The Tokaimura Accident

Nuclear Energy and Reactor Safety

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Part I — Nuclear Power and Nuclear Fuel Reprocessing in Japan

Since the worldwide oil crises of the early 1970s, Japan's energy policy has focused on decreasing the country's reliance on foreign fuel imports. With few natural resources, Japan has embraced nuclear energy and currently derives approximately 36% of its electricity from nuclear power. Japan has made substantial investments in nuclear reactor technology. As part of its goal of energy self-sufficiency, Japan has maintained a policy of reprocessing spent nuclear fuel rather than treating or disposing of it as waste.

The Tokaimura nuclear fuel processing plant is operated by JCO Company Ltd. and is located approximately 120 kilometers (70 miles) northeast of Tokyo. JCO is a subsidiary of Sumitomo Metal Mining Company Ltd. and employs approximately 140 persons on a multi-building 0.16-km^2 (40-acre) site. The JCO plant is one of 15 nuclear facilities in Tokaimura. Approximately one-third of the population of Tokaimura is employed by the nuclear industry. The main function of the JCO plant is to convert isotopically enriched uranium hexafluoride into uranium dioxide fuel. This is one step in the process of making reactor fuel rods for some of Japan's commercial nuclear power plants. The uranium used in the process has been enriched to contain up to 5% of the fissile isotope, ^{235}U (compared to the relatively inert isotope ^{238}U).

Heavy nuclei, such as uranium, can split into two lighter nuclei accompanied by an energy conversion of 200 MeV. This process is called *fission* and most of the energy released goes into the kinetic energy of the fission fragments. Some of the energy appears as decay products (beta and gamma rays) and the kinetic energy of neutrons emitted in the fission process.

The JCO plant occasionally purifies uranium to be made into fuel for an experimental fast-breeder reactor known as Joyo, which requires fuel enriched to 18.8% ^{235}U. These higher levels of enrichment require greater precaution because of the higher probability of accumulating a critical mass. A critical mass implies that enough ^{235}U has been amassed that at least one neutron from each fission, on average, stimulates another fission. Japan's Science and Technology Agency (STA), which licenses nuclear facilities, had adopted regulations that placed a mass limit of 2.4 kg (5.3 lbs) on the amount of 18.8% enriched uranium that could be processed at one time at the JCO plant. The license was issued in 1980.

The uranium fuel for the Joyo facility requires a chemical purification procedure. The uranium oxide purification procedure licensed by STA for the Joyo fuel involves feeding small batches of uranium oxide, U_3O_8, in powder form into a dissolving tank, where it is mixed with nitric acid to produce uranyl nitrate, $UO_2(NO_3)_2$. This solution is then transferred to a buffer tank. The buffer tank serves a mixing function and has a geometrical design to prevent criticality. From there, it is sent into a precipitation tank, where ammonia is added in the form of an ammonium salt solution, to form a solid product, ammonium diuranate $(NH_4)U_2O_7$. Any contaminants should remain in solution. Uranium oxide is extracted from the solid precipitate. The purified uranium oxide is reprocessed in the dissolving tanks until the uranium oxide becomes sufficiently pure. The uranium oxide is then converted to uranyl nitrate, transferred to a storage container, and shipped to another facility, where uranium dioxide, UO_2, is prepared and made into Joyo fuel. It is important to note that the purification process does not enrich the uranium isotopes but simply removes the chemical impurities. In recent years only Japan and Kazakhstan have utilized this type of wet process technology.

Questions

1. List several alternative sources of energy for industrial and consumer needs along with their associated advantages and disadvantages.
2. What are the major sources of energy in the United States?
3. Sketch a block flow diagram for the uranium oxide purification process.

Part II – Accident Chronology

The JCO plant needed to mix some high-purity enriched uranium oxide with nitric acid to form uranyl nitrate for shipping. The dissolving and mixing began on September 28, 1999. On the morning of September 30, 1999, three technicians, Hisashi Ouchi, Masato Shinohara, and Yutaka Yokokawa, were running fuel through the last steps of the conversion process. To speed up the process, they mixed the oxide and nitric acid in 10-liter stainless steel buckets rather than in the dissolving tank. In doing so, they followed the practice that JCO had written into its operating manual but which had not received STA approval. For convenience, they added the bucket contents directly to the 45-cm-diameter, water-jacketed precipitation tank rather than to the buffer tank. That was a crucial error because the tall, narrow geometry of the buffer tank was designed to preclude the onset of criticality. In filling the precipitation tank, the crew added seven buckets, amounting to a total of about 16 kg (35 lbs) of enriched uranium, or roughly seven times more uranium than permitted under the STA license.

The three technicians were working in a small processing bay. Masato Shinohara stood on a platform and was pouring the uranyl nitrate solution into the precipitation tank while Hisashi Ouchi held a glass funnel in an inlet at the top of the tank. The third technician, Yutaka Yokokawa, was seated at a desk approximately 4 meters (13 feet) away from the precipitation tank. At approximately 10:35 a.m. the technicians added the seventh bucket and saw a blue flash. The two technicians near the vessel began to experience pain, waves of nausea, some difficulty in breathing, and problems with mobility and coherence. The gamma radiation alarms activated immediately. The blue flash that they had seen was a result of the Cherenkov radiation that is emitted when nuclear fission takes place and ionizes air. The addition of the seventh bucket had caused a self-sustaining chain reaction. The mixture, in other words, had gone critical. Mixing in the precipitation tank caused the fissile uranium species to disperse so that the reaction fizzled out. However, the critical mass later reassembled, initiating another chain reaction that released more neutrons and gamma radiation. This cycle was repeated several times over many hours.

None of the three technicians realized what had happened. Mr. Ouchi had been draped over the top of the tank and was experiencing the greatest difficulty. The other two workers helped him out of the building in response to the gamma radiation alarms. A worker in an adjoining building noticed the injured and confused technicians and called for medical assistance. An ambulance arrived quickly and removed the affected workers. No one at JCO initially understood the nature of the problem and management eventually requested help from other nearby technical facilities. Uncertainty existed among workers and management about evacuation of the premises or other action that should be taken. Workers were given the option to remain at their jobs or to go home.

The exact critical mass for the 18.8% uranium mixture in the JCO precipitation tank is not known. In the Joyo reactor, the minimum critical mass for the solid 18.8% uranium fuel is about 46 kg (101 lbs). But the critical mass is greatly reduced when the fuel is in solution because water acts as a "moderator." Light atoms such as hydrogen slow the neutrons released by decaying ^{235}U nuclei between fissions, making it more likely that they will be absorbed and trigger another nucleus to decay. The critical mass was further reduced at Tokaimura because a water jacket surrounding the precipitation tank reflected neutrons back into the tank.

At 2:30 a.m. on October 1, 1999, JCO staff recognized the need to bring the precipitation tank under control and initiated a plan to drain the cooling jacket. Draining water from the cooling jacket would cause the reaction to cease. This proved difficult and required workers to dismantle pipes leading from the jacket. The workers could work in the irradiated building for only a few minutes at a time. The jacket was later purged with argon. Boric acid (effective for absorbing neutrons) was pumped into the tank in order to mitigate the chain reaction. The reaction was arrested at approximately 6:00 a.m. on October 1. Judging from the levels of gamma and neutron radiation measured near the plant perimeter, the criticality excursion seems to have lasted about 20 hours. After that time, the radiation levels dropped below detection limits.

Questions

1. What mistakes did the technicians make that resulted in this accident?
2. Were there any flaws in the equipment or design of the process that contributed to the occurrence of this accident?
3. What steps could JCO management have taken to eliminate or reduce the possibility of this type of accident?

Part III – Radiation Exposure

The greatest source of radiation exposure in a criticality accident is the flux of neutrons and gamma rays that emanates directly from the fissioning nuclei and rapidly decaying fission products. Such radiation is most harmful to individuals who are nearby and falls off as the square of the distance. A secondary contribution comes from the volatile fission products, such as isotopes of xenon, krypton, and iodine. At Tokaimura only a very small fraction of the fission decay products are volatile in solution, and concentrations of xenon and krypton are generally thought to have been below the regulatory limits. A third potential source of radiation is the activation nuclei, or nuclei made radioactive by the absorption of neutrons. Studies have found that the decay of activated atmospheric nitrogen can contribute significantly to the total dose if people are not evacuated from the site of the criticality. However, given the neutron absorption cross section of nitrogen, it would appear that at Tokaimura this contribution would have been extremely small.

According to STA, Hisashi Ouchi was exposed to 17 sieverts of radiation and Masato Shinohara was exposed to 10 sieverts of radiation. The other worker in the vicinity at the time the precipitation tank went critical, Yutaka Yokokawa, received a dose of 3 sieverts (the doses were deduced from the measured levels of the relatively long-lived sodium-24 isotope in the victims' bodies).

One sievert (Sv), which equals 100 rems, is a measure of the biological response to the absorbed radiation. A rem refers to "roentgen equivalent in man" and is a measure of dose equivalent. This accounts for the fact that different types of radiation may deliver the same energy per unit mass to the body but do not have the same biological effect. The dose equivalent in rems is found by multiplying the radiation absorbed dose (rads) by a relative biological effectiveness factor. Normally people receive an average of 0.003 Sv annually from natural causes. Half of all individuals exposed instantaneously to 4 Sv die within 30 days. Doses of 10 and 17 Sv are above the levels normally considered fatal.

After the accident the three men were taken by helicopter to the National Institute of Radiological Sciences in Chiba. The two workers who received high radiation doses were transferred to the University of Tokyo Hospital and treated with blood transfusions. Yutaka Yokokawa did not require transfusions and was discharged from the hospital on December 20, 1999.

Hisashi Ouchi, 35, died of multiple organ failure on December 21, 1999. He suffered serious burns to most of his body, severe damage to his internal organs, and had a near-zero white blood cell count. Doctors at the University of Tokyo Hospital had used a radical cancer treatment in an attempt to revive his white cell count. It worked temporarily, but Mr. Ouchi was overwhelmed by his other injuries.

Masato Shinohara, 40, died on April 27, 2000, of multiple organ failure despite a seven-month fight by doctors after his exposure to the large dose of radiation. Their efforts also included the use of a radical cancer treatment. Too weak to cope with conventional blood transfusions, Mr. Shinohara was injected with umbilical cord blood to boost his stem cell count. While this proved successful in restoring his ability to reproduce blood cells, his body was unable to fight infections and other problems, including internal bleeding. Doctors said Mr. Shinohara's condition had declined rapidly after his lung and kidney functions deteriorated.

At least 439 people, including plant workers, firemen, and others who responded to the accident, and 207 local residents were exposed to elevated levels of radiation. In October 2000 the total number of people who received some radiation exposure from the accident was revised upward to 667. Monitors placed at a number of sites outside the plant had detected the radiation levels. At one of the closest monitoring sites, STA reported dose rates of 4.5 mSv/hr for neutrons and 0.50 mSv/hr for gamma rays about 11 hours after the onset of criticality. That gamma dose rate was about 1000 times higher than the normal background level.

Most criticality accidents in the past have not involved exposures of private citizens. The JCO facility is located quite close to the surrounding town. Within the 350-meter (1148-foot) radius evacuated immediately after the accident, there were 47 houses and 150 people. Another 310,000 people living within a 10-kilometer (6.2-mile) radius were ordered to remain indoors for 16 hours. Schools were closed, roads cordoned off, and train services were suspended.

Questions

1. Define the relationship between sievert, rem, and rad.
2. What are the natural sources of radiation to which human beings are exposed?
3. Demonstrate that 0.50 mSv/hr corresponds to approximately 1000 times higher than the normal background level.

Part IV – Immediate Aftermath

There was considerable confusion and some local panic at the time of the accident. Management did not have an emergency plan or an authoritative spokesperson. Rumors circulated that vegetables and dairy products might be contaminated. Authorities warned people not to drink well water or harvest their crops. In an effort to maintain order, some officials suggested that all persons within the 10-kilometer (6.2-mile) radius be checked for radiation exposure. Over a 10-day period following the accident approximately 10,000 residents sought medical check-ups. This was costly and yielded little direct benefit except to ease the concerns of some residents.

Some newsperson or persons flew over Tokaimura in a helicopter and took pictures of a roof damaged in an explosion and fire that had occurred in 1997. This building was located five kilometers (3.1 miles) from the JCO processing plant. However, the picture was published and displayed repeatedly on the Internet. A number of websites quickly came online as information sources. Unfortunately, much of the information was inaccurate and leaned toward sensationalism. Neither JCO nor other local nuclear industries had websites to provide factual information.

Group Assignment

1. Did company officials respond appropriately following the accident? What kind of company response plan would your team recommend?
2. Did government officials respond appropriately following the accident? What kind of government response and action would your team recommend?
3. Discuss briefly how you would have reacted if you:
   (a) were a worker at JCO
   (b) lived in one of the 47 homes adjacent to the JCO plant
   (c) lived in Tokaimura

Part V – Update of Situation

On October 4, 1999, JCO set up an advisory booth in Tokai village to receive compensation claims and to handle other inquiries from people affected by the accident. The entire JCO plant, not just the purification operation, was shut down, and on March 28, 2000, STA cancelled JCO's operating license for the plant, making it the first plant operator in history to be punished under Japan's nuclear regulatory laws. Hiroharu Kitani, the president of the company, resigned in disgrace. Various investigations by police and government agencies were initiated. Several civil suits were filed by companies claiming that their profits suffered as a result of the accident. At the end of July 2000, JCO had settled approximately 6,840 of the roughly 7,015 compensation claims filed. As of April 2001 JCO and its parent company, Sumitomo Metal Mining Co., had paid 12.66 billion yen in compensation to residents and local businesses, including 50,000 yen to anyone living within 350 meters of the accident site, and 30,000 yen to each person who was forced to evacuate if she or he agreed not to sue in the future.

On October 11, 2000, police in Japan arrested six officials from the JCO plant and charged them with "professional negligence." Police concluded that the plant workers were not properly trained and that safety procedures were routinely violated. Among those arrested was Yutaka Yokokawa, who was the technician supervising the other two workers and who was hospitalized for a three-month period due to radiation sickness. At the time this case was written (April 2001), these officials were facing trial. They could be fined up to 500,000 yen (approximately $4,700), serve jail time for five years, and be subject to hard labor. The president of the company had not been arrested. Criminal charges were expected to be brought against the company.

Antinuclear activists seized on the accident to condemn Japan's commitment to nuclear energy. The accident at Tokaimura and others in recent years have called into question government assurances that Japan's nuclear facilities are safely run. A *Mainichi Daily News* poll conducted just days after the accident indicated that 70 percent of the Japanese public opposed nuclear power. Tokaimura elected an antinuclear representative to its assembly for the first time. As of January 1, 2001, oversight for all nuclear facilities, except those confined to research, was transferred from the STA to a new Ministry for Economy, Trade, and Industry.

Group Assignment

1. Discuss the actions taken by the company, particularly with consideration to the company response plan that you have recommended.
2. Discuss the actions taken by the government (including the police) particularly with consideration to the government response plan that you have recommended.
3. Discuss the responsibility for this accident that is borne by (a) the three technicians (b) the technicians' supervisor (c) the plant manager (d) the company president.

Part VI – Lessons Learned

Shunsuke Kondo, a nuclear safety expert from the University of Tokyo who has done an independent analysis of the accident, indicated that the technicians assigned to process the Joyo fuel that day were under time pressure. Apparently the lead technician was anxious to complete the current batch before a new team of workers arrived. Furthermore, the workers were apparently not aware of the mass limitations on the uranium to be added to the precipitation tank. Over an extended time and with changes in staff, the 2.4-kg (5.3-lb) limit became interpreted as a batch limit. The operators strictly adhered to this limit; however, they had no idea that batches could not be combined.

Since the possibility of a critical event was deemed implausible with the JCO design and enforcement of the handling limits, training and priority regarding critical mass (that is usually provided to workers in fissionable fuel processing operations) was minimized. The operators had no real understanding of the relationship between quantity, concentration, and vessel shape with regard to the accumulation of a critical mass. It appears that there were serious failures in communications and operator training, and that regulatory agencies and plant managers were not diligent in following approved procedures.

Besides acting as a neutron deflector, a secondary effect of the water jacket may have been to prolong the chain reaction. Per Peterson and Joonhong Ahn of the University of California, Berkeley, have pointed out that, without the water jacket, the heat generated by the chain reaction would have expanded the solution, decreasing its density and slowing its reaction rate. With the water jacket in place to remove the fission heat roughly as fast as it was generated, however, the solution may have been kept just above the critical density.

Questions

1. In view of this accident, what equipment or design changes, if any, would you recommend for this type of process?
2. In view of this accident, what changes in operating procedures, if any, would you recommend for this type of process?
3. In view of this accident, what policy options would you propose when an accident of this type occurs?

Part VII – Historical Perspective

Several criticality accidents have occurred in the past. Similar incidents to the Tokaimura accident involving the mixing of uranium solutions have taken place in Oak Ridge, Tennessee, in 1958, in Mayak in the Urals in 1958, and in Wood River Junction, Rhode Island, in 1964. On October 7, 1957, at Windscale Pile No. 1, north of Liverpool, England, a fire in a graphite-cooled reactor released a large amount of radioactive pollution over the countryside contaminating a 520-km^2 (200-mi^2) area. On March 28, 1979, a nuclear accident occurred at the Three Mile Island nuclear power plant near Harrisburg, Pennsylvania. One of two reactors lost its coolant, which caused overheating and partial meltdown of its uranium core. Some radioactive water and gases were released. On April 26, 1986, an explosion and fire in the graphite core of one of four reactors occurred at the Chernobyl nuclear power plant near Kiev in the Ukraine. A vast amount of radioactive material was released and spread over the Soviet Union, Eastern Europe, Scandinavia, and later Western Europe. Thirty-one people were claimed dead in the immediate aftermath of the accident. The total number of casualties is unknown.

Questions

1. Research the accident that occurred at Three Mile Island. What were the factors that led to this accident?
2. Research the accident that occurred at Chernobyl. What were the factors that led to this accident?
3. Research fast-breeder reactor technology. What are the benefits that could be derived from this technology?