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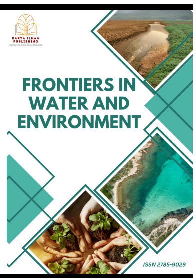

Lessons from Kyshtym and Fukushima: Improving Nuclear Safety, Waste Management and Transparency

Mohamad Aqhmal Fitri Adzhari[1], Nur Ashikin Zulaikha Yulcifly[1], Siti Amira Othman[1,*]

[1] Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia, 84600, Pagoh, Johor, Malaysia

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ABSTRACT

The Kyshtym Disaster and the Fukushima Daiichi nuclear accident are two of the most significant nuclear incidents in history, each leaving lasting legacies in terms of environmental damage, public health, and safety standards. These events provide essential lessons in effective radioactive waste management, transparent safety practices, and preparedness for nuclear emergencies. The Kyshtym Disaster exposed the grave consequences of inadequate radioactive waste management and the dangers of poor safety protocols and lack of transparency in nuclear operations. Similarly, the Fukushima accident, caused by explosions and resulting radiation exposure, illustrated the severe physical dangers of nuclear incidents, including air-blast injuries and the potential for radiation burns, sickness, and death. These events revealed critical gaps in nuclear safety that put both human lives and the environment at immense risk. From the Kyshtym disaster, we learned the necessity of adequate safety measures and transparency in managing radioactive materials. The disaster emphasised the need for clear communication and robust safety protocols in nuclear facilities to prevent such catastrophic failures. Fukushima further demonstrated the importance of preparedness, particularly in handling high-level radiation exposure and preventing the physical harm caused by explosions and thermal radiation. These events highlighted the vital role of global safety standards and best practices in avoiding nuclear accidents. The Kyshtym and Fukushima disasters are critical reminders of the ongoing risks associated with nuclear energy. The lessons learned from these incidents must guide global nuclear policies, focusing on improved safety protocols, enhanced waste management practices, and transparent operations. Integrating these lessons into future nuclear practices can reduce the likelihood of similar accidents and better protect human health and the environment.

1. Introduction

1.1 Kyshtym Disaster

The Kyshtym Disaster was a major nuclear accident that took place on September 29, 1957, at the Mayak Production Association atomic facility near Kyshtym in Soviet Russia’s Chelyabinsk Oblast.

* Corresponding author.
Email address: sitiamira@uthm.edu.my

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This disaster, largely hidden from the world due to Soviet secrecy, is considered the third-most severe nuclear incident in history after Chernobyl and Fukushima. The accident was caused by a failure in the cooling system of a storage tank containing 70-80 tons of highly radioactive waste from spent nuclear fuel. As the waste overheated, a chemical explosion erupted, releasing massive amounts of radioactive material across the environment. The radioactive cloud from the blast contaminated a zone known as the East-Ural Radioactive Trace (EURT), impacting roughly 20,000 square kilometres and exposing around 270,000 people in the Chelyabinsk, Sverdlovsk, and Tyumen regions [1].

In response, Soviet authorities evacuated around 10,000 people from the worst-affected areas, though the delay in evacuation left many exposed to intense radiation levels. Thousands suffered from radiation sickness and later developed long-term health issues such as cancer and genetic mutations. Some villages became uninhabitable and were designated as “forbidden zones.” Because of Cold War secrecy, the Soviet government kept details of the incident classified for years, and it wasn’t until 1976 that the event was revealed by Zhores Medvedev, a Soviet scientist and dissident. The disaster’s full impact gradually became known internationally, and it was later given a Level 6 rating on the International Nuclear Event Scale (INES), just below the highest level of 7, which Chernobyl and Fukushima were assigned [2].

1.2 Fukushima Daiichi

The Fukushima Daiichi nuclear disaster (2011) occurred on 11 March 2011 at the Fukushima Daiichi Nuclear Power Plant in Japan. A significant earthquake as high as 15 meters of tsunami exceeding the plant defences seawall. The tsunami turned off the power supply and cooling of three Fukushima Daiichi reactors, which became overheated. As a result, radionuclides are released into the environment. The weather dispersed the radioactive material locally, regionally, and globally over land and sea. The accident was recorded as level 7 on the International Nuclear and Radiological Event. Up to 40 kilometres radius around the Fukushima Daiichi power plant have to leave their homes due to the high levels of radiation [11].

Foodstuffs are contaminated by the radioactive material deposited on the leaves and might directly on agricultural products like fruits and vegetables or absorbed by the roots. Besides the atmosphere, the water is also affected, where the water primarily feeds into the reactors for emergency cooling, and the groundwater penetrates the reactor. After the incident, the increasing anti-nuclear stance and the nuclear power plant closed over fear of earthquakes and tsunamis in the future. Thus, the plants freeze to build new reactors [12].

2. Chronology of Accident

2.1 Kyshtym Disaster

The Kyshtym Disaster was caused by a failure in the cooling system of a tank holding highly radioactive waste. This tank contained 70-80 tons of waste from processed nuclear fuel, generating substantial heat from radioactive decay. A constant cooling system was essential to manage this heat, but it malfunctioned, possibly from technical issues or a lack of proper maintenance. As the cooling failed, the tank’s temperature rose unchecked.

Mayak’s monitoring systems were insufficient to detect the malfunction early on or stop the overheating, eventually leading to a chemical explosion within the tank. Although this was not a nuclear explosion, it released around 20 million curies of radioactive material into the environment. The resulting radioactive cloud spread over an area known as the East-Ural Radioactive Trace (EURT), contaminating 20,000 square kilometres of land in the Chelyabinsk, Sverdlovsk, and Tyumen regions [3].

However, due to the Soviet Union's secrecy about its nuclear operations, the disaster was not disclosed, and residents received no warnings or evacuations until it was too late. Many people unknowingly remained in highly contaminated areas, resulting in thousands suffering from radiation exposure. This led to widespread radiation sickness and long-term health issues, including cancers and genetic effects.

2.2 Fukushima Daiichi

The failure of technical components, human error or natural disaster can cause nuclear accidents. Meanwhile, the expert teams from Japan concluded Fukushima was less of a natural disaster than a 'man-made' one. On 11 March 2011, Japan was shaken by a significant earthquake known as the Great East Japan Earthquake, followed by a tsunami that reached 10 meters in height. At approximately 8.15 pm, an earthquake with a magnitude of 9.0 near the coast of Honshu, Japan's island. The quake lasted six minutes and caused a tsunami [13].

The tsunami caused the Fukushima Daiichi nuclear disaster. Many electrical generators ran out of fuel. As a result, heat builds up and generates hydrogen gases. The next day, on 12 March 2011, the temperature in reactor 1 increased. Thus, the operators attempted to vent steam to reduce pressure, releasing radioactive material into the environment. Then, the temperature continued to rise at reactor three due to cooling failures. The explosion at reactor 3 causes more structural damage, releasing more radioactive materials into the environment. Next, reactors 2 and 4 were affected, but the reactor was offline. This accident was categorised as a level 7 major accident on the International Nuclear and Radiological Event Scale [14].

3. Lessons learned from the accident

3.1 Kyshtym Disaster

The Kyshtym Disaster is a powerful reminder of the inherent risks in nuclear energy, especially when safety protocols and transparency are lacking. From one angle, it illustrates how waste management and technology failures can lead to catastrophic, long-term impacts on people and the environment. The severe health consequences faced by residents—many exposed to harmful radiation without their knowledge highlight the moral responsibility of prioritising safety and openness in nuclear activities. The Soviet government's delayed evacuation and secrecy around the event exemplify how Cold War-era information control tragically overshadowed public welfare, leaving communities to bear the consequences [4].

However, the Kyshtym Disaster also prompted critical changes in nuclear safety practices. The scale of the disaster, coupled with global scrutiny, eventually led the Soviet Union to adopt more rigorous safety protocols, setting an example that influenced worldwide standards. As such, Kyshtym has become an essential case study underscoring the need for careful, regulated nuclear operations where human health and environmental protection take precedence over political priorities. Today, the disaster is a reminder of the importance of ethical and transparent atomic policies to prevent energy development from carrying severe human and environmental costs [5].

The Kyshtym Disaster taught crucial lessons that have influenced nuclear safety regulations and practices. One of the main lessons was the importance of having redundant safety systems. The failure of the cooling system demonstrated the need for backup systems and automatic shutdown features to prevent the overheating of radioactive waste. It also highlighted the necessity for regular maintenance and the upgrading of equipment to ensure that technology remains dependable and capable of managing high-risk operations. The absence of effective real-time monitoring systems pointed to the critical need for advanced monitoring and early detection systems, which can alert staff to potential problems before they become severe. Additionally, the disaster emphasised the importance of transparency and external oversight in nuclear operations. The Soviet Union's secrecy and lack of openness delayed the response. They worsened the consequences, highlighting the need for independent inspections and global monitoring to ensure that nuclear facilities follow safety protocols and act quickly in emergencies [6].

The disaster also underscored the importance of having well-defined emergency response protocols and clear public communication strategies. The delay in evacuations and lack of communication left people vulnerable to radiation exposure, showing that timely evacuations and transparent information are essential to protect public health. Moreover, radiation exposure's long-term health and environmental impacts demonstrated the need for continuous monitoring and clean-up efforts in affected areas. Finally, the event revealed the significance of international collaboration on nuclear safety. The Soviet Union's isolated approach contributed to mishandling the disaster, underscoring the need for global cooperation through organisations like the International Atomic Energy Agency (IAEA) to share best practices and ensure nuclear safety worldwide. These lessons have been crucial in shaping modern nuclear safety standards, strongly emphasising protecting human health, preserving the environment, and ensuring accountability [7].

3.2 Fukushima Daiichi

Several lessons can be learnt from the accident, like seeking more information about hazards. Improve nuclear plant systems and resources for severe accidents. Examine offsite emergency response capabilities and make essential improvements [15].

Firstly, seeking more information about potential hazards is essential for effective risk management and emergency response planning. Organisations and communities can make informed decisions about preparing, preventing, and mitigating associated risks by understanding hazards in-depth—analysing their likelihood, severity, and possible impacts on health, infrastructure, and the environment. This proactive approach identifies vulnerabilities, helps prioritise resources, and supports the development of targeted safety measures, reducing the potential for harm. Additionally, having accurate information on hazards promotes public awareness and engagement. When community members understand the risks they may face, they are more likely to participate in preparedness activities, follow recommended safety procedures, and make informed decisions during emergencies. Collective preparedness strengthens overall resilience by ensuring that individuals and organisations are better equipped to respond effectively in a crisis. Moreover, continuous hazard research allows for ongoing risk assessment and improvement in emergency response planning. New technologies, such as geographic information systems (GIS) and predictive modelling, provide valuable insights into the scope and progression of potential hazards, enabling more precise and adaptable planning. By staying informed and incorporating new information, organisations and communities ensure their strategies remain effective and aligned with best practices, ultimately enhancing safety and preparedness in an ever-changing world [16].

Next, nuclear plant systems and resources for severe accidents should be improved. Nuclear plant systems, operating procedures, and operator training should be upgraded regularly. The Fukushima Daiichi disaster underscored several critical lessons for nuclear safety. First, nuclear plants must have resilient systems and dedicated resources for severe accident scenarios. This means having robust, flood-resistant backup power systems, advanced cooling mechanisms that can operate even during power failures, and on-site emergency resources like mobile generators and water supplies. These measures help ensure that plants can maintain cooling and containment functions even when facing catastrophic events. Another lesson is the importance of regularly upgrading plant systems and procedures. Safety protocols, equipment, and systems should be consistently reviewed and updated based on the latest technological advancements and insights from previous incidents. By continuously upgrading these systems, nuclear facilities can address emerging threats, adapt to new safety standards, and reinforce defences against extreme events. Additionally, enhancing operator training for severe scenarios is essential. Training should go beyond routine operations to include comprehensive preparation for unexpected scenarios, such as power outages, natural disasters, and critical equipment failures. Regularly scheduled drills and simulations that mimic severe accident conditions prepare operators to respond effectively and make vital decisions under pressure during emergencies. These lessons highlight the importance of a proactive, flexible approach to nuclear safety, where continuous improvements and rigorous training safeguard against known and unforeseen risks [17].

Lastly, The Fukushima Daiichi disaster underscored the importance of strengthening offsite emergency response capabilities to protect surrounding communities effectively [18]. One critical area of improvement is establishing robust, reliable communication systems that ensure clear, uninterrupted information sharing between plant operators, government agencies, emergency responders, and the public [19]. Reliable backup communication channels are essential for providing timely guidance on evacuation, shelter-in-place orders, and health protocols during fast-evolving crises. Public education and preparedness also play a vital role in emergency response; communities near nuclear plants should be well-informed about evacuation routes, shelter locations, and health measures for radiation exposure. Regular educational programs, community drills, and accessible emergency resources help empower residents to act quickly and safely in emergencies. Coordinated emergency drills are also necessary to test and refine response plans, involving local, regional, and national agencies to identify and resolve logistical gaps. Enhancing evacuation infrastructure, such as transportation routes, shelter facilities, and medical resources for radiation exposure, is equally important, especially for supporting vulnerable populations needing assistance during evacuation [20]. Finally, establishing real-time radiation monitoring systems around nuclear plants allows authorities to track radioactive releases accurately, enabling quick, informed decision-making. By making real-time data accessible, emergency responders and the public can act with greater confidence and transparency. Overall, these communication, preparedness, coordinated drills, evacuation support, and real-time monitoring improvements are essential for a strong, effective offsite emergency response in nuclear emergencies[21].

4. Recommendations

4.1 Kyshtym Disaster

To avoid disasters like the Kyshtym Disaster, several key measures can be implemented to enhance safety, monitoring, and management at nuclear facilities. First, ensuring the cooling system is reliable with backup systems is essential. A failure in the cooling system caused the Kyshtym disaster, so having redundant systems that automatically activate if one fails can prevent overheating of radioactive waste. Regular maintenance and upgrades to equipment are also crucial to avoid system breakdowns. Outdated or poorly maintained infrastructure can lead to catastrophic failures, so routine checks are necessary. Additionally, implementing advanced monitoring and early detection systems would allow real-time tracking of temperature and pressure within waste storage, enabling corrective actions before critical conditions develop. These systems should be connected to automated shutdown mechanisms for safety [8].

Training staff thoroughly and establishing comprehensive safety protocols are equally important. Staff should be well-prepared to handle emergencies and regularly practice safety drills to react swiftly to unexpected events. Another lesson from the Kyshtym disaster is the lack of transparency and oversight; the Soviet Union's secrecy prevented proper management and reporting of the incident. To address this, implementing external oversight and independent inspections would ensure accountability and timely identification of safety risks. Moreover, more secure storage methods for radioactive waste, with advanced monitoring and built-in safety measures, would help prevent accidents like overheating or leaks. Regular assessments of storage conditions would further ensure long-term safety [9].

Public education and emergency preparedness are also critical in an accident. Clear and transparent communication about risks and well-established evacuation plans would help minimise health impacts by allowing people to evacuate quickly when necessary. Finally, international cooperation on nuclear safety standards would help ensure that best practices are shared and global nuclear safety is maintained. Organisations like the International Atomic Energy Agency (IAEA) can play a key role in setting safety benchmarks, improving transparency, and ensuring that nuclear operations are conducted safely and responsibly. By implementing these measures, the risks of nuclear disasters like Kyshtym could be significantly reduced, guaranteeing excellent safety for people and the environment [10].

4.2 Fukushima Daiichi

Several critical systems and protocols must be prioritised to enhance nuclear plant safety. Reliable DC power for instrumentation and safety control is essential, ensuring that vital systems remain operational during power loss. Tools for estimating real-time plant status under power outage conditions are also crucial, allowing operators to assess conditions accurately in emergencies. Effective decay-heat removal, reactor depressurisation, and containment venting systems and protocols help maintain stability and prevent overheating. In contrast, instrumentation for monitoring key thermodynamic parameters in reactors, containment areas, and spent fuel pools provides precise data to support decision-making [22]. Hydrogen monitoring, both within reactors and in reactor buildings, along with mitigation measures, helps prevent explosions by detecting and managing hydrogen buildup. Additionally, robust onsite and offsite radiation and security monitoring systems ensure continuous oversight and safety. Communications and real-time information systems are indispensable for effective coordination between control rooms, technical support centres, field teams, and offsite support facilities, fostering clear communication and efficient response. To maintain high standards, the quality and completeness of these system upgrades and procedural changes should be thoroughly peer-reviewed, ensuring that improvements align with best practices and rigorous safety protocols [23].

Several critical areas must be addressed to strengthen nuclear plant safety and emergency response. First, staffing levels for emergencies involving multiple reactors at a site, particularly those that last for extended durations or involve stranded-plant conditions, must be adequately planned to ensure sufficient personnel can handle complex, prolonged crises. Additionally, emergency procedures should be strengthened and integrated with extensive damage mitigation guidelines and severe accident management protocols [24]. These procedures must specifically address challenges such as coping with the complete loss of AC and DC power over extended periods, depressurising reactor pressure vessels, and venting containments when power and air supplies are unavailable.

Furthermore, protocols for injecting low-pressure water when plant power is down and transitioning between reactor pressure vessel depressurisation and low-pressure water injection while maintaining sufficient water levels to protect the core must be robust. Preventing large hydrogen explosions and their effects on cooling systems and containments, as well as keeping cold shutdown in reactors undergoing maintenance outages when critical safety systems are disabled, should also be prioritised. Finally, operator and plant emergency response organisations must receive specific training on ad hoc responses for safe reactor shutdown during extreme beyond-design-basis events, alongside more general training to reinforce understanding of plant systems and improve emergency management capabilities. To ensure these changes' effectiveness, the recommendations' quality and completeness should undergo thorough peer review to align with best practices and safety standards [25].

5. Conclusion

In conclusion, The Kyshtym Disaster stands as a powerful reminder of the dangers that can arise from nuclear energy when safety measures, maintenance, and transparency are neglected. It highlighted the urgent need for redundant safety systems, advanced monitoring technologies, and well-defined emergency response protocols to prevent catastrophic failures in nuclear facilities. The incident also emphasised the importance of transparency, independent oversight, and global cooperation to ensure atomic operations are safe, accountable, and effectively managed. The disaster's long-lasting environmental and health impacts further stress the importance of ongoing monitoring, cleanup, and comprehensive risk management. Although the catastrophe prompted significant changes in nuclear safety practices, it also reinforced the need to prioritise public health, environmental well-being, and ethical responsibility in atomic technology. By applying the lessons learned from Kyshtym, the nuclear industry can reduce risks and ensure safer, more responsible use of nuclear energy in the future.

The Fukushima Daiichi nuclear disaster was a stark reminder of how critical it is to prioritise safety and preparedness in the atomic energy industry. It revealed vulnerabilities in plant systems, emergency procedures, and response coordination, especially when faced with extreme, unexpected events. The disaster showed us that even the most advanced facilities need continuous improvements to withstand severe challenges like prolonged power loss, hydrogen explosions, and the failure of multiple safety systems. One of the most important takeaways is the need to strengthen emergency responses, both onsite and offsite, ensuring that people and communities are protected in times of crisis. Regular training, better communication systems, and updated safety protocols are essential to prepare operators and responders for the most challenging scenarios. It also highlighted the importance of keeping plant systems and equipment up to date and ready to handle extreme conditions beyond what they were initially designed for. Ultimately, the lessons from Fukushima remind us that safety must always come first. Nuclear power has immense potential, but it comes with significant responsibilities. By learning from the past and committing to more innovative, stronger safety practices, we can build a future where nuclear energy is both a reliable and safe part of our world.

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