

largely dormant since 1995, when a massive leak of sodium coolant caught fire at Monju, a prototype breeder reactor. In a report issued exactly two years before the Tokaimura accident, Japan's Atomic Energy Commission noted that "it is premature to make a decision about when Japan can put the fast-breeder reactor into practical use." The report blamed Monju's operators, the state-owned Power Reactor and Nuclear Fuel Development Corp (PNC) for causing "a loss of public faith," through its mismanagement of the accident and its attempts to cover up the incident with doctored videos and incomplete reports. PNC was also criticized for its mishandling of a 1997 fire at its reprocessing plant in Tokaimura; the reopening of that facility has been put on indefinite hold. (Last year, PNC was reorganized and reborn as JNC, the Japan Nuclear Cycle Development Institute. It was a fuel order for JNC's Joyo experimental breeder reactor that the workers at Tokaimura were rushing to complete when the criticality accident occurred.)

And so, with no immediate

demand for reprocessed fuel, Japan is quickly amassing a plutonium surplus. According to ISIS estimates, at the end of 1998, Japan had 29 tons of separated plutonium, of which 24.4 tons were still stockpiled in Europe awaiting return shipment. "To Japan's credit, they have said they want to reduce the amount of separated plutonium to zero," Albright notes. "So they at least agree that separated plutonium is not desirable. And I would say it's dangerous."

No more like Tokaimura

Clearly, Japan can ill afford to have another accident on the scale of Tokaimura. During the last decade, growing antinuclear sentiment has significantly slowed down the expansion of the country's nuclear power industry. A *Mainichi Daily News* poll conducted just days after the accident showed that 70% of the Japanese public opposed nuclear power. Responding to such fears, the Ministry of International Trade and Industry recently began holding seminars around the country, to try to shore up support for nuclear power. "We need to increase public under-

standing of nuclear energy, as it is the government's firm position to continue using nuclear power as a principal source of energy," a MITI official told reporters in announcing the promotion campaign.

Public opinion will likely play an increasing role in determining Japan's nuclear future. Already, in the last few years, nuclear critics have had some success in democratizing the planning process. Prefectural governments are now putting nuclear energy questions to voters in local referendums. In one such vote, held in 1996 in the town of Maki, 61% voted against selling public land for a new nuclear reactor; construction has since been suspended. In June, Japan's Atomic Energy Commission began a review of the nation's "long-term program for research, development, and utilization of nuclear energy," something it does every five years or so. The 32-member committee appointed to carry out the review includes, for the first time, two people critical of nuclear development. Their report is expected by the end of next year.

JEAN KUMAGAI

What Happened at Tokaimura?

On 30 September, as workers at a Japanese nuclear fuel processing plant in Tokaimura were adding enriched uranium to a precipitation tank, they saw a blue flash—signaling the onset of a nuclear chain reaction. Exactly how did this accident occur? It will be some time before we get an official report and learn about the accident's impact on Japan's nuclear power program. (See previous story.) However, as *PHYSICS TODAY* goes to press, independent analysts have already gleaned enough information from preliminary accounts such as those posted on the Web by Japan's Science and Technology Agency (STA), which licenses nuclear facilities,¹ to piece together a picture of how a solution containing enriched uranium became critical, what power levels were reached, and what releases of radiation ensued.

Cautions not heeded

The plant where the accident occurred is operated by JCO Co Ltd. Its main function is to convert uranium hexafluoride into uranium dioxide fuel for some of Japan's commercial nuclear power plants. This uranium has been enriched to contain up to 5% of the fissile isotope, U-235. In addition, the JCO plant occasionally

Analysts are trying to figure out how workers ended up putting enough uranium in one tank to initiate a chain reaction.

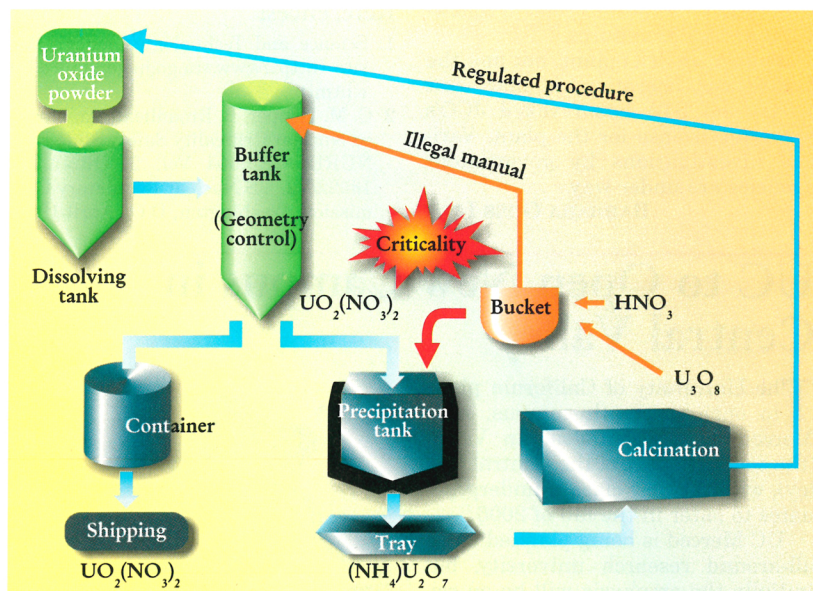
purifies uranium to be made into fuel for an experimental breeder reactor known as Joyo, which requires fuel enriched to 18.8% ²³⁵U. For these higher levels of enrichment, one has to be far more careful because of the higher probability of accumulating a critical mass—that is, amassing so much ²³⁵U that at least one neutron from each fission, on average, stimulates another fission.

STA regulations place a mass limit of 2.4 kg on the amount of 18.8% enriched uranium that can be processed at one time at the JCO plant. Nevertheless, the workers there added a total of about 16 kg to the tank, causing a self-sustaining chain reaction.

The purification procedure licensed by STA for the Joyo fuel is shown by the blue lines in the figure on page 53. The workers feed uranium oxide (U₃O₈) in powder form into a dissolving tank, where it is mixed with nitric acid to produce uranyl nitrate, or UO₂(NO₃)₂, which is then transferred to a buffer tank. From there, it is sent

into the precipitation tank, where ammonia is added to form a solid product (with contaminants remaining in solution). Uranium oxide is extracted from that solid, and the process is repeated until the oxide becomes sufficiently pure. At that point, the uranyl nitrate in the buffer tank gets shipped to another facility, where uranium dioxide is prepared and made into Joyo fuel.

On the day of the criticality accident, workers were running fuel through the last steps of this process, according to Thomas McLaughlin of Los Alamos National Laboratory, one of three nuclear experts sent by the US Department of Energy to learn about the accident. The JCO plant only needed to mix some high-purity enriched uranium oxide (U₃O₈) with nitric acid to form uranyl nitrate for shipping. During this operation, the workers deviated from the licensed procedure in three basic ways. First, to speed up the process, they mixed the oxide and nitric acid in 10-liter buckets rather than in the dissolving tank (in doing so, they followed the practice that JCO had written into its manual—without STA approval). Second, for convenience, they added the bucket contents to the precipitation tank rather than to the buffer tank.



PROCESS FLOW for the conversion facility at the JCO plant. Blue lines indicate the procedure approved by Japan's Science and Technology Agency. Uranium oxide and nitric acid are fed through a dissolving tank into a buffer tank. Orange lines indicate a company-initiated procedure not approved by STA, in which uranium oxide and nitric acid are added by bucket directly to the buffer tank. The red line indicates buckets dumped directly into a precipitation tank—a further deviation from licensed procedure. (Adapted from ref. 1.)

That was a key misstep, because the tall, narrow geometry of the buffer tank precludes criticality. Third, in filling the precipitation tank, the crew added seven buckets, or roughly seven times more uranium than permitted by the STA license. It was the seventh bucket that caused the mixture to go critical.

According to Shunsuke Kondo, a nuclear safety expert from the University of Tokyo, who has done an independent analysis of the accident, the crew assigned to process the Joyo fuel that day was under time pressure: The crew chief was anxious to complete the current batch before a new team of workers arrived. Furthermore, Kondo reports, the workers were apparently not aware of the mass limitations on the uranium to be added to the precipitation tank.

Reaching criticality

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. But the critical mass is greatly reduced when the fuel is in solution because light atoms such as hydrogen slow neutrons between fissions, making it more likely that they will be absorbed. The critical mass was further reduced at Tokaimura because

a water jacket surrounding the precipitation tank reflected neutrons back toward the center of the reaction.

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, point out that, without the water jacket, the heat generated by the chain reaction and the dissociation of water into hydrogen and oxygen 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.

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. The chain reaction was shut off by draining the cooling water out of the jacket and made safe by adding boric acid.

Radiation exposures

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 second contribution comes from the volatile fission products, such as isotopes of xenon, krypton, and iodine. At Tokaimura, these gases were vented (an exhaust fan was not shut down until 12 October), but concentrations of xenon and krypton are generally thought to have been below the regulatory limits. Levels of iodine-131 measured on 8 October were about twice those allowed by STA regulations. A third source of radiation is the activation nuclei, or nuclei made radioactive by the absorption of neutrons. Valerie Putman, who works on criticality safety issues at the Idaho National Engineering and Environmental Laboratory, told us that studies have found that the decay of activated atmospheric nitrogen can contribute up to half the total dose if people are not evacuated from in and around the site of the criticality.²

According to STA, the three workers in the room at the time the precipitation tank went critical received doses of 17, 10, and 3 sieverts (the doses were deduced from the levels of radioactive sodium in the victims' bodies). (One sievert, which equals 100 rems, is a measure of the biological response to the absorbed radiation.) Doses of 10 and 17 Sv are above the levels normally considered fatal, but the two workers who received such high doses were still alive at press time, perhaps because they were treated with blood stem cell transplants. The worker who received a dose of 3 Sv did not require transfusions and is expected to recover fully. In addition to these three severe cases, there were 66 individuals—plant workers, firemen, and others who responded to the accident, and a few city residents—who were exposed to measurable levels of radiation. Most criticality accidents in the past haven't involved exposures of private citizens, but the JCO facility is sited quite close to the surrounding town. Within the 350-meter radius evacuated immediately after the accident, there were 47 houses and 150 people.

Monitors placed at a number of sites outside the plant 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.

The magnitude of the accident

Based on the observed neutron radiation levels, Hiroshi Sekimoto from the Nuclear Reactor Institute of the Tokyo Institute of Technology initially estimated that the chain reaction may have involved $1-8 \times 10^{18}$ fissions, consistent with a steady-state power 0.7–4 kW. (The thermal output of a typical commercial power reactor is about 3000 MW.) Since then, using information about the fission products found in samples taken from the precipitation tank on 20 October, he has revised his estimate to $1.8-2.8 \times 10^{18}$ total fissions.

Peterson and Ahn have also made a preliminary estimate of the power level reached during criticality and hence the maximum radioactive releases, by making some assumptions about the heat balance in the tank. They have concluded that the chain reaction generated heat at a rate of 5–30 kW. At that power level, it may have produced 30 to 180 curies of xenon-133 and 10–60 curies of iodine-131. (The explosion at the 1986 Chernobyl nuclear power plant in Ukraine spewed out tens of millions of curies of these isotopes.)

Thomas Cochran of the Natural Resources Defense Council has put the Tokaimura episode in perspective by examining 22 criticality events at US nuclear facilities other than reactors (all but one of which occurred before 1964). He found that the number of fissions generated by fairly similar accidents was in the range of 10^{17} – 10^{19} . Assuming that the Tokaimura accident was in the same ballpark, Cochran estimates releases of ^{131}I that overlap with those calculated by Peterson and Ahn. Cochran has concluded that the radiological impact on the public of the Tokaimura episode is not likely to be larger than that of the 1979 nuclear accident at the Three Mile Island nuclear power plant in Pennsylvania.

McLaughlin has been working over the past year to update a report on criticality accidents around the world by incorporating data now available on accidents in the former Soviet Union. Although he can't yet say what happened at the JCO plant, he did refer us to the list of "lessons learned" from past accidents. He noted that what many of the accidents have had in common have been failures in communications and operator training, improper procedures, lack of fissile-material accountability, and new or unfamiliar operations. Judging by the standards in the US, McLaughlin said, it appears that, in the Tokaimura incident, regulatory agencies and plant

managers were not diligent in following approved procedures.

The entire JCO plant, not just the purification operation, is now shut down, and STA has revoked JCO's operating license for the plant. Various investigations by government agencies are under way.

BARBARA GOSS LEVI

UC to Open New Campus in Central Valley

The University of California plans to open its tenth campus, near Merced in the San Joaquin Valley (the southern part of the Central Valley), with the first class of undergraduates to enter in the fall of 2005.

UC Merced is being planned as an all-around research university, but initially the emphasis will be on science and technology, says psychologist Carol Tomlinson-Keasey, who was named chancellor of the new campus this past summer, and has held academic and administrative positions at UC for nearly two decades.

To that end, UC Merced planners have begun forging ties with Lawrence Livermore National Laboratory, the Department of Energy weapons lab located about 85 miles northwest of Merced, with whom they hope to collaborate in areas such as environmental sciences, computing, and nonpolluting transportation. Also planned is the Sierra Nevada Research Institute, which would begin as a coalition of several existing UC multicampus research organizations, and would focus on natural resources and policy topics relevant to the region, such as water, air quality, and climate change.

In choosing a site for the new campus, "we quickly narrowed it down to the Central Valley," recalls Tomlinson-Keasey. "The reason was that it is woefully underserved in terms of higher education." The plan is to set up several UC Merced satellite sites around the valley—the first one opened in Fresno two years ago—where professional courses will be offered and some UC Merced courses will be available by video conference. Planners are also working closely with ten or so community colleges up and down the valley, so that "folks can get some portion of their education" cheaply and without leaving home, explains Tomlinson-Keasey.

Eventually, the new campus may serve up to 25 000 undergraduate and graduate students. But to begin with, the planners are aiming for

References:

1. Science and Technology Agency's Web site (<http://www.sta.go.jp/genan/jco/jcoe.html>).
2. C. M. Hopper, B. Broadhead, An Updated Nuclear Criticality Safety Slide Rule, NUREG/CR-6504 Vol. 2; ORNL.TM-13322/V2. US Nuclear Regulatory Commission, Washington, D.C., April 1998.



FUTURE UC MERCED STUDENTS?

Local fourth graders survey the site selected for the new campus, and draw their ideas of what it might look like when completed.

1000, and 100 faculty members, growing to 5000 and 300, respectively, within five years. That's only a small fraction of the 60 000 additional students that the UC system expects to be enrolling by 2010, notes Tomlinson-Keasey. "It's a terrific squeeze." There is also talk at UC of switching from the nine-month academic calendar to a year-round schedule, adds Karen Merritt, UC Merced's chief of academic planning.

The state of California is expected to provide about \$250 million for construction of the new campus, and UC is seeking other sources of public and private funding. "It's not like it was in the sixties, when the state funded almost everything," says Merritt, referring to the establishment of the three youngest UC campuses, in San Diego, Irvine, and Santa Cruz.

TONI FEDER

Canadian Institute Starts Program in Nanoelectronics

Nanoelectronics is the thrust of a network of scientists recently set up by the Canadian Institute for