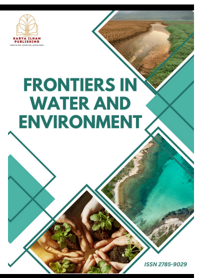
Frontiers in Water and Environment

Journal homepage:
https://karyailham.com.my/index.php/fwe/index
ISSN: 2785-9029



Key Lessons from the Three Mile Island and Tokaimura Nuclear Accidents: Enhancing Safety, Accountability and Public Trust

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ARTICLE INFO

Article history:
Received 15 July 2025
Received in revised form 7 August 2025
Accepted 19 August 2025
Available online 25 August 2025

Keywords:
Three Mile Island; Tokaimura; nuclear accidents; safety; radiation

ABSTRACT

The Three Mile Island catastrophe taught us significant and diverse lessons. It serves as a reminder of the need for operator training and readiness, as well as the need for open communication with the public during an emergency. Such events are entirely preventable with enhanced safety measures and human factors engineering. Furthermore, the disaster sparked major revisions in nuclear policy, emphasising accountability and proactive risk management in the sector. As we reflect on this incident, we must ensure that its lessons are not lost but incorporated into continuing efforts to improve nuclear safety and restore public trust in this critical energy source. Another nuclear accident is the Tokaimura atomic accident. However, Japan keeps shaping its energy policies in response to these tragedies, and it is critical that all involved parties, including workers, authorities, and businesses, collaborate to ensure that safety is always the number one priority. The lessons of Tokaimura must be remembered and used to guide future practices, ensuring that such significant disasters do not occur again.

1. Introduction
1.1 Three Mile Island

The Three Mile Island catastrophe, which happened on March 28, 1979, is widely regarded as the most significant event in the history of the American commercial nuclear energy sector. A malfunction in the Unit 2 reactor caused a partial meltdown at 4:00 a.m., caused by a combination of system faults and human error. Despite the emission of minor volumes of radioactive gases, there were no immediate injuries or deaths among plant personnel or citizens in the nearby areas. The disaster, however, revealed serious flaws in nuclear safety regulations and operational processes, raising widespread concerns about nuclear energy safety in the United States.

The Three Mile Island catastrophe had far-reaching implications. It was a critical moment that transformed public opinion and regulatory frameworks about nuclear power. Following the disaster, there was a significant drop in public faith in nuclear energy, resulting in a suspension of new reactor

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https://doi.org/10.37934/fwe.8.1.3950

licensing and a revision of safety rules by the Nuclear Regulatory Commission (NRC). This event highlighted the possible risks connected with nuclear reactors and emphasised the need for significant reforms in emergency response planning, operator training, and overall reactor safety management. The accident's legacy continues to impact nuclear policy and operating standards today.

A succession of technical faults and human mistakes occurred on the morning of March 28, 1979, leading to the Three Mile Island catastrophe. The incident happened at 4:00 a.m., when an automatically controlled valve in the Unit 2 reactor accidentally closed, cutting off the water supply to the central feedwater system, which is responsible for cooling the reactor core. This error resulted in a quick shutdown of the reactor, which should have activated emergency systems to preserve coolant levels. However, a stuck-open pilot-operated relief valve (PORV) enabled huge volumes of coolant to escape from the pressurised water reactor (PWR), resulting in a loss-of-coolant accident (LOCA) that operators failed to detect in time.

The technological difficulties got worse by procedural deficiencies and operator errors. Despite signals to the contrary, operators first felt that normal coolant circulation had been maintained. As coolant levels plummeted, the reactor core began to overheat, and operators made decisions based on faulty assumptions, such as turning off emergency core cooling pumps for fear of overloading the system. This lack of situational awareness and poor training in emergency protocols contributed significantly to the situation's escalation. The inability to adequately monitor and interpret instrumentation compounded the problem, as operators were misled by inaccurate indications that claimed the PORV had closed while remaining open for more than two hours.

The pressurised water reactor design, which relies on maintaining high pressure to prevent water from boiling and creating steam, was one of the key systems in the catastrophe. Critical components such as primary feedwater pumps and relief valves failed, contributing significantly to the event's advancement. Furthermore, design deficiencies in control systems and alarms hampered operators' capacity to analyse and respond appropriately to the emerging problem. The combination of these elements culminated in a partial meltdown of the reactor core, marking a watershed moment in nuclear safety history and requiring substantial reforms in regulatory supervision and operating practices within the industry.

1.1.1 Root causes

The primary causes of the Three Mile Island catastrophe were a mix of operational failures, technological problems, and communication breakdowns among employees. One of the most crucial operational failures was poor plant operator training, which left them unprepared to deal with the intricacies of the emergency scenario. Investigations indicated that operators lacked sufficient training to grasp the safety systems and their interconnections, notably the pilot-operated relief valve (PORV). Due to their lack of comprehension, they misinterpreted the indications from the control instruments, assuming the PORV was closed when it was stuck open. This confusion was worsened by design defects in the control systems, which failed to offer clear indicators of valve positions and system statuses, resulting in a delayed and inadequate reaction to the crisis. The primary causes of the Three Mile Island catastrophe were a mix of operational failures, technological problems, and communication breakdowns among employees. One of the most crucial operational failures was poor plant operator training, which left them unprepared to deal with the intricacies of the emergency scenario. Investigations indicated that operators lacked sufficient training to grasp the safety systems and their interconnections, notably the pilot-operated relief valve (PORV). Due to their lack of comprehension, they misinterpreted the indications from the control instruments,

assuming the PORV was closed when it was stuck open. This confusion was worsened by design defects in the control systems, which failed to offer clear indicators of valve positions and system statuses, resulting in a delayed and inadequate reaction to the crisis.

Technical faults contributed significantly to the accident's progression. The relief valve's failure to shut after activation was a critical point that enabled the reactor coolant to escape from the primary system. This breakdown was not a unique incidence; previous faults with the PORV had been reported, but no corrective action was made to replace or fix it properly. The instrumentation design also failed to effectively transmit vital information, resulting in operators receiving deceptive signals indicating that the system was operational when it was not. For example, a light on the control panel showed that a "close" signal had been delivered to the PORV but did not validate that the valve had closed. As a result, operators were left without the critical information required to diagnose and resolve the issue.

Communication problems between employees and management worsened these concerns throughout the crisis. Critical information was not always effectively relayed or understood by team members. For example, obstructing signage in the control room made it difficult for operators to see key valve status signs. The absence of clear communication and situational awareness hampered quick decision-making and increased the severity of the catastrophe. The confluence of these factors—operational mistakes resulting from insufficient training, technological failures of essential safety systems, and inefficient communication created a perfect storm, culminating in one of the most devastating nuclear catastrophes in history.

1.1.2 Impact on public perception

The Three Mile Island tragedy had a significant influence on public opinion of nuclear energy, resulting in both immediate terror and long-term scepticism. Following the catastrophe, the public reacted with increased worry and scepticism about atomic technology. Surveys performed immediately after the disaster revealed a dramatic loss in public trust, with acceptance of nuclear power falling from around 60% to 45% within months of the occurrence. The media's frequently sensationalised presentation of the disaster fuelled dread, as many people struggled to appreciate the technical aspects and possible consequences. According to reports, around one-third of residents in adjacent Middletown evacuated, indicating a visceral response motivated by uncertainty rather than a reasoned appraisal of the real threats [1].

In the long run, the Three Mile Island tragedy established a more cautious public attitude towards nuclear energy. Studies show that initial approval ratings for nuclear power fell dramatically, but they stabilised over the next few decades without entirely rebounding to pre-accident levels. For example, despite some improvement in favour, a Gallup survey in March 2023 indicated that 44% of Americans continue to reject nuclear energy, an attitude driven by previous tragedies such as Three Mile Island, Chernobyl, and Fukushima. This continuing scepticism has resulted in greater hostility to future nuclear projects and a significant "not in my backyard" (NIMBY) mentality among communities surrounding prospective nuclear power facilities [2].

1.1.3 Policy and regulatory changes

The Three Mile Island catastrophe led to substantial policy and regulatory reforms in the nuclear sector, including the formation of the Institute of Nuclear Power Operations (INPO) and adjustments to Nuclear Regulatory Commission (NRC) rules. INPO was founded in 1979 as a direct reaction to the Kemeny Commission's recommendations following the disaster to improve operational safety and performance at nuclear power facilities across the United States. INPO's principal mission is to promote "operational excellence" by creating performance targets and guidelines for plant operations, conducting reviews, and encouraging the exchange of best practices among member utilities. This organisation is critical in detecting safety concerns and developing an industry-wide culture of continuous improvement, dramatically increasing overall reactor safety. According to a report published in Nuclear Safety, INPO's assessments have improved plant dependability and safety performance metrics, indicating its success in promoting high operating standards across the nuclear industry [3].

In connection with INPO's formation, the NRC made significant adjustments to its regulatory framework to improve reactor safety. Following the disaster, the NRC recognised that following existing laws was insufficient to ensure safety. Therefore, it began implementing risk-informed decision-making processes. This approach creates a more flexible regulatory environment that prioritises safety based on accurate risk assessments rather than rigid adherence to prescriptive regulations. For example, research has found that incorporating probabilistic risk assessments (PRA) into regulatory methods has successfully enhanced the NRC's capacity to manage complex safety concerns. The NRC's emphasis on maintenance and operational performance has also resulted in decreased maintenance-related safety occurrences at nuclear facilities, as data shows a fall from 48% of recorded events in 1985 to 42% by 1988 [4].

The joint efforts of INPO and NRC regulation changes have resulted in a stronger safety culture within the nuclear sector. According to research, facilities that follow INPO recommendations tend to have superior management practices, resulting in fewer unexpected outages and improved overall safety records. Furthermore, regular reviews of these procedures demonstrate their usefulness in reducing the hazards connected with nuclear activities. The NRC's supervision mechanisms continue to change, with current proposals to emphasise reactor safety culture as part of its inspection programs [5].

1.1.4 Economic and environmental impacts

The Three Mile Island catastrophe had far-reaching economic and environmental consequences, notably regarding cleaning costs and public perceptions of nuclear energy. The cleaning of the TMI-2 reactor, which began in August 1979 and was completed in December 1993, cost over $973 million. This massive endeavour included decontaminating the facility, treating more than 10.6 megalitres of accident-generated water, and removing almost 100 tonnes of damaged uranium fuel from the reactor vessel. The cleaning was technically complex, requiring nearly 1,000 professional personnel to ensure safety throughout the operation. The financial burden extended beyond direct cleanup costs; General Public Utilities Corporation (GPU) faced additional expenditures estimated between $500 million and $600 million for decontamination and repairs, along with $2 to $3 billion in capital expenditures necessary to maintain reliable electric service during the crisis [6].

Environmental tests undertaken following the accident revealed that, while radioactive elements were released, the amounts were relatively low and did not pose significant health concerns to the local population. For example, the average radiation dosage received by people around Three Mile Island was approximately 1.4 mrem, equal to the radiation exposure from a conventional chest X-ray. The Environmental Protection Agency (EPA) closely monitored radiation levels and discovered negligible pollution, with no observable health impacts linked to the incident. According to reports, most radioisotopes emitted were noble gases like xenon and krypton, which do not cause substantial long-term environmental damage [7].

Comparative analyses from other publications and government reports support these conclusions. For example, an American Nuclear Society investigation stated that typical area radiation exposure was similar to living in a brick house rather than a frame house, implying that natural background radiation levels were a more significant influence than those caused by the disaster. Furthermore, environmental monitoring by several agencies revealed that any leftover radiation in air, water, or foodstuffs was low and did not constitute a significant risk to public health. Thus, while the Three Mile Island catastrophe had a significant economic impact, impacting utility businesses and increasing operating expenses, regulatory authorities considered environmental repercussions tolerable [8].

1.1.5 Comparison to other nuclear accidents

The accident at Three Mile Island has been a key point of reference for comprehending and reacting to later nuclear accidents, especially Chernobyl and Fukushima. Although all three events involved major operational failures, they were very different in their causes, effects, and public reactions. At Three Mile Island, a partial meltdown was caused by equipment failures and human error. Still, there were no immediate injuries or long-term health effects, allowing for a relatively quick repopulation of the area. In contrast, Chernobyl's catastrophic failure was caused by a defective reactor design and operator negligence, resulting in widespread radioactive contamination and the permanent evacuation of more than 350,000 people. The long-term exclusion zone surrounding Chernobyl is still largely uninhabitable because of persistent radiation levels. Meanwhile, Fukushima was caused by an extraordinary natural disaster—a tsunami that crippled essential cooling systems, resulting in massive radioactive emissions into the environment. Although the initial evacuation procedures at Fukushima were better organised than those at Three Mile Island, the psychological and social consequences for evacuees were severe, with over 2,200 disaster-related fatalities due to evacuation stress [9].

The lessons learnt at Three Mile Island have helped shape reactions to subsequent catastrophes. Following TMI, the nuclear industry improved its training standards and formed organisations such as the Institute of Nuclear Power Operations (INPO) to promote safety culture and operational excellence. These methods helped to strengthen emergency preparedness and response techniques during the Fukushima catastrophe. Despite these advances, both Chernobyl and Fukushima demonstrated that systemic difficulties such as insufficient communication and regulatory supervision persisted. For example, although INPO's influence helped reduce hazards at US reactors after TMI, the lack of equivalent control in Soviet-era Chernobyl contributed considerably to the accident. Thus, while Three Mile Island gave valuable insights into reactor safety and emergency management, it also highlighted the importance of continuing development in regulatory frameworks and safety cultures at all nuclear plants worldwide [10].

1.1.6 Ethical considerations

The ethical concerns surrounding nuclear facility operations are critical, especially concerning previous mishaps such as Three Mile Island, Chernobyl, and Fukushima. Engineers and operators must prioritise safety above all else since their actions can have far-reaching effects on human health and the environment. The concept of nonmaleficence, which emphasises the duty to avoid inflicting damage, reinforces the ethical imperative to choose safety over cost. This idea is especially essential in the nuclear business, where the risk of catastrophic catastrophes compels adherence to stringent safety standards and processes. For example, Xiang and Zhu's work emphasises the necessity for fully disclosing operational risks and open communication with stakeholders to create trust and responsibility in nuclear energy programs [11].

Case studies from several nuclear catastrophes demonstrate the ethical quandaries engineers and operators encounter. For example, following the Fukushima catastrophe, it became clear that cost-cutting initiatives had endangered safety regulations, resulting in insufficient readiness for natural disasters. This issue exemplifies an excellent ethical dilemma in the industry: reconciling economic reasons with the obligation to ensure safety. Articles analysing these ethical quandaries emphasise the need to use a cautious, risk-based approach in decision-making processes, with safety taking precedence above financial benefit. Furthermore, organisations must foster a strong safety culture, which includes maintaining a "blame-free" reporting environment that promotes openness and proactive detection of possible dangers [12].

Eventually, the ethical obligations of nuclear facility operators and engineers are crucial in determining the future of atomic energy. As several studies have shown, incorporating ethical concepts into operational methods improves safety and helps rebuild public trust in nuclear technology. Lessons from previous incidents highlight the necessity of prioritising safety over cost and cultivating a culture that values ethical decision-making at all levels of atomic operations. By doing so, the industry may endeavour to reduce the risks connected with nuclear energy while also addressing public concerns about its safety and environmental impacts.

1.1.7 Relevance today

The Three Mile Island tragedy remains relevant today, as evidenced by the advancement of contemporary reactor designs and the continued issues of balancing nuclear power as a clean energy source with safety concerns. One of the most significant advances in reactor technology has been implementing passive safety measures, which use natural forces like gravity and convection to cool the reactor core without the need for active intervention from operators or external power sources. As demonstrated in previous incidents, these advancements attempt to improve safety by lowering reliance on sophisticated mechanical systems that can fail.

Despite these advances, the issue continues to strike a balance between nuclear power's position as a low-carbon energy source and public safety. The worldwide effort for decarbonisation has reignited interest in atomic energy, especially as governments look for dependable alternatives to fossil fuels. However, public concern about nuclear safety remains, inspired by past mishaps such as Three Mile Island, Chernobyl, and Fukushima. Recent studies show that while support for nuclear energy has changed, safety concerns impede its adoption. For example, a report from the International Atomic Energy Agency (IAEA) projects significant growth in nuclear capacity by 2050, driven by new technologies such as small modular reactors (SMRs). Still, it emphasises that regulatory frameworks must evolve to effectively address safety and public trust issues.

1.2 Tokaimura Nuclear Accident

Tokaimura is a large village in Ibaraki Prefecture, about 120 kilometres northeast of Tokyo. The town of Naka-machi is also close to the JCO site in Tokaimura. About 150 people reside within 350 meters of the JCO facility, and nine municipalities have a combined population of about 310,000 within a 10-kilometer radius. The conversion building where the accident happened is only 200 meters from the nearest residence. The Japan Atomic Power Company (JAPCO) nuclear power plant, several nuclear reactors, the Japan Atomic Energy Research Institute (JAERI), and a fuel reprocessing plant are among the nuclear facilities located in Tokaimura [13].

On the night of September 30, 1999, a serious accident occurred at the uranium conversion facility operated by JCO Company Limited in Tokaimura, Ibaraki Prefecture, Japan. Around 10:35 PM local time, a concerning event unfolded, shocking the local community and raising alarm across the nation. The incident was primarily caused by negligence by the workers and their supervisors, who failed to adequately monitor safety protocols because the workers mistakenly added too much uranium, exceeding the critical mass needed for a reaction. As a result, an uncontrollable nuclear chain reaction happens in the tank and releases radiation. This incident lasted about 20 hours long after the radiation began. In a significant breach of established procedures, a concentrated solution of enriched uranium, containing 18.8% 235U, was improperly poured into a precipitation tank. This reckless act violated critical safety measures designed to prevent risks associated with nuclear operations.

As a result of the mishap, several workers and nearby residents were exposed to radiation. Three employees of JCO fell ill with radiation sickness, and authorities took precautionary measures, advising roughly 310000 individuals to stay indoors for 18 hours. Additionally, around 161 people were relocated from within a 350-meter radius of the facility to ensure their safety. From a legal perspective, the accident sparked discussions around the Convention on Early Notification of a Nuclear Accident. This agreement stipulated that Japan wasn't required to notify the International Atomic Energy Agency (IAEA) or neighbouring countries since the incident didn't result in the release of radioactive materials that could pose a threat beyond the local area. Nonetheless, the IAEA's Emergency Response Centre communicated with Japanese officials, fielding numerous inquiries from other nations [14].

The accident's severity led Japan to classify it as Level 4 on the IAEA's International Nuclear Event Scale, indicating that it was serious but did not present a significant risk beyond the immediate location. This incident served as a stark reminder of the importance of stringent safety protocols and effective communication in nuclear safety, emphasising the need for international cooperation in responding to such emergencies. By 1st October 1999, the secretariat of the IAEA had offered itself to the Japanese authorities in response to the accident, but this was declined because they believed they did not need the help. By that time, it was not that necessary.

After discussions with government officials concluded successfully, the Director General of the IAEA dispatched a team of three specialists from the IAEA Secretariat to Tokaimura for an assignment between October 13 and October 17 1999. These experts possessed knowledge in emergency preparedness and evaluation of accident impacts, environmental surveillance and radiation measurement and oversight of the nuclear fuel cycle and related regulations. However, the secretariat has been tasked with rooting out the problems, getting any information or missing information from the incident, preparing a factual report and proposing it to the Director General of the IAEA. The report was narrowed down to the events that led to the incident, the consequences to the person who was exposed to the nuclear radiation (radiation exposure) and their medical treatment, emergency response and action that can be taken to prevent the incident from being repeated [15].

1.2.1 Chronology of the accidents

Two significant events in Japan that revealed critical weaknesses in nuclear safety procedures are known as the Tokaimura nuclear accidents. The first of these incidents occurred on March 11, 1997, at the Power Reactor and Nuclear Fuel Development Corporation (PNC) facility in Tokaimura, Ibaraki Prefecture. This event highlighted significant deficiencies in safety protocols and regulatory oversight, representing a pivotal moment in Japan's nuclear history.

On March 11, 1997, an explosion occurred at the PNC radioactive waste bituminisation facility during an experimental procedure with solidified nuclear waste. The incident was sparked when an experimental batch of solidified waste ignited, resulting in a significant release of radiation. More than twenty individuals were exposed to dangerous levels of radiation due to this accident. The explosion was concerning not only for its immediate physical consequences but also for highlighting the weaknesses in Japan's nuclear safety system. Investigations showed that poor safety protocols and a lack of regulatory oversight played a role in the incident. The facility had not implemented essential safety technologies and alarms that could have averted such an explosion. Furthermore, the regulatory body in charge of nuclear safety failed to conduct regular inspections that might have uncovered these issues.

The Tokaimura accident was primarily caused by human error, which was worsened by systemic failures within the organisation. A weak safety culture meant workers lacked proper training to manage hazardous materials safely. Additionally, the lack of criticality accident alarms and other safety protocols highlighted significant oversights by management and regulatory bodies. As for the consequences, the incident led to over twenty individuals being exposed to radiation, resulting in hospitalisations and ongoing health concerns for those impacted. This event significantly undermined public trust in nuclear safety, leading to demands for stricter regulations and improved training for workers in the atomic sector [16].

After the tragic 1997 incident, nuclear safety gained much greater attention in Japan. Extensive investigations into the disaster led the government to pursue significant nuclear regulation reforms and file lawsuits against the PNC site involved. Responding to widespread public concern, authorities introduced new safety measures at numerous atomic facilities nationwide. The Tokaimura catastrophe served as a wake-up call for the Japanese government and the global nuclear industry, emphasising the critical need for strict safety protocols, regular inspections, and thorough training programs for all personnel handling radioactive materials. The first Tokaimura disaster is a powerful reminder of the serious risks associated with nuclear energy when safety measures are neglected. This tragedy highlighted the need for strict regulatory oversight and a strong, safety-focused culture within the nuclear industry. Although training and regulatory systems have improved since then, the lessons from Tokaimura remain profoundly relevant to today’s discussions on nuclear safety.

The Tokaimura nuclear disaster, one of the most severe accidents in Japan’s history, occurred on September 30, 1999, at a uranium processing plant. The catastrophic consequences of this tragedy, which involved the community and, of course, the most significant implications for their workers, have revealed their weaknesses in nuclear safety practices and safety. This disaster was caused by human error, mistakes, and a lack of oversight from professionals or authorities, significantly impacting Japan's nuclear industry.

JCO (Japan Nuclear Fuel Conversion Co.), a Sumitomo Metal Mining Co. division, operated the plant at the accident scene. Established in 1988, the facility processed up to three tons of uranium enriched to 20% U-235 annually, focusing on creating fuel for experimental reactors. Three employees were making the first batch of fuel for the Joyo experimental fast breeder reactor in three years on the day of the incident. Unfortunately, no formal requirements had been set for the workers, so they lacked the training and qualifications necessary to handle this complex task.

Around 10:35 AM, the workers unintentionally exceeded the critical mass required to initiate a nuclear chain reaction while working with a uranyl nitrate solution containing roughly 16.6 kg of uranium. They poured a significant amount of enriched uranium straight into a precipitation tank that wasn't made for the safe containment of this kind of reaction rather than following safety procedures that required combining the solution in a dissolving tank with a buffer to avoid such risks.

An uncontrollable nuclear fission reaction was started by this mistake and continued intermittently for almost 20 hours [17].

Three employees- Hisashi Ouchi, Masato Shinohara, and Yutaka Yokokawa—were exposed to hazardously elevated radiation levels during the criticality event. Shinohara was given about 10 sieverts, while Ouchi was given an estimated 17. For comparison, a dose exceeding 8 sieverts is typically fatal. After 83 days of critical hospital care, Ouchi died from severe acute radiation sickness brought on by extreme radiation exposure, and Shinohara died seven months later. The accident generated widespread alarm among emergency responders and residents. Altogether, 667 people received radiation doses that exceeded safe limits, and many had to be hospitalised. This incident heightened concerns about nuclear safety protocols across Japan, sparking demands for industry-wide reforms.

Japanese authorities classified the accident as a Level 4 event on the International Nuclear Event Scale (INES), meaning that although the local impact was profound, there was minimal risk of radiation exposure beyond the immediate area of the plant. As a precaution, roughly 310,000 residents were advised to stay indoors, and about 161 people within a 350-meter radius of the facility were evacuated.

Research into the Tokaimura accident showed that fault was a primary factor in the disaster. The workers involved had previous experience with lower-enriched uranium. Still, they lacked a thorough understanding of the criticality risks associated with higher enrichment levels, such as the 18.8 per cent of the total U-235 they were handling. Furthermore, the incident was primarily caused by failures in JCO's safety culture and poor regulatory oversight.

The plant had not been adequately inspected by authorities, with inspections occurring infrequently and frequently when the plant was not operational. The International Atomic Energy Agency (IAEA) discovered serious safety violations at JCO, prompting criminal charges against several people involved in the accident.

Following the Tokaimura accident, Japan took significant steps to improve nuclear safety throughout its facilities. To help prevent similar accidents in the future, the government implemented stricter regulations for worker training and operational procedures. This disaster also harmed public trust in nuclear energy, prompting a closer look at current nuclear operations nationwide. The JCO facility's operating license was revoked early in 2000 as part of these reforms. This incident was a stark reminder of the serious risks associated with nuclear energy when safety protocols are ignored or poorly enforced. This second incident will be the most serious disaster that the civilians have gone through and would be a lesson to the whole world.

1.2.2 Lesson learnt

The lesson that can be taken could be started by the authorities, the company and the workers themselves. Each of these people needs to be alert in handling any machine, nuclear radiation material, and any potentially dangerous material that will cause an accident. Firstly, Workers must receive extensive training to fully understand the risks of their roles, especially in environments where critical events can occur. In the case of the Tokaimura accident, the operators were unaware of the dangers of handling enriched uranium, which contributed directly to the disaster. Ongoing training programs are required to ensure all employees understand safety protocols and emergency procedures. The Tokaimura accident highlighted the critical need for comprehensive safety training and proper handling of hazardous materials. Workers must recognise the importance of strictly following established procedures and not cutting corners. In this case, workers bypassed crucial safety protocols under pressure to speed up operations, leading to the incident. This serves as a reminder of the need to foster a culture where safety is prioritised over speed [18].

Workers should feel empowered to speak up or halt operations if they believe safety procedures are being compromised. Effective communication between team members is crucial for maintaining safety standards. In this case, the failure to communicate between engineers and operators about changes in operations and potential risks was a significant factor in the accident. Workers should be encouraged to speak up about any uncertainties or potential dangers they notice, creating a culture where everyone shares responsibility for safety.

Next, the authorities must ensure that systematic assessment protocols and safety regulations are followed. This includes conducting regular audits and evaluations of operational procedures at nuclear facilities to identify potential risks before they cause accidents. Regulatory bodies must actively promote a safety-first culture at all nuclear facilities. This goes beyond simply enforcing the rules, encouraging organisations to prioritise safety in their operational mindset. Authorities could assist by providing resources for training programs and establishing clear guidelines prioritising safety over production efficiency. Authorities must develop effective crisis management plans that can be implemented quickly in the event of an accident. During the Tokaimura incident, local emergency services and regulatory agencies were slow to respond due to confusion and a lack of readiness. To improve future responses, it is critical to establish clear communication channels and ensure emergency responders are well-trained in dealing with nuclear incidents, which can improve both response time and overall effectiveness during a crisis.

Lastly, the lesson that a company can take is that companies that operate nuclear facilities must fully commit to safety protocols and ethical management practices. At the JCO facility, managerial decisions that focused on production efficiency over safety resulted in disastrous outcomes. Companies must cultivate a culture prioritising safety, ensuring every employee understands their role in maintaining a secure environment. To stay current with the latest best practices and advancements in nuclear safety, the company should review and update its operational manuals and procedures on an ongoing basis. The Tokaimura incident was adversely affected by out-of-date procedures that did not account for the possible threats associated with handling higher-enriched uranium. Continuous improvement efforts should include input from all employees, particularly those directly involved in operations, to ensure that safety measures always align with current standards and challenges. Organisations must develop a culture of public accountability in their operations and hold everyone responsible for meeting safety standards. Following the Tokaimura accident, several managers were charged with negligence, highlighting a broader issue of accountability within corporate structures. To avoid future incidents, establish clear responsibilities and encourage employees to report unsafe practices without fear of punishment.

2. Recommendations

To improve workplace safety in the nuclear industry, workers, authorities, and companies must implement clear guidelines based on the lessons learned from the Tokaimura nuclear accidents. Each party carries different responsibilities and roles in creating a safer environment. First and foremost, the workers should receive complete and accurate training that includes operational procedures and the potential risks of handling radioactive materials. This training should consist of emergency simulations and criticality safety protocols to ensure workers understand the significance of following safety procedures in all situations. It is critical to cultivate a culture where employees feel comfortable reporting unsafe conditions or behaviours without fear of consequences [19].

Implementing anonymous reporting systems can give employees a safe way to express their concerns about safety practices or potential risks. Regular safety drills are also essential because they allow employees to practice emergency response procedures and improve their understanding of safety protocols. These drills should cover a variety of scenarios, including criticality incidents, to ensure that workers are adequately prepared for actual emergencies.

Moreover, the authorities part, could improve control and supervision by conducting more frequent inspections and audits of nuclear facilities. These inspections should ensure compliance with health and safety regulations and confirm that radiation protection and contingency planning best practices are followed. Regulatory bodies should work to impose a strong safety culture in nuclear organisations. This can be accomplished by establishing guidelines and frameworks prioritising safety over production goals and recognising and rewarding facilities that excel at safety practices. Authorities should also work with industry experts to create updated guidelines and training programs that meet current nuclear safety standards. Sharing lessons from previous incidents as part of this collaboration can help to prevent future accidents.

Companies must make safety a primary focus of their operational ideology, incorporating it into every decision-making process and ensuring all employees understand their role in maintaining a safe workplace. Organisations should implement and enforce strict safety protocols that stick to international standards. Regularly reviewing these protocols and gathering employee feedback helps identify improvement areas and ensures procedures remain relevant and practical. Investing in advanced safety technologies, such as real-time radiation monitoring and criticality alarms, is crucial to improve workplace safety. These technologies can provide early warnings of potential hazards, allowing for timely interventions to avoid accidents [20].

3. Conclusion

These incidents provided significant lessons for the nuclear industry. Workers must be adequately trained in safety protocols and emergency procedures, and regulatory bodies must enhance supervision and control and encourage a safe culture within atomic organisations. Companies must commit to high safety standards and invest in advanced monitoring technologies to avoid similar incidents in the future. The Tokaimura accidents are a clear sign of the dangers of nuclear energy when safety precautions are ignored. They emphasise the critical need for robust training, stronger regulatory oversight, and a commitment to safety in the industry.

The legacy of the Three Mile Island tragedy is still significant in today's talks regarding nuclear energy, reinforcing the crucial need for safety in the sector. The lessons learnt from this disaster have considerably impacted current reactor design, emphasising the importance of robust safety systems and rigorous operator training. The formation of organisations like the Institute of Nuclear Power Operations (INPO) has promoted a culture of safety and responsibility, which is critical for averting future catastrophes. Furthermore, developments in reactor technology, notably the introduction of passive safety devices, demonstrate a commitment to prioritising safety over cost, answering public concerns raised by the TMI event.

Both incidents were primarily the result of human error, insufficient training, and inadequate regulatory oversight. Workers in the 1999 Tokaimura accident lacked the training to handle higher-enriched uranium safely and deviated from established safety protocols due to operational pressure. Regulatory bodies also failed to conduct regular inspections, which could have identified these safety gaps. The lack of criticality alarms and other essential safety technologies exacerbated the situation. The consequences were devastating. The Tokaimura accidents not only resulted in tragic deaths but also caused widespread panic among locals. As a precaution, approximately 310,000 people were instructed to remain indoors during the criticality event. The public's trust in nuclear safety was now worse, demanding stricter regulations and improved safety protocols at atomic facilities throughout Japan.

Acknowledgement
The authors would like to thank the Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia, for the facilities provided that make the research possible.

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