



## The Tokaimura Criticality Accident: Lessons in Nuclear Safety

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### ABSTRACT

The Tokaimura criticality accident of 30 September 1999 was Japan's most severe nuclear incident prior to the Fukushima Daiichi disaster, occurring at the Japan Nuclear Fuel Conversion Co. (JCO) facility in Ibaraki Prefecture. An unauthorized uranium-handling procedure, involving manual transfer of highly enriched uranium into a precipitation tank, triggered an uncontrolled chain reaction. Three workers received severe radiation doses; two died from acute radiation syndrome, and hundreds of residents were exposed to elevated radiation levels, prompting evacuations and shelter-in-place orders. This paper examines the accident's root causes, including inadequate regulatory oversight, weak safety culture, and insufficient worker training. The emergency response comprising evacuations, medical interventions, radiation monitoring, and facility shutdown was followed by criminal prosecutions, compensation programs, and sweeping regulatory reforms. Long-term consequences included lasting health impacts for survivors, economic losses for the community, and a decline in public trust in nuclear safety. Lessons learned emphasize the need for robust safety protocols, strict government oversight, comprehensive worker training, and transparent public communication. The Tokaimura accident remains a pivotal case study in nuclear safety management, underscoring the importance of prevention, preparedness, and accountability in facilities handling fissile materials.

## 1. Introduction

The Tokaimura criticality accident occurred on 30 September 1999 at the Japan Nuclear Fuel Conversion Co. (JCO) facility in Tokaimura, Ibaraki Prefecture, Japan. It was the most serious nuclear accident in Japan before the Fukushima Daiichi accident of 2011. It resulted in severe radiation exposure to three employees and widespread emergency measures among the local community [1].

The JCO facility was intended to convert uranium hexafluoride ( $UF_6$ ) into uranium dioxide ( $UO_2$ ) nuclear fuel for the reactor. On the day of the accident, operators were conducting an unauthorized operation to prepare a uranium solution for a fast breeder reactor fuel cycle. The accident occurred when workers manually transferred a uranium solution with highly enriched uranium (HEU) from a transfer tank to a precipitation tank past the critical mass point, causing an uncontrolled chain reaction [2].

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The uranium solution had become supercritical due to faulty procedures and relaxed safety measures, which caused a self-sustaining nuclear fission reaction. The reaction emitted a powerful burst of radiation, which exposed three workers, Hisanori Yoshida, Masato Shinohara, and Yutaka Yokokawa to lethal doses. Yoshida and Shinohara, the two workers closest to the tank, suffered severe radiation burns and acute radiation syndrome (ARS), which killed them within months [3].

The accident declared a national emergency, requiring residents to be evacuated from within 350 meters of the plant and to shelter over thousands of others. Government authorities struggled to keep the public's radiation exposure under control while at the same time ensuring public safety. The accident seriously questioned Japan's nuclear safety regulations and operating procedures in privately owned nuclear facilities [4]. This accident revealed severe training failures, regulatory breaches, emergency preparedness failures, and the dangers of human error in handling nuclear materials. It ultimately led to far-reaching reforms in Japan's atomic industry to prevent such incidents in the future.

## **2. Methods of Handling Nuclear Emergency**

The Tokaimura criticality accident triggered an urgent response from the Japanese government, local authorities, and the JCO Company. The emergency measures were divided into immediate actions to contain radiation exposure and long-term strategies to prevent future incidents. Upon confirming the criticality event, authorities swiftly evacuated 161 residents within a 350-meter radius of the facility to minimize radiation exposure. Those living within a 10-kilometer radius were instructed to stay indoors, close windows, and avoid consuming locally grown food or water due to potential contamination. Schools and public facilities were temporarily closed as a precaution. The evacuation zone was later adjusted based on real-time radiation readings, demonstrating a flexible yet cautious approach to public safety.

Specialized teams from the Japan Atomic Energy Agency (JAEA) and local emergency services were deployed to monitor radiation levels in the air, soil, and water. Portable Geiger counters and aerial surveys were used to track the spread of neutron and gamma radiation. Authorities established exclusion zones around the facility to prevent unauthorized access while decontamination efforts began. The highest radiation levels were recorded near the precipitation tank where the criticality occurred, reaching up to 20,000 times normal background levels in some areas [5].

Three JCO workers were directly exposed to lethal radiation doses during the accident. Hisashi Ouchi and Masato Shinohara suffered acute radiation syndrome (ARS), with Ouchi receiving an estimated 17 sieverts (Sv) far beyond the fatal threshold of 8 Sv. Both underwent experimental treatments, including bone marrow transplants and stem cell therapy, but died within months. A third worker, Yutaka Yokokawa, survived with lower exposure (3 Sv) but suffered long-term health effects. Over 600 emergency responders, employees, and nearby residents were screened for radiation exposure, with some receiving potassium iodide tablets to reduce thyroid uptake of radioactive iodine.

The JCO plant was immediately shut down, and Japan's Nuclear Safety Commission (NSC) launched a full investigation. The inquiry revealed that workers had improperly mixed uranium in stainless steel buckets, bypassing automated safety systems. The company was found guilty of criminal negligence, leading to arrests of executives and permanent closure of the facility. JCO paid over ¥13 billion (~\$120 million USD) in compensation to affected residents, workers, and local businesses. Compensation included medical expenses, property devaluation, and psychological distress claims. The Japanese government also funded long-term health monitoring programs for exposed individuals [6].

The accident exposed flaws in Japan's nuclear oversight, prompting sweeping reforms:

- **New Safety Laws:** The Nuclear Reactor Regulation Law was amended to enforce stricter handling of enriched uranium.
- **International Collaboration:** Japan joined the IAEA's Incident Reporting System to share lessons globally.

### **3. Discussion**

The Tokaimura criticality accident was the consequence of a combination of problems that can be broadly classified as poor regulatory monitoring, inadequate safety culture, and underdeveloped staff training and certification. Each of these aspects was key to the accident's occurrence and has profound consequences for universal nuclear safety measures. One of the major contributors to the Tokaimura accident was the Japanese authorities' failure to exercise regulatory monitoring. The regulatory framework controlling the facility was insufficient to ensure that safety measures were successfully implemented and followed. Due to current administrative safeguards, the licensing evaluation procedure judged incorrectly that a criticality accident was uncertain. This false sense of security resulted in the absence of criticality accident alarms and other vital safety elements. The facility was not listed in the National Plan for the Prevention of Nuclear Disasters, resulting in poor response to an emergency (Nuclear Safety Commission [7]).

When the accident happened, misunderstanding about the criticality status delayed the emergency response. Rescuers were originally confused about whether a criticality had occurred, delay in their reaction, and putting them at risk of further exposure. Furthermore, the lack of regular inspections meant that the facility was not monitored for compliance with safety rules. This regulatory violation produced an environment in which safety measures could be neglected without fear of consequences, resulting in a life-threatening outcome (International Atomic Energy Agency [8]).

Additionally, the absence of regular inspections meant that the facility had not been monitored for adherence to safety regulations. This regulatory oversight lapse allowed unsafe practices to go unchecked, creating an environment where safety protocols could be ignored without consequence. The failure to conduct periodic inspections further exacerbated the situation, as there was no early warning system in place to detect and address emerging safety issues before they escalated into a critical incident [9].

The second key contributing factor to the Tokaimura catastrophe was a general lack of safety culture within the JCO plant. Safety culture is defined as an organization's common values, attitudes, and behaviours related to safety. JCO clearly prioritised speed of production over safety precautions. This mentality resulted in the creation of numerous unauthorised operating practices established to increase output without regulatory approval. Company management was under economic pressure, worsened by recent reductions in employment, which influenced their decision-making (Nuclear Safety Commission [10]).

The operators' disregard for established safety measures reflected a lack of safety culture. Deviations from protocols had been going on for years, and the lack of proper oversight allowed these activities to continue unrestricted. Management accepted new procedures without conducting appropriate safety reviews, resulting in operators who were unaware of crucial safety limits. As staff concentrated on satisfying production targets, this situation eventually created a culture in which shortcuts were not only tolerated but encouraged.

Moreover, the absence of a safety culture was reflected in the operators' responses during the criticality event. Many operators lacked the necessary training to understand the unique risks associated with high-enriched uranium. This deficiency meant that when faced with a critical situation, operators were not equipped to respond appropriately, further exacerbating the risks associated with the accident [11].

The third significant factor leading to the Tokaimura accident was the inadequate training and qualification of workers involved in uranium processing. The personnel at JCO were not sufficiently prepared to handle the specific risks associated with operating high-enriched uranium processes. This lack of training left them ill-equipped to recognize the dangers of criticality and to adhere to the necessary safety protocols designed to mitigate such risks.

The operational procedures in place were not effectively communicated or enforced, leading to misunderstandings about safe handling practices among the staff. Many operators were accustomed to handling low-enriched uranium, which has different safety parameters than the 18.8% enriched material involved in the accident. This unfamiliarity created a dangerous situation where operators failed to appreciate the implications of their actions (International Atomic Energy Agency).

Furthermore, there was no verification or validation process for the procedures used, nor were there adequate checks on operator training and qualifications. This oversight meant that when the criticality accident occurred, the operators did not fully understand the risks involved, leading to catastrophic outcomes.

The Tokaimura accident had profound long-term consequences for both the individuals directly involved and the broader community. Among the three primary operators affected, one tragically lost his life due to acute radiation syndrome, while the others faced serious health complications requiring extensive medical treatment [12]. The incident raised significant concerns about the long-term health effects of radiation exposure, both for the workers and for the surrounding population. Although the IAEA concluded that there was no widespread contamination, the psychological impact on local residents was considerable, leading to heightened anxiety and distrust towards nuclear safety.

Economically, the incident imposed substantial financial burdens on JCO and the local community. The company faced numerous compensation claims, estimating costs of at least \$93 million for affected residents and businesses [13]. This financial strain stemmed from direct compensation for evacuations and indirect losses resulting from reputational damage and decreased public confidence in nuclear safety. The economic repercussions extended beyond monetary compensation; local businesses experienced reduced patronage due to public fears over safety, affecting livelihoods and community stability.

The social implications of the accident were also significant. Residents expressed concerns about potential health risks and the safety of their environment, leading to long-lasting fear and distrust of nuclear facilities. This incident highlighted the need for better communication and transparency in the nuclear industry. To rebuild trust, stakeholders must prioritize community engagement and provide clear, accurate information regarding safety measures and emergency preparedness. The psychological and economic impacts of the Tokaimura accident serve as a crucial reminder of the importance of safety in nuclear operations and the need for ongoing vigilance.

The JCO accident, which resulted in employee deaths and the emergency evacuation of nearby residents, is among the most thought-provoking events to occur in a nuclear energy-related facility, not only in Japan but worldwide. It raises numerous issues that need to be discussed among those who handle radioactive materials, other nuclear industries, and the nuclear fuel processing industry. The management system, which is necessary to guarantee both product quality and safety as part of "satisfaction of interested parties," had not taken hold at JCO [14]. After numerous unapproved

revisions, the licensed design of the nuclear fuel process was ultimately rendered more susceptible to a criticality incident. The management who permitted the final process change, in addition to the three employees who caused the tragedy, lacked a practical knowledge of the importance of safety. There are three key lessons learned:

- Competency of Human Resources
- Organization Drift and Safety Culture
- Authorization Scheme

Ensuring that staff handling nuclear materials are properly trained is essential for nuclear safety. Workers must be familiar with operational processes, understand safety limits, and be able to identify and respond to abnormalities. Managers must also enforce compliance and ensure safety measures are followed. In the JCO accident, insufficient knowledge and poor safety culture contributed to the disaster. Workers were unaware of criticality safety limits, and safety procedures were modified without proper authorization. This lack of competency led to unsafe decisions and delayed emergency responses, worsening the situation. To prevent such failures, training programs should include technical training on operation processes and nuclear safety controls, communication training to ensure effective response to abnormalities and management training to establish and enforce safety procedures. It is also important to identify personnel who require deeper safety training, as experience alone does not guarantee technical understanding. Overconfidence can lead to dangerous assumptions, making proper education critical for all levels of staff [14].

A strong safety culture is essential in any nuclear facility. It must prioritize safety over production pressures and be consistently reinforced through training, leadership, and operational discipline. At JCO, weak safety culture and organizational drift contributed to the accident. Long-term reliance on short-term contracts led to a loss of critical safety knowledge. Over time, small, unauthorized process changes accumulated without oversight, increasing the risk of an accident. Warning signs were ignored, and there was no system to detect or correct deviations. To prevent such failures, organizations must:

- Regularly review all operational changes to prevent unintended safety risks.
- Ensure strict compliance with approved procedures and reinforce accountability.
- Document and authorize process changes to prevent unsafe workarounds.
- Encourage reporting of deviations and involve safety specialists in decision-making.

A clear and well-enforced authorization system is crucial for nuclear safety. At JCO, a staff member without proper authority allowed workers to use a precipitation tank in an unauthorized way, directly contributing to the accident. The lack of a structured approval process enabled dangerous deviations from licensed procedures. To prevent such failures, organizations must define clear lines of authority and supervision, especially after organizational changes. Only qualified personnel should have the authority to approve operational changes, and workers must understand who holds this responsibility. Training should be provided for both workers and managers to reinforce their roles, responsibilities, and the importance of compliance. A well-established authorization scheme is essential to prevent unsafe decisions, unauthorized changes, and future accidents [15].

The JCO criticality accident was a harsh reminder that nuclear safety requires constant vigilance. To prevent similar tragedies, the nuclear industry must focus on five critical areas: worker training,

strict safety protocols, government oversight, effective emergency response, and public transparency.

1. **Investing in Worker Education:** Handling nuclear materials is not a job for the unprepared. Workers need thorough training, not just in technical procedures but in risk awareness and emergency response. Regular refresher courses and hands-on drills should ensure they remain sharp and ready to act at a moment's notice.
2. **Implementing and Enforcing: Safety Measures** Human error is a major cause of accidents, which is why strict safety protocols must always be in place. Facilities should have detailed operating procedures, independent safety inspections, and automated monitoring systems to detect hazards before they escalate. No process should be changed without thorough safety reviews.
3. **Stronger Government Regulation & Oversight:** Regulatory bodies must hold nuclear facilities accountable by conducting frequent safety inspections. Companies that violate safety standards should face swift penalties, ensuring that profit never comes before safety. Staying updated with global nuclear safety standards is also essential.
4. **Enhancing Emergency Preparedness:** Even with strict regulations, accidents can still happen. Nuclear facilities must have automated shutdown systems for emergency situations (OECD-NEA, 2000). Workers and first responders should train regularly for crisis scenarios, ensuring swift and efficient action when needed. Real-time radiation monitoring can also help guide evacuation strategies.
5. **Building Public Trust Through Transparency:** Misinformation about nuclear energy can cause unnecessary panic and economic losses. The Tokaimura accident showed that clear and honest communication is critical. Authorities must provide accurate updates and educate the public on nuclear safety, helping them make informed, rational decisions.

#### **4. Conclusions**

The Tokaimura Criticality Accident of 1999 is regarded as one of Japan's most significant nuclear disasters, exposing severe flaws in nuclear safety culture, regulatory supervision, and emergency response protocols. The accident occurred due to poor adherence to established safety procedures and insufficient worker training, illustrating how human error can lead to devastating consequences. JCO workers, unaware of proper uranium-handling techniques, unintentionally triggered an uncontrolled nuclear reaction, which released dangerous radiation [1]. The initial emergency response involved urgent medical care for the affected employees, the evacuation of local residents, and widespread radiation monitoring. However, the long-term effects were severe. The two most heavily exposed workers died from radiation poisoning, while many others developed serious health complications. The wider community suffered financial losses, psychological distress, and declining trust in nuclear power.

This accident provided valuable lessons for the global nuclear industry. It emphasized the need for strict regulatory frameworks, thorough worker education, and unwavering adherence to safety protocols. Additionally, it showed the importance of strong safety leadership, rigorous government oversight, and well-prepared emergency plans [1]. Without these safeguards, nuclear facilities

remain at high risk of serious accidents. To prevent similar events, nuclear plants must strengthen safety measures, including mandatory training, strict operational procedures, better monitoring technology, and improved emergency preparedness. Transparent communication with the public is also essential to ensure trust and prevent misinformation. The Tokaimura accident serves as a serious warning about the dangers of overlooking nuclear safety. While nuclear energy is a critical resource, it must be managed with extreme care and strict oversight. By learning from past mistakes and continuously improving safety standards, future accidents can be effectively prevented.

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