr which are radioisotopes with a half-life of more than a million years. Zr has a melting or freezing point of 1854°C and a boiling point of 4406°C.

To understand the element zirconium Nielsen and his colleagues stated in their study of 2013 that Zr is a naturally occurring element as a silicate or oxide compound. It is considered a gem material, and it is a highly active metal. However, it is resistant to corrosion by water, steam, chemicals such as mineral acids or alkalis, salts, and other corrosive agents. The main usage of Zr in our case study is useful in welding rod coating. In other words, Zr is used as a coating of nuclear fuel rods, which is why it is found in NPPs. It is related to the spent fuel pools as it covers the fuel pellets inside the nuclear reactor and is made from Zr alloy which has extremely high resistance to corrosion and elevated temperature. These Zr Cladding are used to keep the fuel pellets stable and protect the fuel from damage while not preventing the transfer of heat, so it will not prevent the cooling process.

Based on Park et al. in their publication in 2015, after Fukushima Daiichi incident, many publications were focusing on the loss of coolant accident especially related to Zirconium, and based on the finding of these publications, the research stated that when zirconium alloy cladding is heated to a specific point and cladding is reaching a fully oxidized state, this phenomenon named as zirconium fire. The findings also indicate a dramatic decrease of oxygen as the zirconium cladding is heated. Based on the findings, this dramatic decrease of oxygen is happening almost at a temperature of 1,100 K (826.58°C), which is also shown as the ignition point.

Based on the IAEA report regarding the Fukushima Daiichi accident, there was a hydrogen migration from unit 3 to unit 4, which caused an explosion as the decay heat was increasing. Based on Len Fisher, Hydrogen is considered a flammable gas. Hydrogen's Lower flammability limit is 4% of hydrogen in the air and ignition temperature is around 500°C as explained in hydrogen safety. So, based on the findings, basically, the hydrogen in the air was morethan 4% as the zirconium cladding was more than 827°C which initiated the explosion in the Fukushima incident.

Applications

The current applications of fire protection globally in the nuclear industry are divided into two ways. The first method is prevention. As is known, prevention is to avoid the occurrence of fire from the beginning, and it has different and multiple ways. On the other hand, the second way is to extinguish or mitigate the fire after its occurrence. In nuclear power plants, the focus is to prevent. However, in cases of a huge disaster, like Fukushima Daiichi, the fire will start and there should be a way to mitigate and extinguish the fire. Such probability exists and therefore, there are different methods.

Prevention:

The first way as discussed is the prevention or to avoid the initiation of fire. The prevention has four important ways that we are going to focus on, which are MELCOR, Diffusion, recombiners, and Fuel Rod Cutoff.

MELCOR

This tool is an example of an application used by NRC. Basically, it is an integrated coding software that has beenused to mode loss-of-coolant accidents in spent fuel pools.

Diffusion

Although diffusion is a slow process it can be a useful means of controlling hydrogen concentrations in storage drums/ sealedflasks/ packages in which the hydrogen generation rate is sufficiently small. Ex: for low-level waste storage in drums, it may often be possible to keep the hydrogen concentration in the drum below 1%(v/v) by fitting a filter to the drum through which hydrogen could diffuse.

Recombiners

Essentially these are noble metal catalysts (usually palladium) that promote the low temperature recombination of hydrogen produced in the ullages of enclosures/vessels with oxygen to form water.

Fuel Rods Cut

By dividing the spent fuel rods into smaller batches and separating the rods with different cladding and cooling systems could be a huge improvement in the safety of these rods. (Spent fuel cutting devices are available worldwide)

Extinguishing:

On the other hand, one of the worst-case scenarios that could occur at any nuclear power plant is when a fire starts. This situation takes fire protection from initiative-taking to a reactive process. Therefore, examples of fire extinguishing in nuclear power plants are Seismic Category I, Covering the spent fuel with solid material, and ventilation gas treatments system.

- **Seismic Category I Safety Grade Water Spray system**
  Pool spray decontaminates the radiological release which reduces consequences.
- **Covering Spent Fuel Debris with Solid Material (Sand, Clay, Dolomite, Boron, or Lead)**
  Reduces radiological releases and covers debris in case of fire progression.
- **Ventilation Gas Treatment System**
  Ventilation & filter system which can reduce airborne radioactivity concentration.

Methodology

As shown in Figure 1, the Methodology process depends on Historical Analysis which includes events and Accidents related to Fire in the Spent fuel pool. Based on the findings and identified risks, several risk assessments were determined to find recommendations and improvements in this field. The first approach was HAZOP analysis which identifies fault root causes and their consequences. The second approach used is Fault Tree Analysis, where itis managing both qualitative and quantitative methods. Aside from the risk assessment methods, another approach was used as a problem-solving technique which is known as the Five Whys for Finding the Root Cause.

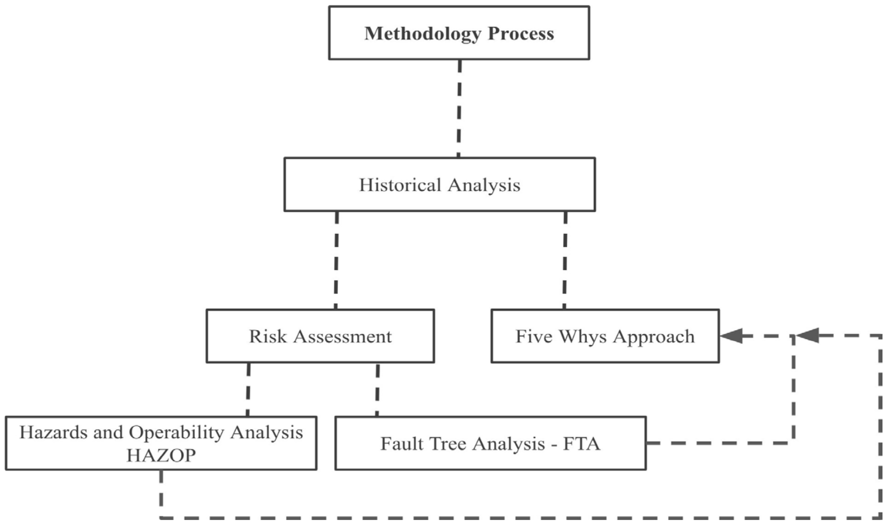


Figure 1. Methodology Process

Historical Analysis

Based on **Table 1**, there are different origins of accidents or experiments done to analyze the fire related events in spent fuel pools.

Table 1. Fire Related Events and Experiments in Spent Fuel

Location & Date	***Origin of Accident***	***Description***
Unit 4 Reactor, Fukushima Daiichi, Japan, In 2011	complete loss of coolant accident	The spent fuel pool caught on fire after loss of cooling. As a result, Radioactivity was being released to the atmosphere.

Hazards and Operability Analysis (HAZOP)

According to Nieuwenhuijsen et al. (2017) This structured and qualitative assessment will help us to evaluate and identify all potential hazards associated with the operation of Barakah Nuclear Power Plant Spent Fuel Pools. Moreover, this analysis reviews all existing protection systems.
Looking at the HAZOP analysis process is shown in **Figure 2.**

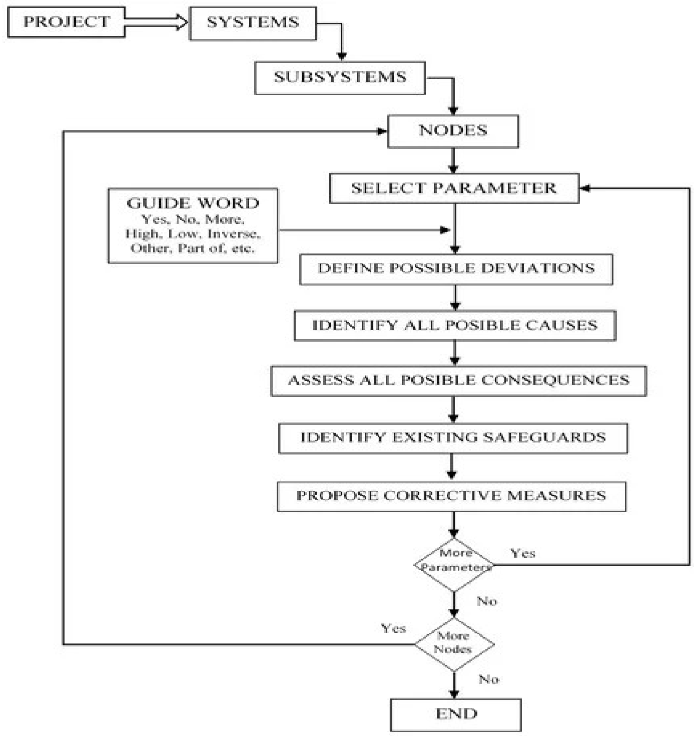


Figure 2. HAZOP Approach Process

As per **Figure 2**, the first stage will include Systems, subsystems, and nodes. The second stage will include the Guide Words and Parameters used in the analysis. The third stage is to construct the HAZOP analysis chart.

Guide Words are applied to each process parameter. These Words are used to describe the deviations.

NO, MORE, LESS, AS WELL AS PART OF, REVERSE and OTHER THAN.

Key Parameters to be evaluated in this process: flow, pressure, temperature, level, time, reaction, start-up, shutdown, fuel movement, and maintenance.

HAZOP Analysis Study:

As mentioned earlier, HAZOP is a systematic tool that is used to list and identify hazards associated with a specific process. HAZOP was used in this project to identify existing hazards related to the Spent Fuel Pool system and different approaches to mitigate such hazards. There are several cases analyzed using HAZOP for Spent Fuel and an analysis will be conducted for each case separately.

Loss of Spent Fuel Cooling flow

There are several causes that can result in a low flow or no flow condition for the spent fuel cooling system. For example, a sudden trip of the spent fuel pump with no backup pump can result in no flow condition for the spent fuel resulting ultimately in rising spent fuel temperature. Because of the evaporation of water in the spent fuel pool, the actual level of the spent fuel will be lower as well. Safeguards identified during the HAZOP study for this case was adding an extra redundant spent fuel cooling pump that is using a different power supply in order to ensure its availability in case of incidents. This will greatly increase the safety margin of the spent fuel pool cooling system. Refer to *Section 4. Data Collection and Attachments, 4.1. Hazard & Operability Analysis (HAZOP) (1/2): 4.1.1. Loss of Spent Fuel Cooling flow.*

3.1.1. Loss of Inventory in Spent Fuel Cooling Water Storage Tank

Another case that was analyzed using the HAZOP (Attachment II) is the possibility of losing all Spent Fuel Cooling Water Storage Tank inventory due to a rupture or crack in the tank. Irradiation Assisted Corrosion Cracking (IASCC) can contribute to the accelerated cracking of the tank. This project proposes an innovative design for the redundant Spent Fuel Cooling Water Storage Tank that can be used during accidents to add water to the spent fuel pool. Refer to: *Section 4. Data Collection and Attachments, 4.1. Hazard & Operability Analysis (HAZOP) (2/2): 4.1.2. Loss of Inventory in Spent Fuel Cooling Water Storage Tank.*

Fault Tree Analysis (FTA):

As Shown in **Figure 3**, Fault Tree Analysis (FTA) is a top-down method that is used to identify the main contributing causes of system failure and develop contingency plans in order to mitigate those events before they happen. This approach can highlight the vulnerabilities of the systems and allow the design engineer to counteract such weaknesses with design improvements. The first stage of the (FTA) is to identify the top undesirable event and then the first level events that contribute to causing the top undesirable event. Logical gates are used to link the lower-level events to the top undesirable event until reaching the basic events causing the chain of events. After that,the minimal cut set for the system can be identified.

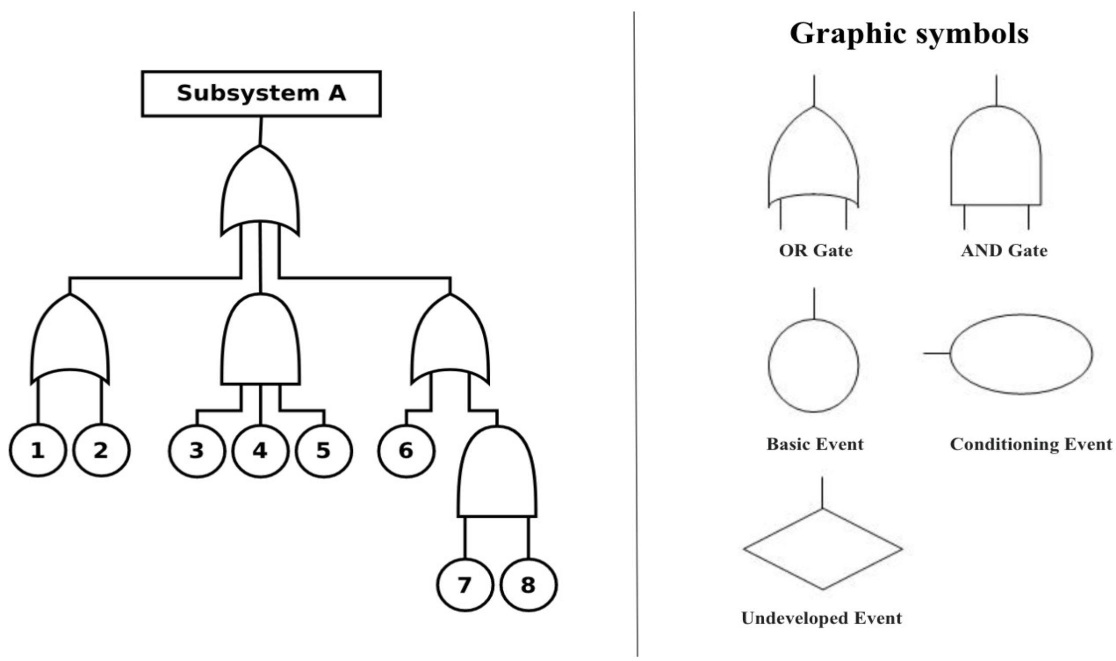


Figure 3. Fault Tree Analysis Diagram Overview and Basic Graphic Symbols.

In this assessment, the top undesirable event analyzed is the melting of the spent fuel. This is crucial to investigate because once the spent fuel is melted, it becomes more of a coolable geometry, and this makes it exceedingly difficult to cool the fuel uniformly once a cooling source is later obtained. Also, molten spent fuel emits much greater amounts of radiation compared with intact coolable spent fuel. (FTA) was performed for spent fuel melting and it identified several basic events as can be seen in *Section 4. Data Collection and Attachments, 4.2. Fault Tree Analysis Chart,* ***Figure 6.***

First, an earthquake that causes direct damage to the standby cooling pump will cause the event of the standby cooling pump not to start when needed. If this happens at the same time as the running cooling pump stops,then there will be insufficient cooling to the spent fuel pool causing the fuel temperatures to drastically increase and ultimately causing fuel melt (the top undesirable event). The other branch of events that might cause fuel melt will be the unavailability of the original makeup water sources to the Spent fuel pool and at the same time, the diverse makeup path to the spent fuel pool becomes unavailable. This would cause a loss of inventory in the spent fuel pool if it happened at the same time as having a leak in the spent fuel pool. No water inventory in the spent fuel pool will cause the spent fuel to eventually melt due to a lack of cooling water. This (FTA) analysis highlights the importance of having a passive makeup water source for the spent fuel pool that does not rely on power supplies to deliver cooling water to the spent fuel pool. This project highlights in detail the initial design of such a tank and how it will be utilized in order to lower the probability and risk of spent fuel melting.

3.2. The Five Whys for Finding the Root Cause

The five whys technique consists of a list of questioning processes designed to drill down into the details of a problem or a solution and peel away the layers of symptoms. The technique was originally developed by Sakichi Toyoda who stated that: "*By repeating why five times, the nature of the problem as well as its solution becomes clear*."

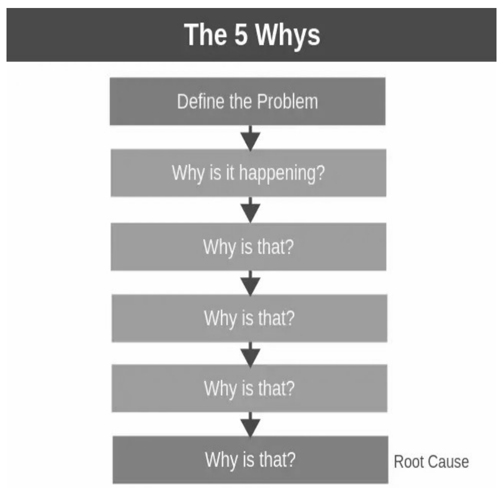


Figure 4. The 5 Whys Approach Process.

This technique is designed to bring clarity and refinement to a problem statement or a potential solution and get to the root cause of a problem in a much simpler form. Looking into our problem statement and applying the five whys technique on the incident, the following can be concluded as seen in **Figure 5**.

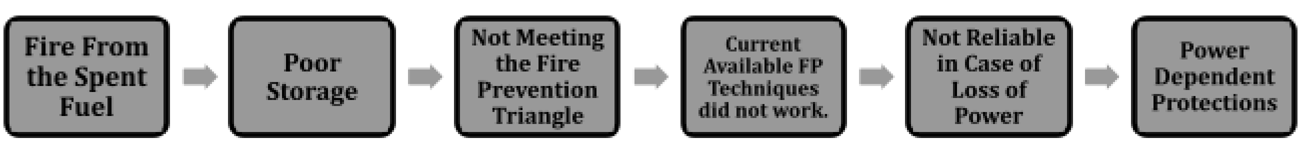


Figure 5. The 5 whys technique applied on spent fuel fires.

To start the 5-whys technique with the problem/event that needed to be analyzed, which is in our case “Fire from thespent fuel”, there are many reasons why it could happen, However, after listing down all possibilities, it was decidedto select poor storage as the main reason. Furthermore, going to the second reason, it was mainly due to not meeting the fire prevention triangle which led to the fire in the first place. To avoid such fire taking place, there are many protection systems in place, however, none worked during power loss which led to the event taking place. Last but least, it was concluded in the last part of the 5-whys technique that the main reason for the event taking place is that during the Pre-Feed study, the scenario of unavailable protection systems during power loss was not captured. By using such scenarios and direct approaches such as 5-whys, all incidents can lead to one main root cause which will clearly identify the problem so a remedial action can be put in place to ensure the nonoccurrence of such an event in the future.

Data Collection & Attachments

The Data collection includes Hazard & Operability Analysis (HAZOP) and Fault Tree Analysis Templates.

Hazard & Operability Analysis (HAZOP):

Loss of Spent Fuel Cooling flow

Loss of Inventory in Spent Fuel Cooling Water Storage Tank

Fault Tree Analysis

Five Whys Approach

Flying Tank 3D modeling

Tank Replacement Criteria Chart Data

4.1. Hazard & Operability Analysis (HAZOP) (1/2)

4.1.1	Loss of Spent Fuel Cooling flow

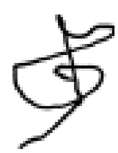
HAZOP Template

Barakah Nuclear Power Plant / Shaikh Ali Alnuaimi / 2 May 2023

Client / Site
Barakah Nuclear Power Plant
Location Western Region-UAE
Conducted on 02.05.2023 00:50 +04
Prepared by Shaikh Ali Alnuaimi
Node 1
Node
Spent Fuel
Guide Word
No or Not
Element
Spent fuel cooling flow.
Deviation
No Spent fuel cooling flow
Possible Causes
Spent fuel pool pump trip or damage to the pump.
Consequences
Increase in the temperature of the spent fuel due to lowering the level of the spent fuel with no makeup.
Safeguards
Adding an extra redundant pump that is getting power from the different power supplies.
Comments
Spent fuel level and temperature indicators should always be checked.

Name and Signature of HAZOP Team Lead

Shaikh Ali Al Nuaimi



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4.1. Hazard & Operability Analysis (HAZOP) (2/2)

4.1.2.	Loss of Inventory in Spent Fuel Cooling Water Storage Tank

HAZOP Template

Barakah Nuclear Power Plant / Shaikh Ali Alnuaimi / 2 May 2023

Client / Site
Barakah Nuclear Power Plant

Location Western Region-UAE

Conducted on 02.05.2023 00:50 +04

Prepared by Shaikh Ali Alnuaimi

Node 1

Node
Spent Fuel

Guide Word
No or Not

Element
Spent fuel cooling flow.

Deviation
No Spent fuel cooling flow

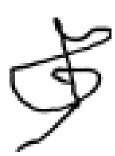
Possible Causes
Crack or rupture in the tank

Consequences
Tripping of the spent fuel pool cooling pumps due to cavitation and not enough cooling flow to the spent fuel pool

Safeguards
Adding an extra redundant tank in case of rupture or unavailability of the Spent Fuel Cooling Water Storage Tank

Name and Signature of HAZOP Team Lead

Shaikh Ali Al Nuaimi



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4.2. Fault Tree Analysis Chart

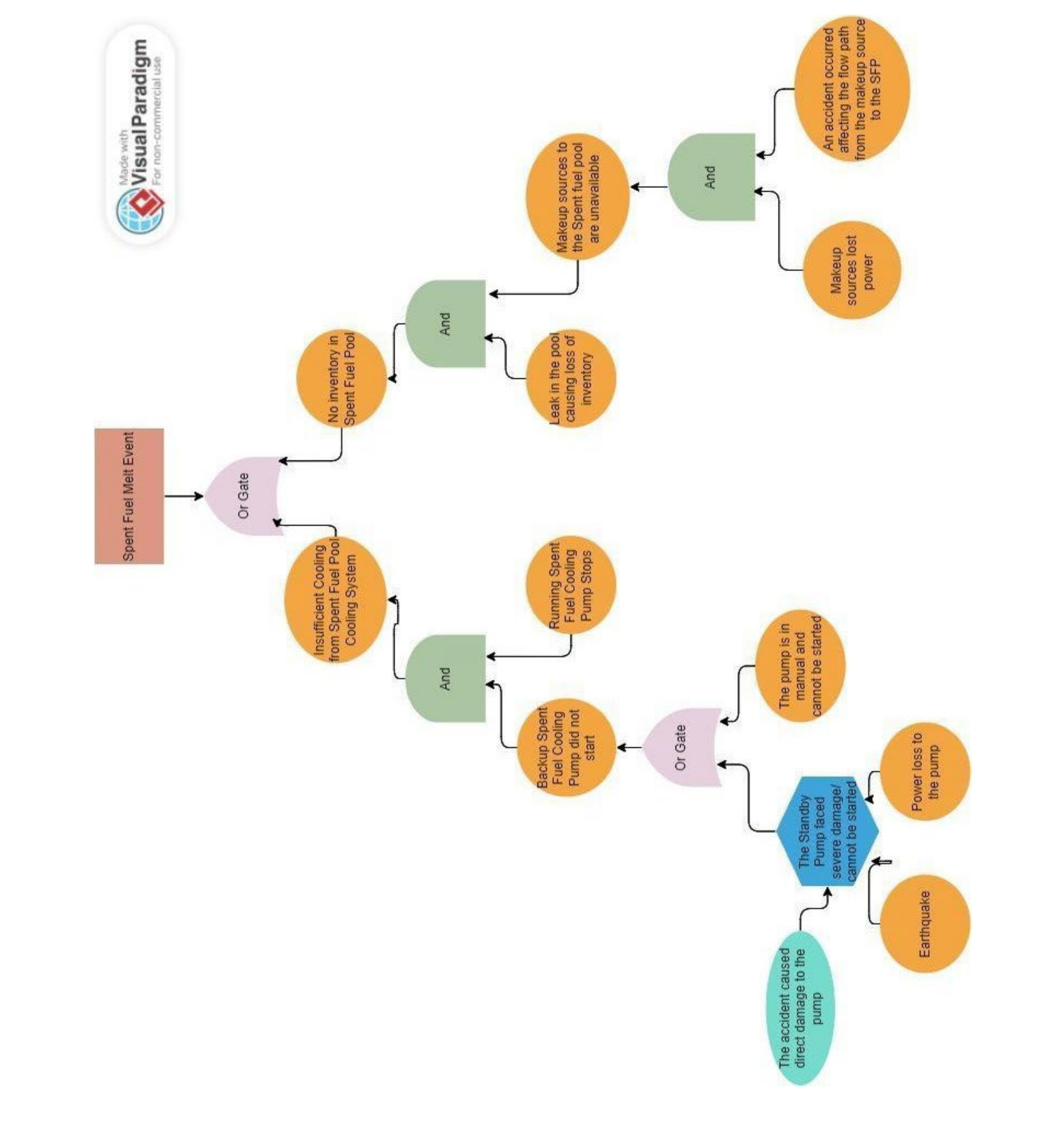

Figure 6. A 2D Visual Chart of the (FTA) created using https://online.visual-paradigm.com/

4.3. Five Whys

4.3.	The Five whys technique was applied on Fukushima Daiichi Accident Case Study, where the main reason for spent fuel pool fire was due to failure of protections due to loss of all power sources including AC and DC power supplies. It went through 5 stages where it showed the reasons which led to such an incident taking place. The analysis was done using a chart which is shown in **Figure 4** and **Figure 5.**

4.4. 3D modeling for Spent Fuel Flying Tank: (1/3)

This is a 3D modeling of the Floating Tank using SketchUp Pro 3D Modelling Software. The following is an illustration of the major components of the concept.

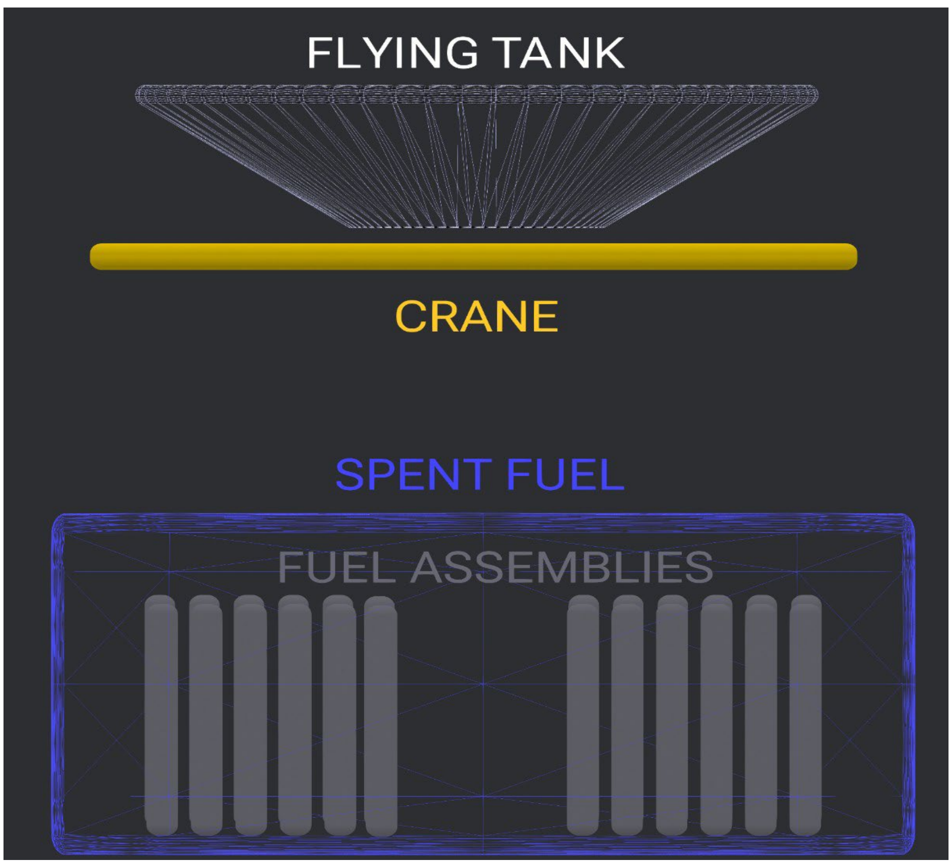

Figure 7. Flying Tank Overview

4.4. 3D modeling for Spent Fuel Flying Tank: (2/3)

This is a 3D modeling of the Floating Tank using SketchUp Pro 3D Modelling Software. The following is an illustration of the major components of the concept.

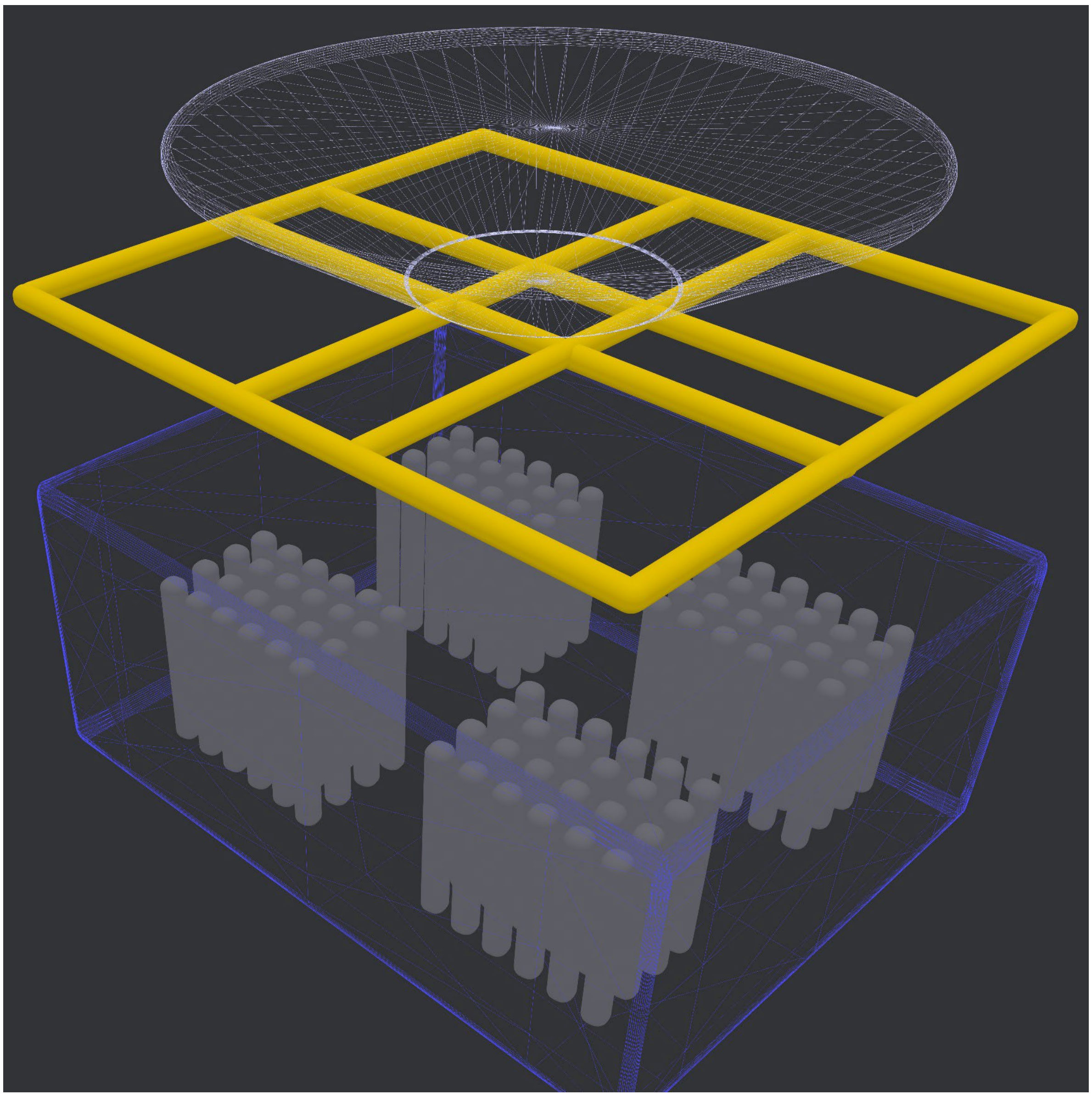

Figure 8. 3D Angle View of the Flying Tank.

4.4. 3D modeling for Spent Fuel Flying Tank: (3/3)

This is a 3D modeling of the Floating Tank using SketchUp Pro 3D Modelling Software. The following is an illustration of the major components of the concept.

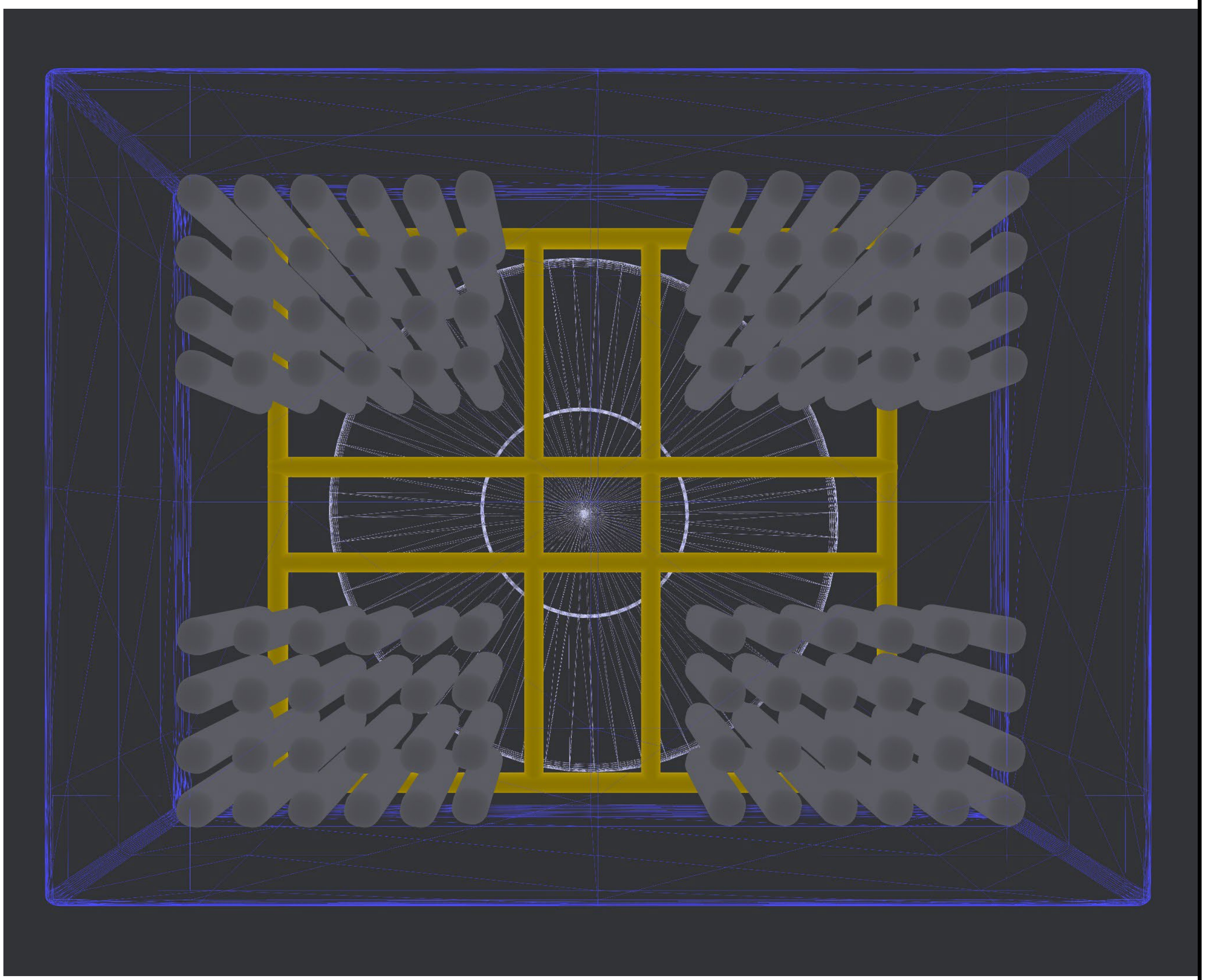

Figure 9. Flying Tank Alignment View.

<table>
<tr><th colspan="2">4.5. Tank Replacement Criteria Chart Data Collection</th></tr>
<tr><td>1</td><td>● Boron Concentration Requirement shall be ranging Between 4,000 to 4,400 ppm.
● As per the Technical Requirement Manual published in the technical report of Arizona Public Service Company (APSC), the fuel pool boron concentration is needed to be at least 4000 ppm.
● As per Design Control Document "APR1400", The (SFP) boron concentration should be ranging between 4,000 to 4,400 ppm.</td></tr>
<tr><td>2</td><td>Demineralized Water Storage Tank:
● Instrumentation on all non-quality systems such as Demineralized water could be lost during total loss of power. Therefore, it will not be available.
● The demineralized water system (DWS) does not connect directly to the spent fuel pool cooling system or the spent fuel pool. Hard to be moved to (SFP) Area as per the "Palo Verde Nuclear Generating Station Spent Fuel Pool Boron Dilution Analysis".
● Holds no Boron Acid as it supplies demineralized water.
● The Demineralized Water Storage Tank capacity is around 100,000 gallons (380 m^3) based on Westinghouse AP1000. Therefore, the ability is not enough.</td></tr>
<tr><td>3</td><td>Boric Acid Storage Tank (BAST):
● (BAST) is a primary water source of water to the (SFP).
● The boric acid storage system has a maximum concentration of boric acid (4,400 ppm boron) based on the design control document "APR1400".
● (BAST) is at least 70,000 gallons (264 m^3). Relatively closer to the (BAST) Volume. It should be upsized by 100% to meet the requirement.</td></tr>
<tr><td>4</td><td>Passive Auxiliary Feedwater System (PAFS):
● Based on Cheon et al. and per the schematic drawing of APR+, (PAFs) is elevated above the Steam Generator. This means that this tank can be elevated.
● It is available during the loss of power. Availability is assured.
● The volume determined is about 370,000 gallons (1400 m^3). Oversized.
● Not enough information on the water source if it has boron.</td></tr>
<tr><td>5</td><td>In-Containment Refueling Water Storage Tank (IRWST):
● Based on Korea Electric Power Corporation and Korea Hydro & Nuclear Power Co., the Boron concentration is kept between 4,000 ppm and 4,400 ppm.
● IRWST water volume is greater than 2,373.5 m^3 (627,000 gal) and > 2,540.6 m^3 (671,162 gal). This system is exceptionally large compared to the proposed design. So, it is not meeting the volume dimension.
● It is available during emergencies as it supplies critical systems.
● Elevation is not met as the system is found near the flooring of the Containment Building.</td></tr>
<tr><td>6</td><td>Reactor Drain Tanks (RDT):
● As per TR-APR1400-01, the elevation is not met as the system is found below the flooring of the Containment Building.
● System only available when other systems fill this tank using drains. So, it is always not available.
● Source of water will be a mixture of various sources. Therefore, the boron concentration is not assured to meet the requirement all the time.
● Volume is not found.</td></tr>
</table>

1. Results and Discussion

After looking through the literature review covering the case study of Fukushima Daiichi, to understand the reasons behind the incident that occurred in Fukushima, taking into consideration the analysis of (HAZOP) and (FTA) applied to (BNPP) to prevent such cases from occurring, there are some process improvements that can be done to encounter and reduce the risks to tolerable levels which are Adding alarms that warn of deviations, Modifying ventilation systems if needed, Increasing the frequency of sampling and testing. Nevertheless, the paper provides a proposal for a new method to avoid the occurrence of fire in the spent fuel pool. This proposal is a prototype concept of a cooling system.

1.1 Proposed Improvements:

Flying Tank: A prototype concept of a passive source of cooling system for spent fuel pool cooling.

The main objective of the "Flying tank" is to cool the SPF when power is not available as shown in **Figure 10.** This design has certain requirements as discussed below.

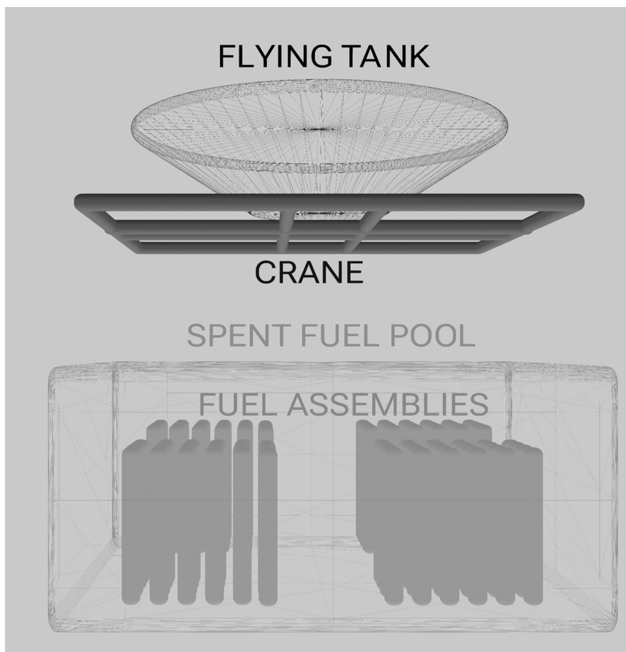

Figure 10. Flying Tank 3D Modeling Concept

Design Requirements:

- Tank should always be filled to have gravity feed when needed. Therefore, this tank can be a replacement for an existing tank. This will provide a cost-effective advantage to the system.
- Tank should be elevated from the pool level to feed the Spent Fuel pool when all valves are open.
- The design will not interfere with crane operation.
- Ensuring the minimum level of cooling is achieved by having the right water volume.
- Water sources should be relatively low in temperature to provide efficient cooling.

- Multiple valves are distributed around the pool to have a uniform water supply and cool the pool evenly.

This system will operate when the heat of the pool reaches a certain temperature the Heat sensitive detector will open the check valves around the pool and the pool will be filled by the water using gravity feed.

Design Analysis:
To be able to determine the right dimensions for the flying tank, we referred to the National Academies of Science, Engineering, and Medicine publication in 2018. As per their publication, a typical size of a spent fuel pool is about 12 meters deep, and each side is 12 meters. Therefore, the spent fuel pool volume is determined to occupy **1728 m^3** (cubic meters) and is equivalent to **1.728×10^6 Liters**. Moreover, each Fuel assembly height ranges from **4 to 4.5 meters**.

In normal operation, the water temperature is always kept below 50°C. Once the SPF loses cooling, the water temperatures will reach its boiling point (100°C) and will cause the level to drop. Therefore, the SFP water level above the fuel assemblies must always be maintained as well as its temperature. This concept will provide cooling and level coverage until the power is back to service. Moreover, the level coverage also shields against radiation. Based on Wright, D. and as shown in **Table 2**, the time to reach boiling point was estimated to be 2.7 days. This is due to the heat generated in Unit 4 with heat generation of 1,600*(Mcal/h)*.

Table 2. Spent Fuel Pools at the Fukushima Dai-Ichi (No.1) Plant

Unit	*Heat generation (Mcal/h)*	*Pool Volume (m^3)*	*Assumed Water in Pool (tons)*	*Time to Heat to 100 ^{0}C (days)*	*Assumed water above fuel (tons)*	*Time to Boil off Water Above Fuel (days)*
1	60	1,020	900	50	600	225
2	400	1,425	1,300	11	850	48
3	200	1,425	1,300	22	850	96
4	1,600	1,425	1,300	2.7	850	12
5	700	1,425	1,300	6.2	850	27
6	600	1,497	1,350	7.5	850	32

As a comparison, the Unit 4 spent fuel pool reached that boiling point temperature just three days after the earthquake. However, it takes longer to boil the water above the fuel. This means that the heat generated was not thereal cause for the level drop. Some reports suggested that Units 2, 3, and 4 all had pool leakages caused by the earthquake. Those leaks eventually led the level to drop before the estimated time. **Table 2** was determined using the following equations;

The time for the temperature of M_t tons of water in the pool to increase by ΔT is:

$$t\,\Delta T = \frac{CM_t\,\Delta T}{H}$$

and the time for M_b tons of water at 100^{0}C to boil away is: $t_{boil} = \frac{LM_b}{H}$

where: C is the heat capacity of water = 1 Mcal/Ton-deg, L is the latent heat of vaporization of water = 540 Mcal/ton, H is the heat generation by the spent fuel.

As a learned lesson, we need to count for other water level losses not only from heat generation (evaporation) but also from other sources such as leakage. The minimum level allowed for water level above fuel is 3 meters and the maximum level achieved above the fuel is 7.5-8 meters (since fuel is about 4 to 4.5 meters). In our concept, we designed the flying tank to provide the SPF with at least **432 m^3 which is (3 m × 12 m × 12 m)** to keep the fuel covered in case of any water drop and if there was no leakage it will be a source of cooling. As shown in **Figure 11**, the shape of the flying tank is a Conical Frustum Shape. This design provides an easy supply of water when the valve opens.

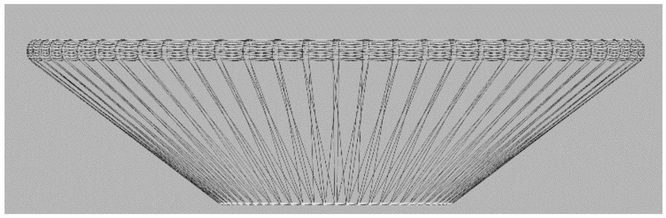

Figure 11. Flying Tank illustration

Tank Dimensions Calculations:
As discussed earlier, the minimum volume of the flying tank is required to be 432 m^3. An additional 100 m^3 was added to the volume of 432 m^3 to ensure the availability of water at all times. Therefore, (V= 532 m^3) is the required volume for our calculations. We determined the height, lower radius (r1), upper radius (r2), and slant height (s) using thefollowing calculations:

The volume (V) of the frustum of the cone can be expressed as: $V = \frac{1}{3}\pi \times h\,(r_1^2 + r_2^2 + (r_1 \times r_2))$.

And slant height (s) of conical frustum is equal to $s = \sqrt{(r_1 - r_2)^2 + h^2}$

As the calculations below shown for the Volume (V):

$V = \frac{1}{3}\pi \times h\,(r_1^2 + r_2^2 + (r_1 \times r_2))$. Where **V = 532 m^3**; π = pi = 3.1415926535898,

Unknown: **r_1, r_2, h,**

532.2 m^3 = $\frac{1}{3}\pi \times 5.3\,(2.5^2 + 8.3^2 + (2.5 \times 8.3))$. After Calibrating; r_1 = 2.5 m, r_2 = 8.3 m, h = 5.3 m

To find s = slant height.

$s = \sqrt{(r_1 - r_2)^2 + h^2}$ s = 7.856 m

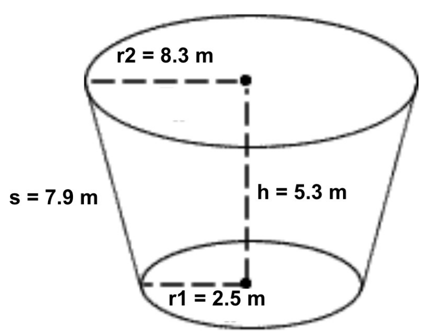

Figure 12. Flying tank dimensions

Tank Replacement Selection Criteria:

Based on IAEA Advanced Power Reactors plus in 2020, and shown in **Figure 13**, an APR+ schematic Diagram wasselected as a reference. APR+ is an advanced design compared to BNPP which is an APR1400 design. However, both designs have similar layouts. The primary and secondary have many systems that consist of water reservoirs. Furthermore, for our purpose in this paper, we have selected five (5) Tanks to be studied.

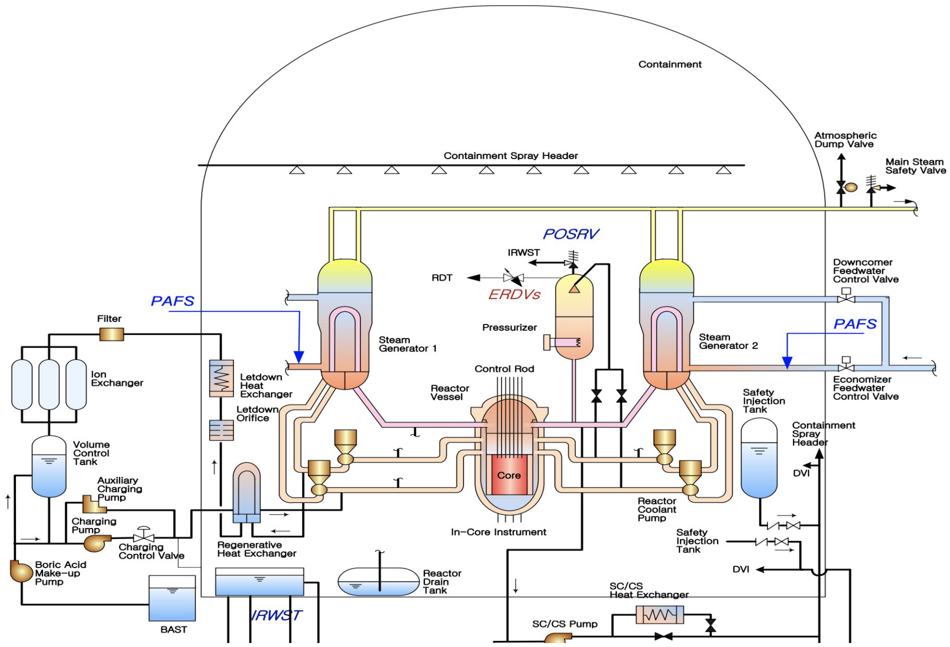

Figure 13. Schematic Diagram of the tanks

in the APR+The five (5) selected tanks to be studied are:

1. **Demineralized Water Storage Tank:**
   The main function of this tank is to supply demineralized water for the turbine's cooling. However, if this source is used to supply the Spent fuel pool, it will dilute the existing boron in the pool, causing the fuel to react and add positive reactivity. As a result, this tank was eliminated.
2. **Boric Acid Storage Tank (BAST):**
   The main function of this tank is to supply boric acid to the primary to control power. The available boron in the (BAST) tank will ensure the neutrons absorption in the spent fuel.
3. **Passive Auxiliary Feedwater System (PAFS):**
   The only function of this system is to cool down the secondary and remove the decay heat by replacing the auxiliary feedwater system. It is a passive system that was introduced in APR+ reactors.
4. **In-Containment Refueling Water Storage Tank (IRWST).**
   The IRWST supplies several functions such as storing refueling water. In addition to that it is a water source for the Safety Injection System, Shutdown Cooling System, and Containment Spray System.
5. **Reactor Drain Tank (RDT).**
   It is a tank that collects water from several lines through drain lines.

Comparison Criteria:

As illustrated in ***Table 3***, The elements of the selection criteria are the availability of the system during the loss of power emergency, Tank volume to be 532 m^3 or greater, Elevation. It should have a similar elevation to the height of the design, and Meeting Spent fuel Boron Concentration (Boron %) requirement.

The data were collected from diverse sources and based on the values **Table 3** was created. To sum up, the playing factor used to differentiate between the tanks was the boron concentration (Boron %) as it is a key factor for controlling neutron reactions in the spent fuel pool. Both (BAST) and (IRWST) tanks hold a good amount of Boron.

Table 3. Tank Replacement Criteria Chart

#	***Tanks***	***Availability***	***Volume***	***Elevation***	***Boron %***	***Ranking***
1	Demineralized Water Storage Tank	x	x	x	x	**4**
2	Boric Acid Storage Tank (BAST)	✓	✓	x	✓	**1**
3	Passive Auxiliary Feedwater System (PAFS)	✓	x	✓	x	**3**
4.	In-Containment Refueling Water Storage Tank (IRWST).	✓	x	x	✓	**2**
5.	Reactor Drain Tanks (RDT)	x	x	x	x	**5**

As a conservative approach, the (IRWST) was eliminated due to its critical function to provide several systems with water during emergencies. As a result, only the Boric Acid Storage Tank (BAST) meets the criteria and can support the spent fuel as a passive source of water during emergencies. However, the (BAST) should be upsized twice the current size to make sure it meets the Flying Tank's dimensions. Furthermore, further research and studies should be done to understand the impact of changing BAST's elevation and location on the plant.

For detailed data refer to *Section 4. Data Collection and Attachments, 4.5. Tank Replacement Criteria Chart Data Collection.*

Conclusion

Summary

This paper aims to cover the risk assessment of the spent fuel pool fires and support the need of the country to produce energy based on nuclear fuel. As seen in the literature review section, the main function of the spent fuel is to store the used fuel and cool it as the fuel will generate decay heat. So, the cooling of the fuel rods is critical to avoid fires or explosions and based on the literature review, the failure in cooling the spent fuel pools or the loss of the energy that supplies cooling will lead to fire or explosion in the presence of hydrogen gas. This is supported by the Fukushima Daiichi incident, where a tsunami led to the loss of energy that led to the loss of cooling and an explosion in unit 4 as hydrogen gas was present. This is related to the heating of the used fuel rods covered with Zirconium, a metal that at a certain heating range will start ignition. Therefore, the focus of this paper is to find new ways of extinguishing or preventing such types of fire in nuclear power plants as spent fuel is necessary in all nuclear power plants. The paper reviews what is available in today's world and suggests modifications or new methods to succeed with the paper's aims. The paper covered several assessments starting with Historical analysis, HAZOP, and Fault Tree Analysis (FTA). Each of these together supports finding the major risk in the support of the literature review to avoid spent fuel first. As a result, the paper proposes an innovative design of a system that works in case of losing the energy in the spent fuels. This proposal includes calculations of the design and its ability to cover and cool the fuel, in addition to a 3D illustration with actual diminutions.

Recommendation and Suggestions

Based on the findings, we suggest doing further research that includes testing the prototype that has beendesigned in this paper. The testing shall include the durability of holding such weight above the spent fuel pools. In addition, the tests shall involve alternative ways of starting the designed tank in case of a total loss of energy. We recommend further risk analysis of the design to ensure that the prototype is not adding new risks to the current situation. In addition, both the (HAZOP) Analysis and Fault Tree Analysis (FTA) suggest further points of the spent fuel pool assessment, which can be further studied to add another layer of protection by eliminating or substituting a risk that can be avoided with further study. Combined with the literature review and the data analysis, the paper suggests a design of a passive source of water and cooling supply for the spent fuel pool. This tank is a flying tank, which is also suggested to replace the Boric Acid Storage Tank (BAST) as it has a good concentration of Boron acidranging between 4000-4400 ppm based on "*proposed technical specification changes related to boron injection tankelimination*". It is recommended to have further study and research to understand the dynamic effects of such a choice on other systems.

Conclusion

To conclude, the usage of nuclear energy as a source of renewable and clean energy is the trend of countries in the world as it produces less CO_2 in comparison to traditional fossil fuels. Nuclear energy fuel, like all other sources of energy, imposes certain risks, and with the vision to seek less production of CO_2 with the growing need for energy,countries shall seek cleaner energy with the highest safety measures. The nuclear energy industry had two major accidents that changed the way the world sees such sources. However, in this paper, the aim is to learn from earlier experiences and accidents to suggest new methods, ways, and designs to prevent one of the major incidents in Fukushima Daiichi, which is the spent fuel pool explosion and fire. This paper designed a flying tank with the abilityto ensure the cooling of the spent fuel even in major shutdowns of energy by any circumstances. The design is a prototype and requires further analysis and testing to ensure the suitability of the design in the real world and analysis of what kind of other risks this design could add to the spent fuel pool area.

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