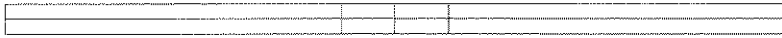


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Hisashi Ouchi tapped the shiny bottom of the upturned stainless steel bucket with the tips of his fingers to empty the contents one last time. A drop of bright yellow liquid dripped from the rim. He placed the bucket on the workbench and stepped back to inspect the result of the morning's efforts: the last of the partially filled glass beakers of uranyl nitrate, a concentrated solution of 18.8% enriched Uranium-235 — today's *theme ingredient*.

Some might think it odd to admire a purely industrial product such as the heavy fluid he had just poured from the bucket to the beaker, but to Hisashi it was visually attractive, particularly the way the transparent glass wrapped itself around the thick saffron solution they had brewed, giving it all the appearance of a crystal bowl of fine lacquer. But this, of course, was not a bowl of pretty yellow paint. It was the material for fabricating yellow cake — nuclear fuel pellets for Japan's high-tech Joyo ("everlasting sun") experimental fast breeder reactor. Once poured into the precipitation vessel with the previous batches, all 40 liters would be thoroughly mixed and, later, dried, powdered, and molded into stout little cylinders of uranium at another location. A few months from now the finished pellets would be stacked neatly inside metal tubes in the Joyo reactor at its next scheduled refueling, configured for sustained, controlled, and contained nuclear fission. It was regal material indeed, and cooking up the liquid uranyl nitrate was an impressive bit of chemistry, especially considering that it had all

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been done in their trusty stainless steel bucket. Chairman Kaga would be proud.



Hisashi and his coworkers, Masato Shinohara and Yutaka Yokokawa, had completed the same steps of chemistry seven times since yesterday afternoon, each time producing 5.7 liters of fluid in their metal pail. They began by carefully weighing out 2.4 kg of the uranium powder, technically known as triuranium octoxide, and adding it to the empty bucket. Next, they measured and poured in a liter of pure water and mixed it thoroughly into a soupy paste. The 6.49 liters of nitric acid came next, which was measured precisely and added to the triuranium octoxide and water mixture, a little at first and then more as the uranium paste blended with the acid. They mixed and stirred, this way and that way, around and around and back and forth, until all that remained was the smooth paintlike solution with no clumps or lumps.

As with the preceding batches, transferring the mixture into the smaller beaker from the bucket would make it easier to pour this last batch of uranyl nitrate into the slightly elevated and inaccessible precipitation vessel. The partially filled beaker was smaller and lighter than the bucket. He had to hold it up high and pour the liquid into the funnel his coworker held over the precipitation vessel's small round opening. They had gone to so much trouble to make sure that all of their measures were exact, and they certainly didn't want to spill any of the U-235 solution onto the floor or the equipment.

Each bucket of concentrated uranyl nitrate had taken the three-man crew about an hour to produce. This did not include the many days of preparation here in the conversion building at the northwest corner of the JCO Nuclear Fuel Processing Facility

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in Tokaimura, a small village on the Pacific coast northeast of Tokyo. They had made four batches in the afternoon the day before. And now, 10:30 the next morning, the 30th of September, 1999, the precipitation vessel held six buckets of material — four from yesterday and two from today. Only the last bit of the last batch, which now sat on the workbench beneath the admiring eyes of Hisashi Ouchi, had not been added. The electrically powered mixing blades inside the big bowl-shaped precipitation vessel turned slowly, awaiting the final beaker of blended ingredients. Masato would return in a minute to help Hisashi get the last of this batch into the funnel and the precipitation vessel.



Hisashi, 35 years of age, had spent much time at the JCO plant during his 16 years with the company, but he had not worked exclusively in the conversion building, at least not until recently. The company had gone through some financial difficulties this past year, and, with the layoff of nearly a third of their people, he and the others who remained had been asked to take on more responsibility than in the past, including the campaign to produce the enriched U-235 for the Joyo reactor. They had had no special training for the new line of work — or much of any training at all in the physics of fission. Yet Hisashi, Masato, and Yutaka had accomplished a great deal in these few short days, certainly more than they would have accomplished with a larger crew or if forced to use all of the built-in processing machinery and the accompanying slow procedures. There was some truth to that old adage: *Give a small group of capable men good and simple tools and they can do just about anything.*



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An enriched uranium solution of 141 kg was first produced at the facility in 1993, when JCO Co., Ltd. was known as Japan Nuclear Fuel Conversion Company. A campaign to manufacture a batch of triuranium octoxide was undertaken in 1994 and was followed by two campaigns for batches of uranium dioxide in 1995 and 1996. With a handful of other campaigns running up until June of 1998, the facility produced a total of 963 kg of enriched uranium-based material, all for the Joyo experimental fast breeder reactor. Unlike the more automated and controlled manufacturing processes used to make standard uranium fuel for commercial reactors, the process here in the conversion building was very hands-on. It was also a "wet" as opposed to a "dry" process. The requirements of their customers and their unique nuclear reactors demanded a special operation and a custom product.

Most of the time Hisashi and the other JCO employees at the Tokai Works (as the facility was sometimes called) were involved in the production of uranium dioxide (UO_2) from enriched uranium hexafluoride (UF_6), the resulting substance being a relatively common 3 to 5 percent enriched uranium. The fuel for the Joyo breeder reactor required more of a punch, so the manufacturing process, as well as the enrichment level of the resulting product, was different this time around. Most importantly, the main ingredient — uranium powder — was much more concentrated. The uranium fuel they were now manufacturing was to be enriched to 18.8 percent, only slightly less than the 20 percent maximum allowed by JCO's operating license.

The single-story conversion building where the operation was taking place was made of cinder blocks. The structure was rather small, only 15 or so meters on a side. Three interconnected rooms lay inside the square outer walls. A short hallway linked the largest room to an adjoining building. The

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smallest room, a narrow L-shaped space, contained most of the processing equipment and the precipitation vessel which now held the previous batches of concentrated liquid uranium. Hisashi and the others paid close attention when working around the unusual equipment in the tight corridors.

The interior of the conversion building was a blend between an industrial chemistry lab and a small factory, with an odd mixture of different shapes and sizes of tanks, pipes, pumps, and support structures. A dissolving process performed in the dissolution tank where raw uranium oxide (U_3O_8 powder) was mixed with nitric acid was the starting point. Pipes from the dissolution tank ran to a solvent extraction system, consisting of a pump, a solvent extraction column, and an extraction stripping column. Both the solvent extraction column and the extraction stripping column were tall and narrow.

Exiting the stripping column, the resulting solution flowed through a pump and more plumbing to two tall and narrow buffer columns, and, lastly, to the precipitation vessel, a bowl-shaped tub about 45 cm wide and 60 cm deep. An internal mixer in the precipitation vessel stirred the contents. Mixing materials in the precipitation vessel could generate heat from common chemical reactions, so the tank was fitted with an integral cooling system — a 2.5-cm-thick metal water-filled jacket that surrounded the bottom half of the tank. Pipes for the cooling water in this closed-loop cooling system ran through the cinder block wall of the conversion building to a pump, drain valve, and heat exchanger, all of which were located outside on the other side of the cinder block wall.

At this stage of the process the contents of the precipitation vessel were infused with gaseous ammonia to create ammonium diuranate. The ammonium diuranate was filtered as it exited the bottom of the precipitation vessel and transferred to large flat trays. The trays, in turn, were to be loaded into a furnace, and

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converted into triuranium octoxide. They were later transferred to another furnace with an ammonia-containing cover gas and converted to purified uranium dioxide, the desired end product of the operation.

The entire system and process — starting with the mixing of the powdered uranium oxide and nitric acid in the dissolution tank and ending with the purified uranium oxide removed from the second furnace at the other end — had been approved by JCO when the process was designed. The process had also been approved by the Japan Science and Technology Agency, which concluded that there was “no possibility of criticality accident occurrence due to malfunction and other failures.” The government regulators had determined that the process was foolproof and that there was no chance of things going terribly wrong.



The irony of the moment would not have been lost on anyone familiar with the facilities in the conversion building, the proper handling of fissionable material, and the decidedly low-tech production methods being employed by the well-intentioned three-man crew. Here sat a small fortune in laboratory and process equipment, designed to produce liquid uranyl nitrate (18.8 percent enriched uranium-235) in carefully controlled and metered batches. The maze of metal that lay between the solution tank at the beginning of the process and the entrance to the precipitation vessel about halfway through was designed to manufacture precisely the same material the three-man crew had mixed up in their bucket. The complexity and uniqueness of the hardware alone would make most anyone believe it not possible to replicate such a process in a bucket, but this was not the case. Unbeknown to the Japan Science and

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Technology Agency, which was responsible for overseeing the operations at the Tokai Works, JCO had developed procedures to bypass the equipment, saving considerable manufacturing time, cost, and labor required to clean out all of the equipment after a batch had been made.

The first change in the procedure was developed shortly after the system went on-line years before and involved bypassing the initial dissolution process in the dissolution tank. Instead of mixing the raw uranium oxide, water, and nitric acid in smaller batches in the dissolution tank at the beginning of the process, JCO personnel had developed a procedure for mixing the ingredients in the stainless steel bucket. The change was circulated around the company, and formal approval was given by the manufacturing division and the division of quality assurance. The safety management division was not consulted about the change. A formal procedure was printed for use by the conversion building workers and used for a number of years. Contrary to the original licensing agreement for the operation, JCO did not notify any regulatory body of the change. Nor did they submit the change to a special criticality review committee which was to have been created under the original terms of their licensing. In fact, no such committee had ever been formed.

As months passed, it was realized that using the bucket saved so much time that another simplification was developed and approved: batches of enriched uranyl nitrate were now being pumped and accumulated in the tall narrow buffer columns located a few feet beyond the dissolution tank. As with the first change in the process, no individual, department, or regulatory agency with a full understanding of the process and the reasons behind it was consulted.

Unfortunately for Hisashi, Masato, and Yutaka, but also much of the population of the entire prefecture, JCO's willful modification of the process and the regulatory agencies' failure

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to monitor the operation would have dire consequences. The enriched uranium manufacturing system laid out before Hisashi was designed to make small batches of uranium solution, each containing no more than 2.4 kg of raw uranium — the amount Hisashi had added to *each* of the seven bucketfuls that had been mixed yesterday and today. The designers of the original process and the government regulators who approved it had no idea that anyone would try to make larger batches or circumvent part or all of the process.

A third and more critical modification had been made to the process in the preceding days, the result of the crew's well-intentioned efforts to speed up the process further, thus saving the company even more money. Why, Hisashi and the others had wondered, spend all this time making little individual batches and pumping them into the tall buffering tank and individually into and then out of the precipitation vessel? It seemed like such a waste of time. Why not simply mix each of seven 5.7-liter batches in their bucket and mix them all together in the large precipitation vessel which had more than twice the volume necessary to contain the entire 40 liters of concentrated enriched uranium liquid? Necessity, as the saying goes, is the mother of invention.



So this is what the crew had done: bypassed the dissolution tank, the solvent extraction and stripping columns, and the two buffer columns by mixing the material in their bucket and pouring it directly into the precipitation vessel with the aid of a glass beaker and a funnel. They had concocted one big yellow frothy pot of enriched uranium solution. Neither the three-man crew nor the other involved employees and managers at the Tokai Works had any idea that their sizable cauldron of U-235

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was teetering on the precipice between a state of rest and an avalanche of neutrons, the near-instant result of which would be a full-blown and sustained nuclear chain reaction. Unlike the tall and narrow extraction and buffer columns, each of which was designed to prohibit the accumulation of sufficient mass to produce a chain reaction, the bowl-like precipitation vessel was geometrically favorable to such an event by keeping the contents very compact and close together. And although it was not intended to hold such a large volume of highly enriched uranium in the normal small-batch processing mode, the precipitation vessel was perfectly capable of doing so. Furthermore, it was lined with the 2.5-cm-thick blanket of water to remove excess heat during conventional chemical reactions. The lining of water also served as a reflector, however, bouncing neutrons back into the nuclear brew and helping to sustain a nuclear chain reaction should it begin.



Masato Shinohara returned to the small room moments after Hisashi Ouchi placed the empty stainless steel bucket on the workbench, abruptly ending Hisashi's private thoughts about the meaningfulness of their efforts and the beauty of the product they had created. Yes, it was time to get back to work. Yutaka Yokokawa was obviously staying in the adjoining corridor on the other side of the wall to attend to related things. Anyway, only two people were needed to pour the remaining batch.

Hisashi and Masato bounced a series of simple questions and responses back and forth, each asking if the other was ready to finish up the job. They both stepped up to the elevated precipitation vessel, one holding the funnel and the other holding the large glass beaker of enriched U-235.

Up went the funnel, its small end inserted through the 25-

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cm-wide round opening in the top of the bowl-shaped tank, the funnel's upturned wide end waiting for the fluid.

Up went the glass beaker of uranyl nitrate liquid.

A stream of attractive yellow liquid flowed off the lip of the glass beaker and into the funnel, down the spout and down into the precipitation vessel where the slowly rotating blades blended it into the nearly 40 liters of enriched uranium lying in wait and waiting for life.

The scale of misfortune tipped against them within seconds as the total mass of enriched uranium exceeded the limits defined by the laws of nuclear physics.

Liquid uranyl nitrate foamed up lightly like boiling yellow milk. Intense blue light burst from the precipitation vessel, filling the room in a misty aqua glow. A neutron detector at the Japan Atomic Energy Research Institute a full 2 kilometers away recorded a massive spike in neutron radiation and would continue to do so for the next 20 hours. Nuclear criticality had been achieved.

An intense and strange heat washed over Hisashi. He stumbled back, stunned, and slumped halfway to the ground. Instantly, it seemed, he was nauseated, nauseated like he had never been before. To his side was Masato, looking numb and strangely ill, yet only seconds had passed. The room was blue, yes blue! This was incredible. Nothing made sense. They had been pouring the uranyl nitrate into the precipitation vessel. That was all. Why would there have been a fire? But it didn't seem quite like a fire. The heat was strange. It went straight through him, as if he were invisible. But it had to be a fire. He felt so hot.

His stomach turned. Oh, it was going to happen. He could not stop it. The vomit erupted up from his stomach, out and onto the floor. It came and came again. Then it stopped for a few moments, but the nausea flowed back through him once

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more. This time his stomach turned low and deep and he knew he had lost complete control.

Hisashi could no longer stay on his hands and knees and collapsed further, lying down on the cold floor now, low and prone. But the blood still seemed to drain from his brain and the color from his sight.



The paramedics from the local fire department eventually came (although there was not a fire) and wrapped each of the three men in clear plastic and wheeled them off on gurneys. They were rushed to the National Hospital in Mito in an ambulance, then helicoptered to the National Institute of Radiological Sciences in Chiba Prefecture.

Back at the Tokai Works, efforts to stop the uncontrolled reaction were hampered by lack of information, plans, and preparedness for an event that “was not possible.” The nuclear chain reaction was halted 20 hours later only after a crew crushed the pipes leading from the blanket surrounding the precipitation vessel, thereby draining the water onto the ground outside the conversion building. Removing the reflective water was just enough to bring fissioning to an end. In the end, 436 JCO employees, nearby residents, and workers had been exposed to radiation from the event. Economic losses, including financial costs to regional business and agriculture stigmatized by the accident, eventually exceeded 6 billion yen.



Hisashi Ouchi was subsequently transferred to Tokyo University Hospital on October 2 where he received blood transfusions, large-scale skin transplantation, and hematogenous

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function recovery treatments. His injuries were massive: burns, organ damage, fever, decreased immunocompetence, a high white cell count, respiratory deficiency, and continued disturbance of consciousness. Calculations showed he had received 18 sieverts of penetrating radiation, roughly 9,000 times the typical annual exposure and more than three times the suspected fatal dose. In an effort to restore his lymphatic cells and blood-generating capability, he received stem cells from his brother in a first-ever procedure for radiation victims.

Masato Shinohara, who was in a slightly different position next to the precipitation vessel, received 10 sieverts of penetrating radiation, more than 5,000 times the typical annual exposure and two times the usual fatal dose. A suitable adult donor could not be obtained, so he received a transfusion of blood stem cells drawn from a newborn's umbilical cord. Yutaka, who had been in the next room, received a dose of 3 sieverts.

Hisashi Ouchi died of multiple organ failure on December 21 at Tokyo University Hospital. Masato Shinohara, who initially regained his strength and showed hopeful signs of recovery, died seven months later on April 27 at the Institute of Medical Science, University of Tokyo. Yutaka Yokokawa, shielded by the wall and his distance from the precipitation vessel, survived. JCO's fuel processing license was revoked by the Japanese government on March 29.

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