Journal of Energy and Safety Technology
JEST
RESEARCH ARTICLE Open Access

A COMPREHENSIVE LAYERS OF PROTECTION ANALYSIS (LOPA) OF AMMONIA EXPOSURE IN HYBRID OCEAN THERMAL ENERGY CONVERSION (H-OTEC) SYSTEMS

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Article History

Received:	Received in revised form:	Accepted:	Published:
June 3, 2025	July 22, 2025	July 22, 2025	December 12, 2025

Abstract

Ocean Thermal Energy Conversion (OTEC) represents a promising renewable energy technology that leverages the natural temperature gradient between warm surface seawater and cold deep seawater to generate electricity. Closed-cycle OTEC systems commonly utilize ammonia as a working fluid due to its favorable thermodynamic properties. However, the toxic and corrosive nature of ammonia introduces significant safety and environmental hazards. Potential risks include leaks from piping and storage tanks, safety valve malfunctions, operator errors, and structural failures caused by extreme weather conditions. These incidents may result in acute health impacts such as respiratory distress and chemical exposure among personnel as well as broader environmental contamination and ecological damage. This study highlights a recent incident at an OTEC facility where ammonia dispersion led to respiratory distress among four workers at a nearby hatchery. Onsite investigations, coupled with dispersion modeling using ALOHA software, revealed a substantial risk to the surrounding area due to airborne ammonia toxicity. The assessment employed the Layers of Protection Analysis (LOPA) methodology to map out cause-consequence scenarios and evaluate the effectiveness of existing safety barriers. Current protective measures include corrosion-resistant materials, ammonia detection systems, pressure relief valves, routine maintenance, and operator training. The study recommends the integration of additional safeguards such as real time leak detection, automated shutoff systems, AI-based predictive maintenance, and enhanced secondary containment strategies. By systematically assessing and mitigating the risks associated with ammonia use, OTEC systems can enhance operational safety, minimize environmental impact, and ensure long-term sustainability—thus supporting the global transition to clean energy.

Keywords: Ocean Thermal energy Conversion (OTEC); Layers of Protection Analysis (LOPA); Renewal Energy; Hazards; Safeguards.

1.0 INTRODUCTION

Ocean Thermal Energy Conversion (OTEC) is an innovative renewable energy technology that exploits the thermal gradient between warm surface seawater and cold deep seawater to generate electricity [16]. Central to its operation is the use of ammonia as the working fluid in closed-cycle systems. Ammonia's thermodynamic properties, such as its low boiling point and high energy efficiency, make it an ideal medium for the evaporation-condensation cycle necessary for turbine operation. Moreover, ammonia is environmentally compatible in controlled conditions. However, its toxic and corrosive nature introduces significant safety and environmental risks. Accidental releases of ammonia pose potential threats to human health, marine ecosystems, and nearby communities, necessitating comprehensive hazard assessment and mitigation strategies to ensure safe and sustainable OTEC operations.

The toxicity of ammonia can lead to severe respiratory issues, eye irritation, and other health impacts for personnel exposed to leaks. Additionally, environmental contamination resulting from ammonia spills can disrupt marine ecosystems, potentially causing long-term damage to aquatic biodiversity. Key scenarios that can trigger ammonia-related hazards include mechanical failures, such as leaks from corroded piping and storage tanks, malfunctioning safety valves, operator errors during system maintenance, and structural damage caused by extreme weather conditions [13]. Immediate consequences include health risks to workers and localized environmental damage, while long-term effects could lead to legal liabilities, operational downtime, and reputational harm [17].

In managing these risks effectively, the Layers of Protection Analysis (LOPA) methodology is employed. LOPA provides a structured framework to evaluate the likelihood and consequences of hazardous events and assesses the adequacy of existing safeguards. Current measures in OTEC systems include the use of corrosion-resistant materials for pipes and tanks, real-time ammonia detection systems, and robust safety valves to regulate pressure. Operational safeguards, such as routine inspections, preventive maintenance schedules, and comprehensive operator training, also play a crucial role in minimizing risks.

However, additional protective measures are necessary to further enhance safety. Advanced real-time monitoring systems, powered by Internet of Things (IoT) technologies, can provide immediate detection and localization of leaks. Automated shutoff systems can isolate ammonia flow in emergencies, reducing the risk of uncontrolled releases. Predictive maintenance using artificial intelligence (AI) can proactively identify potential system failures, preventing incidents before they occur [18]. Moreover, secondary containment systems and marine barriers can mitigate environmental impacts by containing spills and preventing ammonia from entering aquatic ecosystems.

2.0 OCEAN THERMAL ENERGY CONVERSION

Ocean Thermal Energy Conversion (OTEC) (Figure 1) leverages the temperature difference between warm surface seawater and cooler deep ocean water to produce electricity. Sunlight warms the upper ocean layers, creating a thermal energy source, while deeper ocean waters remain significantly cooler. In OTEC systems, a working fluid—typically a low-boiling-point substance like ammonia—transfers this thermal energy through a thermodynamic process. The warm surface water heats the fluid, causing it to vaporize in a closed-loop system (Figure 1). The resulting vapor then drives a turbine, which generates electricity. To complete the cycle, the vapor is condensed back into a liquid using cold seawater pumped from the deep ocean, and the liquid is recycled to the heat exchanger for reuse [21].

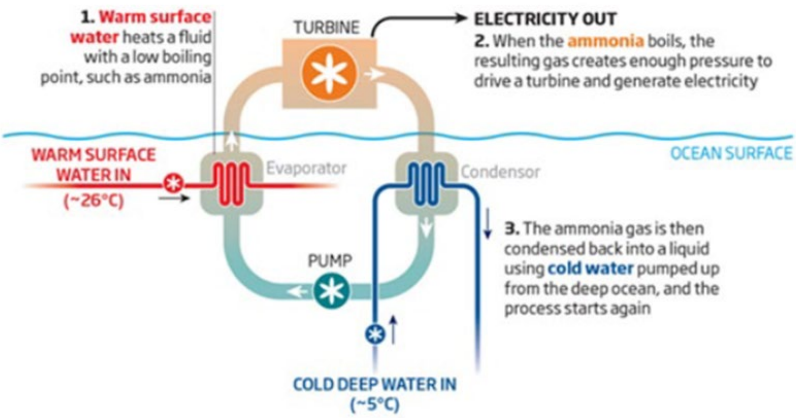

Figure 1: OTEC

There are three primary designs for Ocean Thermal Energy Conversion (OTEC) systems: closed-cycle, open-cycle, and hybrid [19].

a. Closed-Cycle Systems: These systems use low-boiling-point working fluid, such as ammonia. Warm surface seawater flows through a heat exchanger, transferring thermal energy to vaporize the ammonia. The high-pressure ammonia vapor then drives a turbine, generating electricity. Afterward, the vapor is condensed by cold deep seawater, returning it to a liquid state for recirculation. Closed-cycle systems are more thermally efficient than open-cycle systems because they employ a secondary working fluid that operates at higher pressures, allowing for smaller turbines [21].

b. Open-Cycle Systems: In these systems, warm surface seawater directly serves as the working fluid. It enters a low-pressure chamber where it boils into steam. This expanding steam drives a low-pressure turbine connected to a generator for electricity production. The process also generates freshwater as a byproduct since the salt precipitates out within the low-pressure chamber. Deep cold seawater condenses the steam back into liquid form for recirculation [22].

c. Hybrid Systems: These systems integrate features of both closed- and open-cycle designs. Warm seawater is introduced into a vacuum chamber, similar to an open-cycle system, where it evaporates into steam. This steam then vaporizes a low-boiling-point fluid in a closed-loop cycle, driving a turbine for electricity generation [21]

OTEC plants can be configured in various ways, such as onshore (land-based), floating platforms, or fixed offshore structures. This versatile technology provides a clean and reliable energy source, capable of continuous baseload electricity generation 24/7. A heat exchanger and turbine harness power from the temperature difference between the surface and deep ocean. Floating plants situated close to land appear to be the most promising configuration, with electricity transmitted to shore via submarine power cables. According to the National Oceanic and Atmospheric Administration [23], these floating plants are particularly advantageous due to their environmental benefits and sustainability as a long-term energy solution.

3.0 HYBRID OCEAN THERMAL ENERGY CONVERSION

Hybrid Ocean Thermal Energy Conversion (Hybrid OTEC) (Figure 2) integrates elements of both closed-cycle and open-cycle systems to optimize energy production from ocean thermal gradients [3],[24]. The process typically combines the advantages of high-efficiency closed-cycle OTEC, which uses ammonia as the working fluid, with the simplicity of open-cycle OTEC, which directly uses seawater. In a hybrid system, warm surface seawater heats a secondary working fluid like water or a low-boiling point hydrocarbon, which then drives a turbine. This combined approach allows for greater operational flexibility and increased energy output by mitigating the limitations of each individual cycle. Hybrid OTEC systems offer improved efficiency and reliability compared to traditional setups, making them a promising advancement for sustainable energy production in marine environments.[8] & [10].

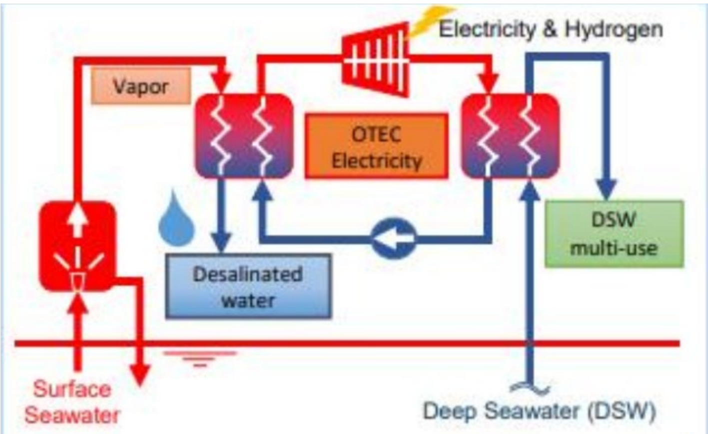

Figure 2: Hybrid OTEC

4.0 AMMONIA CHARACTERISTIC

Physical Properties

Anhydrous ammonia is a colorless liquid with a boiling point of -33.3°C (-28°F). In refrigeration applications, it is stored under pressure in sealed containers. Upon release of pressure, the liquid ammonia vaporizes rapidly, typically forming an invisible gas. This rapid phase change results in a significant cooling effect, as the temperature of the liquid drops to its boiling point like the cooling sensation experienced when water evaporates from the skin. This thermodynamic property underpins ammonia's widespread use in industrial refrigeration systems. In terms of physical characteristics, anhydrous ammonia is less dense than water; approximately 30.3 liters of ammonia equates in weight to 19 liters of water. Both the liquid and gaseous forms of ammonia are subject to volumetric changes in response to fluctuations in temperature and pressure. For instance, if a partially filled, sealed container of liquid anhydrous ammonia is heated from -17.8°C (0°F) to 20°C (68°F), the liquid volume expands by roughly 10%. A container that is 90% full at 0°F would become nearly 99% full at 68°F, with the internal pressure increasing from 16 psi to 110 psi over this temperature range. Furthermore, when vaporized, liquid ammonia undergoes an expansion ratio of approximately 1: 850.Although ammonia gas is significantly lighter than air and tends to rise under dry atmospheric conditions, its strong affinity for moisture causes it to interact rapidly with ambient humidity. This reaction often results in the gas remaining closer to ground level, increasing the risk of human and environmental exposure in the event of a leak. Ammonia has an odor detection threshold ranging from 5 to 50 parts per million (ppm) in air. The Occupational Safety and Health Administration (OSHA) has established a permissible exposure limit (PEL) of 25 ppm, equivalent to 17 mg/m³, based on an eight-hour time-weighted average (TWA). It is advisable that if personnel detect the presence of ammonia by smell, they should immediately retreat from the area and assess whether the use of respiratory protective equipment is necessary to ensure safety.[27]

Table 1: Ammonia Physical Properties

Boiling Point	33.3°C (-28°F)
Weight per gallon of liquid at -33.3°C (-28°F)	2.58 kg
Weight per gallon of liquid at 15.6°C (60°F)	2.34 kg
Specific gravity of the liquid (water=1)	0.619
Specific gravity of the gas (air=1)	0.588
Flammable limits in air	16-25%
Ignition temperature	651°C (1204°F)
Vapor pressure at -17.8°C (0°F)	16 psi
Vapor pressure at 20.0°C (68°F)	110 psi
Vapor pressure at 37.8°C (100°F)	198 psi
One cubic foot of liquid at 15.6°C (60°F) expands to	24 cubic metres of gas (850 cubic foot)

Chemical properties

Anhydrous ammonia is highly soluble in water. At a temperature of 20.0°C (68°F), approximately 700 volumes of ammonia vapor can be absorbed into one volume of water, resulting in an aqueous solution containing up to 34% ammonia by weight. This solution is commonly referred to as aqua ammonia or ammonium hydroxide. Due to its chemical properties, ammonia particularly in moist environments exhibits corrosive behavior towards certain metals, including copper, zinc, and various alloys containing these elements. Consequently, materials used in the storage, handling, and transportation of anhydrous ammonia must be selected with care. Only compatible materials such as iron, steel, specific rubber compounds, certain plastics, and non-ferrous alloys known to resist ammonia-induced corrosion are recommended for the fabrication of containers, piping, and fittings. In addition, ammonia reacts readily with mercury, forming mercury fulminate an unstable and highly explosive compound. Although anhydrous ammonia is classified as non-flammable under normal atmospheric conditions, it can become flammable when its vapor concentration in air reaches levels between 16% and 25% by weight. Such concentrations are rare and are typically associated with confined spaces or significant accidental releases. The fire hazard potential of ammonia is significantly heightened in the presence of oils or other combustible materials. As a strong alkali, anhydrous ammonia poses both chemical and physical hazards and requires stringent safety precautions in handling, especially in industrial applications

Effect of Ammonia

The release of ammonia can have adverse effects on the surrounding area. Table 2 presents the potential impacted items along with the corresponding concentration ranges (in parts per million, ppm) that may pose significant risks to human health, individuals nearby, and the environment. [26]

Table 2: Ammonia

Effect of Ammonia	Part Per Million (ppm)
Normally can be detected by smell	5 – 10 ppm
Permissible exposure limit (PEL)	25 ppm
People who are used to it can work without discomfort	10 – 100 ppm
Causes irritation of the mucous membranes and the eyes, but normally with no lasting consequences	150 – 200 ppm
Immediately Dangerous to Life or Health (IDLH)	300 ppm
● Eyes are affected more quickly, streaming with tears after 30 seconds or less ● Air is still breathabl	500 – 700 ppm
● Breathing is intolerable	≥ 1000 ppm

● Vision is impaired but not lost. Eye injuries constitute the most serious hazards at this concentration in terms of possible permanent disability	
● Can damage or destroy tissue, ● The instant human reaction is, to quickly evacuate the area	≥ 1500 ppm
Risk of fatality	≥ 2500 ppm

Ammonia (NH_3) is a colorless gas with a distinctive pungent odor, consisting of nitrogen and hydrogen. It represents the simplest stable compound of these two elements and serves as a fundamental precursor in the synthesis of numerous nitrogen-based industrial compounds. Widely utilized across various sectors, ammonia plays a critical role in the textile industry, the production of synthetic fibers and resins, petroleum refining, and rubber manufacturing. Beyond its industrial applications, ammonia is naturally present in the human body and the environment. Biologically, it is vital for several metabolic processes, including the biosynthesis of amino acids and nucleotides. Environmentally, ammonia is a key component of the nitrogen cycle, generated through microbial activity in soil and the natural decomposition of organic matter such as plant and animal residues.

Therefore, the installation and commissioning of a Hybrid OTEC system must be carried out in a proper and systematic manner to effectively mitigate the risk of ammonia leakage or system outage, thereby preventing potential fatalities in the surrounding area.

4.1 POTENTIAL SCENARIOS FOR AMMONIA RELEASE IN HYBRID OTEC SYSTEM

Ammonia serves as the working fluid in Hybrid Ocean Thermal Energy Conversion (H-OTEC) systems due to its thermodynamic efficiency, enabling energy transfer in the closed-cycle process [4]. However, its toxic and corrosive properties present significant risks, particularly in marine environments. Identifying potential release scenarios is essential to ensure operational safety and environmental protection. Several key scenarios highlight vulnerabilities in OTEC systems.

a. **Leakage of Piping or Storage Tanks**
One of the most common risks stems from leakage due to corrosion, mechanical wear, or design flaws in ammonia-containing components. The saline and humid conditions of marine environments exacerbate corrosion rates, gradually weakening structural integrity [8].[2]. Mechanical stress and wear, combined with prolonged exposure to these harsh conditions, further increase the likelihood of leaks. Design flaws, such as insufficient material quality or improper welding, also contribute to the risk. Unaddressed, these leaks can lead to significant ammonia exposure, endangering both personnel and marine ecosystems.

b. **Failure of Safety Valves**
Safety valves are critical components designed to relieve pressure during abnormal conditions, but malfunctions can lead to catastrophic ammonia releases. Improper maintenance, such as failure to inspect or recalibrate safety valves, reduces their reliability [9]. Similarly, design deficiencies, including incorrect valve sizing or inadequate materials, can compromise their effectiveness under high-pressure scenarios. A malfunctioning valve can result in an uncontrolled release, exposing workers and nearby ecosystems to ammonia's harmful effects.

c. **Operator Error**
Human error is another significant contributor to ammonia release incidents. Mistakes during maintenance, such as improper tightening of connections or failure to follow safety protocols, can create leak points. Mishandling ammonia during routine operations or neglecting alarm signals further compounds the risk [10]. Even well-trained personnel are susceptible to errors under high-stress conditions, underscoring the need for continuous training and robust procedural safeguards.

d. **Extreme Weather Events**
OTEC systems, often situated in offshore or coastal locations, are vulnerable to extreme weather events. High winds, flooding, and storm surges associated with hurricanes or tropical storms can physically damage critical infrastructure, such as storage tanks and pipelines. Structural weaknesses exacerbated by these conditions increase the risk of ammonia release. The potential for large-scale environmental contamination is especially high, as stormwater runoff can spread ammonia over a wide area, affecting marine life and nearby communities.
The consequences of these scenarios extend beyond immediate injuries or contamination. Long-term repercussions include reputational damage, legal liabilities, regulatory penalties, and costly operational shutdowns. Effective hazard management requires systematic risk assessment and mitigation strategies, such as adopting corrosion-resistant materials, automating safety valve monitoring, enhancing training programs, and reinforcing infrastructure against extreme weather. Addressing these vulnerabilities is critical to ensuring the safe and sustainable operation of OTEC systems.

5.0 METHODOLOGY

The Layers of Protection Analysis (LOPA) is a semi-quantitative risk assessment methodology designed to evaluate the effectiveness of existing safety measures and identify the need for additional safeguards [14]. In the context of Ocean Thermal Energy Conversion (OTEC) systems, where ammonia is used as a working fluid, LOPA plays a crucial role in ensuring operational safety and minimizing risks associated with ammonia's toxicity and environmental impact. By systematically analyzing cause-consequence pathways and assessing independent protection layers (IPLs), LOPA provides a structured framework for risk mitigation [5].

i. *Step 1: Define the Initiating Event*

The first step in LOPA involves identifying scenarios that could trigger an ammonia release. Typical initiating events in OTEC systems include corrosion-induced leaks in piping or storage tanks, mechanical failure of safety valves, operator errors, and structural damage from extreme weather conditions [11]. These events are considered potential causes of hazardous ammonia exposure.

ii. *Step 2: Estimate Initiating Event Frequency*

Using historical data, expert judgment, and system inspection records, the frequency of these initiating events is quantified. For example, corrosion-related leaks may be categorized as moderate frequency due to the harsh marine environment that accelerates material degradation [9].

iii. *Step 3: Identify Consequences and Severity*

The analysis then focuses on determining the potential impact of ammonia release on health, the environment, and infrastructure. Ammonia's toxicity makes its release highly severe, posing risks to personnel and marine ecosystems. The degree of severity is classified as prioritizing risk reduction measures [12].

iv. *Step 4: Determine Target Risk Levels*

Target risk levels are established based on industry standards, regulatory requirements, and organizational risk tolerance. Standards such as ISO 45001 and ISO 14001 guide acceptable thresholds for occupational safety and environmental impact.

v. *Step 5: Assess Existing Independent Protection Layers (IPLs)*

LOPA evaluates the effectiveness of current safeguards, such as corrosion-resistant materials, ammonia detection systems, safety valves, emergency shutdown protocols, and operator training. These IPLs act independently to prevent or mitigate ammonia release events.

vi. *Step 6: Evaluate Risk Reduction and Recommend Additional Safeguards*

If the risk exceeds the acceptable level, LOPA recommends additional layers. Proposed measures include automated ammonia recovery systems, double containment for storage tanks, enhanced emergency response training, and community warning systems. These measures ensure redundancy and comprehensive risk management.

LOPA is a robust tool for analysing ammonia-related risks in OTEC systems. Its systematic approach integrates technical, operational, and procedural safeguards, ensuring compliance with safety standards while supporting sustainable energy production. The methodology highlights the importance of continuous evaluation and adaptation to maintain safe OTEC operations.

6.0 RESULTS & DISCUSSION

Case of Ammonia Exposure Risks in Hybrid in Malaysia (Figure 3)

In Malaysia, several incidents involving ammonia release have been reported. Two of the notable cases occurred at an Ice manufacturing facility and at a Poultry Processing Plant such as:

1. An ammonia leak originated from a damaged internal tube within the freezer tower used for ice production. The leak was detected through a nitrogen foam test, which pinpointed failure in a previously welded section of the tube. Investigations revealed that the repair work had been carried out by an unregistered and unqualified service provider, without proper documentation or prior notification from the Department of Occupational Safety and Health (DOSH). This constituted a clear breach of safety regulations, which mandate official notification, DOSH approval, and certification for any repairs involving unfired pressure vessels. The incident underscores the importance of comprehensive risk assessment, strict regulatory compliance, and effective emergency response planning to prevent workplace accidents and safeguard public safety.
2. Investigation determined that the incident was caused by a failure in the pipeline system of one of the blast freezer

units used for freezing fresh raw poultry. The cooling process was disrupted due to the malfunction of a solenoid safety valve, which was intended to regulate and prevent excessive ammonia flow into the blast freezer. The valve failure led to an overpressure event, ultimately resulting in a rupture and explosion at the ammonia outlet pipe. Further examination of the cooling system revealed that the malfunction of the solenoid valve was due to the degradation of its internal rubber seal, caused by the presence of foreign oil particles within the pipeline. Although the system was equipped with a strainer filter designed to remove impurities from the ammonia refrigerant, the filter failed to perform effectively, allowing contaminants to compromise critical components, including the solenoid valve.[28]

Generally, Ammonia plays a central role in the operation of Hybrid OTEC systems, especially at the plant in Negeri Sembilan, but its hazardous properties necessitate rigorous safety measures [15]. Exposure to ammonia at concentrations as low as 50 parts per million (ppm) can cause irritation to the eyes, nose, and throat, while higher concentrations may lead to severe respiratory distress or even fatalities [6]&[7]. Additionally, ammonia is flammable under specific conditions, with an explosive range of 15–28% volume in air. These risks are heightened in the context of OTEC systems, which often operate in offshore or remote locations where emergency responses may be delayed. Beyond human health concerns, accidental ammonia releases can contaminate marine ecosystems, affect water quality and threaten aquatic life. Given these risks, identifying and addressing potential hazards in the design and operation of OTEC systems is critical to ensure safety and environmental sustainability.

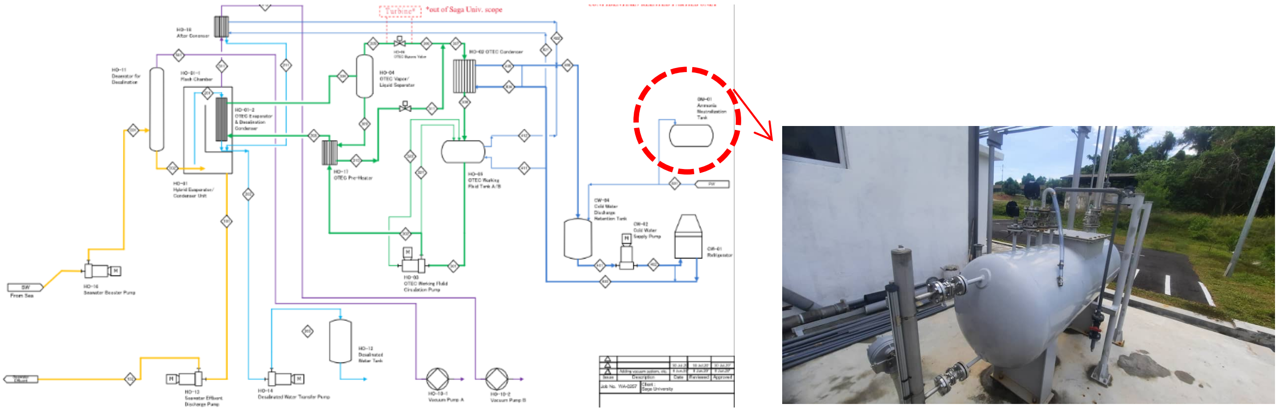

Figure 3: Location Accumulation Storage Vessel (ASV) (Ammonia)

The process of conducting LOPA activities is as follows:

i. *Step 1: Define the Initiating Event*

The possibility of an incident involving the potential release of ammonia has been identified. The ASV in question has an external neutralization system with a total capacity of **approximately 153.23 m³**. Under these circumstances, it is estimated that the ammonia volume released could amount to **approximately 148.11 m³,** which constitutes 90% of the tank's total storage capacity when operating at safe working pressure [1] & [2].

ii. *Step 2: Estimate Initiating Event Frequency*

During the testing and commissioning phase of the OTEC (Onsite Thermal Energy Conversion) System, an unintended release of ammonia occurred due to the manual activation of the pressure relief valve by an operator. The operator, upon suspecting a potential flow anomaly as indicated on the Distributed Control System (DCS) panel in the control room, proceeded to open the pressure relief valve to alleviate system pressure. This action resulted in the uncontrolled venting of ammonia into the atmosphere. The release event extended for a duration exceeding four hours, contributing to widespread dispersion of ammonia vapors into the surrounding environment. Ammonia's inherent physical propertie such as particularly its density relative to air thah could lead to the vapors settling and spreading at lower elevations, thereby increasing exposure risks to personnel, facilities, and the ecological vicinity. Compounding the severity of the incident, the operator temporarily left the facility premises to procure calcium carbonate with the intention of neutralizing the ammonia within the storage tank. During this period, the pressure relief valve remained open, allowing the continuous release of ammonia. It was later acknowledged by the operator that the failure to re-close the valve was inadvertent. Furthermore, the absence of a water sprinkler mitigation system at the external ASV significantly hindered the containment and dispersion control of the vapors. The lack of such critical safety infrastructure amplified the potential hazard, both in terms of human exposure and environmental impact.

iii. Step 3: Identify Consequences and Severity

Thus, Ammonia spread downwards to the surrounding area. Due to no personal isn't in the facility and the pressure relief valve opens vent out 90% of the amount of ammonia exceedinding more than 4 hours. There wasn't even a single safeguard installation near the ammonia tank (such as bun or water sprinkler system). The water sprinkler system is only installed inside the facility approximately **148.11 m³** will disperse and engulfing the surrounding area as such in the ALOHA software [23].

Figure 4: Marplot (Ammonia Dispersion)

Figure 4 shown Aloha out put that the indicator displays toxicity levels as follows: a red mark signifies a highly toxic range of 3–4 meters, an orange mark indicates moderate toxicity within 5–7 meters, and a yellow mark represents a low toxicity level at 8–10 meters, causing mild eye discomfort. Toxic Contour Release (ALOHA), if toxic emissions are released within a range of 1 to 10 meters, Hatchery C, located approximately 2 meters above HOTEC, and Hatchery B, positioned further than 4 meters below, will experience dilution of ammonia toxicity. The release will dissipate into the air, spreading uniformly in a 360-degree direction due to the batch discharge process.

iv. Step 4: Determine Target Risk Levels

The risk level in this case has been qualititative investigated at site by the outage of the ammonia to surrounding area as stated, the point of a source from the release of ammonia from the pressure relief valve exceedingly more than 4 hours of as shown below: (Figure 5: Direction of Ammonia's Dispersion)

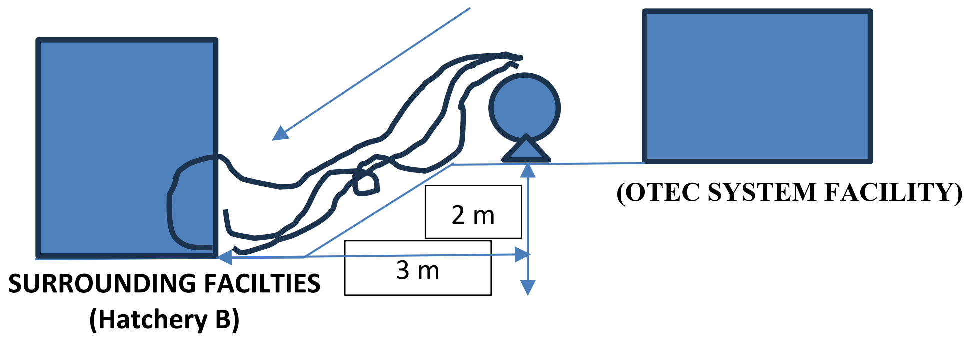

Figure 5: Direction of Ammonia's Dispersion

Therefore, plotted in the Risk Matrix using Apporach Risk = Likelihood dan Severity. [25]

Table 4: Risk Matrx

	Distance Away from Source (meters)									
Likelihood Severity	1m	2m	3m	4m	5m	6m	7m	8m	9m	10m
Highly Toxic										
Moderate Toxic										
Low Toxic										

Hence, it's been quantified and justified by ondsite estimation ad the real site state than a vivdly signifant indicates a highly toxic range of 3–4 meters, an orange mark indicates moderate toxicity within 5–7 meters, and a yellow mark represents a low toxicity level at 8–10 meters, causing mild eye discomfort. In addition, it also concurs with the simulation compute in the ALOHA Software. In result from the Aloha output, the risk quantification and onsite investigation

v. Step 5: Assess Existing Independent Protection Layers (IPLs)

OTEC facilities have been in placed in the house equipped with active systems such as 2 water sprinkle systems at the 1st floor to safeguard the 2 mounted pressurised vessel of ammonia to avoid any cases of dispersion of Ammonia to the surrounding Area and alaram that connected to DSC. Those safeguards are controlled by the DCS System in the Control Room. However, for the ASV outside the OTEC facilities there isn't any safegurad installed. (such as bun) only general conventional drainage. Those are the basic safeguards in the OTEC System, and the plant has been categories as Non-Major Hazard Installation (NMHI) Plant under CIMAH Regulation 1990.

Table 5 : Independece Protection layers (IPLS)

	IPLS	PASSIVE GUARDS (PS)	ACTIVE SAFEGUARDS (AC)
1	Existing ILPS	No Tank Dike	Alarm in the Plant connected to DCS
		No Water Sprikle	
		PRV (Pressure relief Valve)	
2	Recommended Installation IPLS	Tank Dike	Alarm in the Plant connected to DCS
		Water Sprikle	
		PRV (Pressure relief Valve)-functional and connected to DCS	

Therefore, it is essential to develop and implement comprehensive passive and active safety measures for the Ammonia Neutralization Tank, ensuring the overall safety and integrity of the Hybrid Ocean Thermal Energy Conversion (H-OTEC) system.

vi. Step 6: Evaluate Risk Reduction and Recommend Additional Safeguards

To mitigate the risk of ammonia dispersion to the surrounding area, especially at the ASV, it is recommended to implement AIOT an alarm as indicator system, edequate tank dike and drainage to the treatment pool and set up the pressure relieve valve according to ASTM. Those safeguards must be directly connected to the DCS for real-time operator alerts dan ral time data indicators. Additionally, a water sprinler system should be installed to dilute ammonia released into the atmosphere.

Table 6: Passive and Active PS versus Accident

	IPLS	PASSIVE GUARDS (PS)	ACTIVE SAFEGUARDS (AC)	BEFORE ACCIDENT	AFTER ACCIDENT
1	Existing ILPS	No Tank Dike	Alarm in the Plant connected to DCS		
		No Water Sprikle			
		PRV (Pressure relief Valve)			
2	**Recommended Installation IPLS**	**Tank Dike**	**Alarm in the Plant connected to DCS**		
		Water Sprikle	**AIOT Alarm Indicator**		
		PRV (Pressure relief Valve)- functional and connected to DCS	**Proper drainage**		

Legend:
1. **Red** - Insufficient Safety Gurard (Cause accident)
2. **Green** - Additional Safety Guard (After Accident)

Therefore, the process of evaluating risk reduction measures and recommending additional safeguards is essential to prevent the recurrence of similar accidents at an early stage.

7.0 CONCLUSION

Hybrid Ocean Thermal Energy Conversion (OTEC) systems offer a promising and sustainable solution to the global energy crisis by utilizing the ocean's thermal gradient. However, the employment of ammonia as a working fluid presents significant safety challenges, necessitating a comprehensive and systematic risk management approach. This study demonstrates that the application of risk assessment tools such as Layers of Protection Analysis (LOPA), risk matrix evaluation, and ammonia dispersion modeling (ALOHA) can effectively identify, evaluate, and mitigate ammonia-related hazards in hybrid OTEC systems. Addition of integrating multiple layers of protection, including engineering controls, administrative procedures, emergency response mechanisms, and physical barriers, residual risks can be reduced to acceptable levels. The risk matrix and dispersion modeling using ALOHA software (combined with MARPLOT and Google Maps) illustrate toxicity levels as follows: red zones indicate high toxicity (within 3–4 meters), orange zones represent moderate toxicity (within 5–7 meters), and yellow zones reflect low toxicity (within 8–10 meters), with potential for mild eye irritation. The current safeguards or Independent Protection Layers (IPLs), both passive and active, have been found insufficient in effectively addressing the risks associated with ammonia leakage. Therefore, enhanced measures such as tank dikes, water sprinkler systems, and AIoT-integrated alarm relays within the Distributed Control System (DCS) are necessary to strengthen safety. Moving As a result, further research and innovation in materials, technology, and personnel training will be essential to ensure the safe and sustainable deployment of hybrid OTEC systems, and to minimize the risk of unforeseen accidents.

Acknowledgements

This was supported by the Universiti Teknologi Malaysia with Long-Term Research Grant Scheme (LRGS) [grant no: R.K130000.7856. 4L894] and [R.K130000.7843.4L891] funded by the Ministry of Higher Education (MOHE) Malaysia.

References

[1] International Electrotechnical Commission (IEC). "Functional Safety – Safety Instrumented Systems for the Process Industry Sector (IEC 61511)." Geneva: IEC, 2016.
[2] American Petroleum Institute (API). "API 579-1/ASME FFS-1: Fitness-For-Service." Washington, DC: API, 2016.
[3] Doucha, J., & Veziroglu, T. N. "Ocean Thermal Energy Conversion (OTEC): Advances and Challenges." Renewable Energy Journal, vol. 54, 2020, pp. 97–112.

[4] Patel, K., & Sinha, A. "Ammonia as a Refrigerant in Energy Systems: Properties, Challenges, and Safety Measures." Energy Procedia, vol. 103, 2017, pp. 218–225.
[5] Chisholm, R. A. "The Role of LOPA in Modern Risk Management." Safety Science Journal, vol. 61, no. 4, 2019, pp. 289–301.
[6] National Institute for Occupational Safety and Health (NIOSH). "Ammonia: Workplace Safety Standards." NIOSH Pocket Guide to Chemical Hazards, 2022.
[7] United Nations Environment Programme (UNEP). "Ammonia Emissions and Environmental Impacts." UNEP Report, 2021.
[8] Smith, J., Carter, T., & Williams, D. (2020). Energy Systems and Environmental Protection. New York: Springer Publishing.
[9] Gong, H., Liu, Z., & Wang, Y. (2022). "Safety and Risk Management of Ammonia-Based Renewable Energy Systems." Journal of Renewable Energy Systems, 15(3), 200-215.
[10] Zhou, F., Zhang, Q., & Chen, L. (2021). "Advances in Predictive Maintenance for Renewable Energy Systems." Energy Research Letters, 8(1), 120-134.
[11] Smith, J., Carter, T., & Williams, D. (2020). Energy Systems and Environmental Protection. New York: Springer Publishing.
[12] Zhou, F., Zhang, Q., & Chen, L. (2021). "Advances in Predictive Maintenance for Renewable Energy Systems." Energy Research Letters, 8(1), 120-134.
[13] Gong, H., Liu, Z., & Wang, Y. (2022). "Safety and Risk Management of Ammonia-Based Renewable Energy Systems." Journal of Renewable Energy Systems, 15(3), 200-215.
[14] AIChE. (2020). Layer of Protection Analysis: Simplified Process Risk Assessment.
[15] ASHRAE. (2021). Ammonia Safety and Environmental Guidelines for the Ammonia Refrigeration Industry.
[16] DOE. (2022). Ocean Thermal Energy Conversion: Advancing Sustainable Energy Solutions.
[17] Smith, J., Carter, T., & Williams, D. (2020). Energy Systems and Environmental Protection. New York: Springer Publishing.
[18] Zhou, F., Zhang, Q., & Chen, L. (2021). "Advances in Hybrid Ocean Thermal Energy Conversion Systems." Renewable Energy Research, 12(4), 305-320.
[19] Uehara H. and Ikegami Y. 1990. Optimization of Closed-Cycle OTEC System. Trans of the ASME Journal of Solar Energy Engineering. 112(4):247-256.
[20] United State Environmental Protection Agency (UEPA): Alea Locations of hazardous Atmospheres Modelling 2024. ALOHA Software | US EPA
[21] Uehara H., Miyara A., Ikegami Y. and Nakaoka T. 1996. Performance Analysis of an OTEC Plant and a Desalination Plant Using an Integrated Hybrid Cycle. ASME. J. Sol. Energy Eng. 118(2): 115-122.
[22] Vega LA. 2003. Ocean Thermal Energy Conversion Primer. Marine Technology Society Journal. 6(4): 25-35.
[23] National Oceanic and Atmospheric Administration (2010), National Oceanic and Atmospheric Administration
[24] Jaafar, A.B.; Abu Husain, M.K.; Ariffin, A. 2020, Research and Development Activities of Ocean Thermal Energy Driven Development in Malaysia, in Ocean Thermal Energy Conversion (OTEC) – Past, Present, and Progress, A.S. Kim, Ed.; 1–13. IntechOpen: London.
[25] Roy, Prasun Kumar, et al. "Consequence and risk assessment: Case study of an ammonia storage facility." *Archives of Environmental Science* 5 (2011): 25-36.
[26] ABC -SDS No: 000D01021772 1/22, SAFETY DATA SHEET (Ammonia Annhydrous)-Version 2.
[27] Jabatan keselamatan dan Kesihatan Pekerjaan Malaysia (2020) : Guideline of Safe Management of Ammonia Refrigeration System 2020.