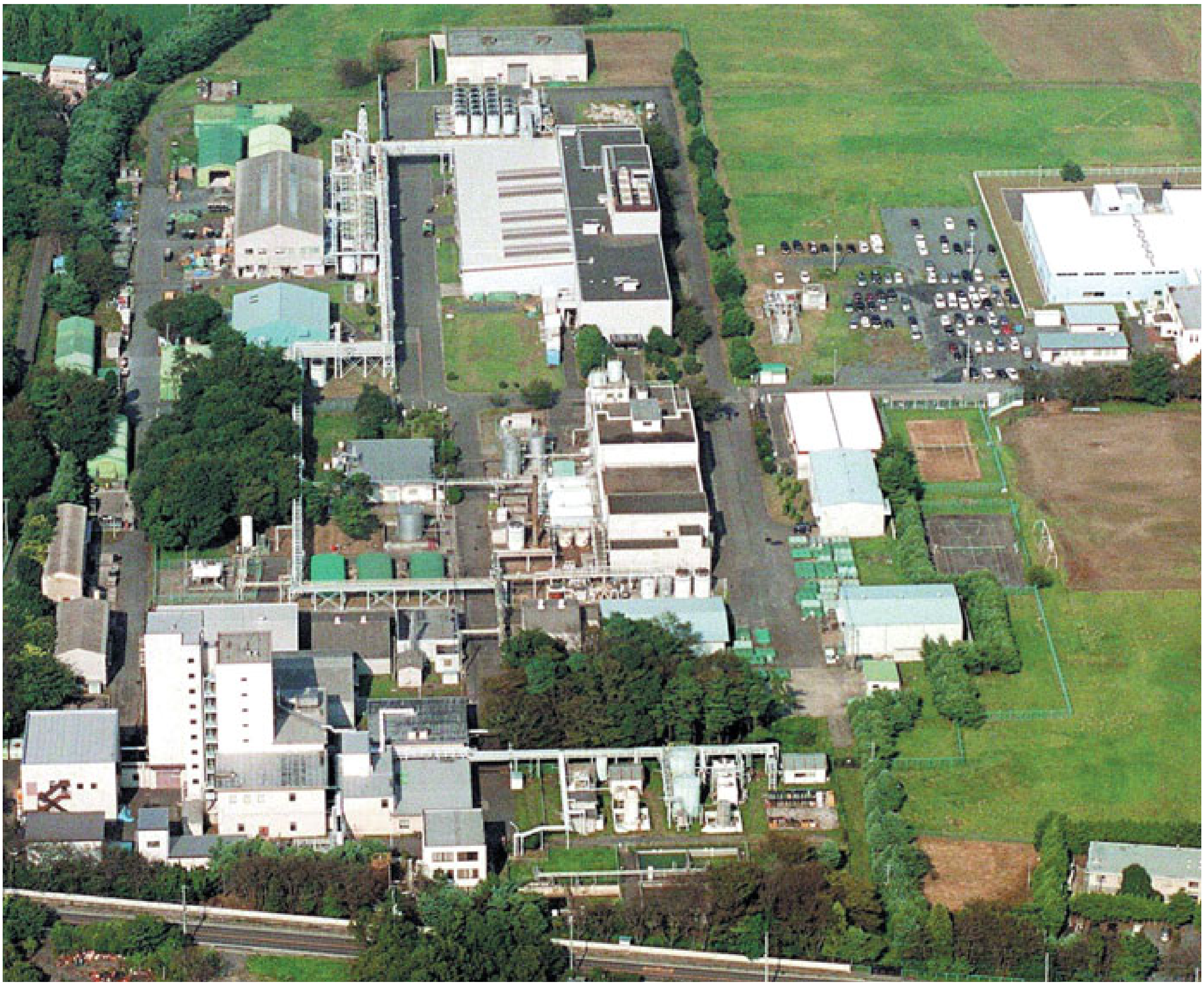
THE TOKAÏ MURA CRITICALITY ACCIDENT

A serious criticality accident occurred on September 30, 1999 in Japan at a nuclear fuel manufacturing facility run by the Japan Nuclear Fuels Conversion Company (JCO) at Tokaï Mura. By reconstructing the circumstances of the accident, its different phases have been characterized and the role played by the human factor has been revealed.



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The Japan Nuclear Fuels Conversion Company (JCO) site at Tokaï Mura, scene of the criticality accident on September 30th 1999.

The accident that occurred on September 30, 1999 in the Japan Nuclear Fuels Conversion Company (JCO) facility, 15 km from the Tokaï Mura site (150 km north-east of Tokyo), was rated a level 4 event on the International Nuclear Events Scale (INES), which goes up to a maximum value of 7[(1)].

(1) The levels on this scale of reference established by the International Atomic Energy Agency go from 1 to 7 (a level 0 anomaly has "no importance from a safety point of view"), with level 7 corresponding to a major accident (Chernobyl). Level 4 corresponds to "an accident with no significant risk outside the site".

The process leading to the accident

The accident occurred during operations to dissolve uranium powder in nitric acid to obtain uranyl nitrate. The uranium was 18.8% enriched in the ^{235}U **isotope**. The process authorized by the Japanese safety authority consisted of dissolving the uranium powder in "safe geometry" equipment, meaning an appliance whose dimensions were such that no criticality accident could occur however much uranium is introduced (see figure 1A). The volume of this equipment was too low, so that not enough uranyl nitrate could be obtained. This meant that several consecutive batches had to be dissolved, resulting in batches with uneven uranium concentration. The operator decided to make three changes to procedures over recent years without referring to the safety authority. The first dated back to 1993. It consisted of dissolving purified uranium in loads of 2.4 kg in buckets instead of in the dissolver and then storing the solutions obtained in safe geometry columns, where they could be homogenized by nitrogen sparging. The second occurred in 1996 and consisted of extending the dissolving of uranium in buckets to include impure uranium. These two modifications were approved by the operator's safety group and listed in the quality assurance manual. The third led to the criticality accident on September 30th 1999. It consisted of replacing the safe geometry columns with a larger diameter precipitation tank, fitted with a mechanical stirrer with the aim of making it easier to homogenize different batches of dissolved material. As this tank was not of safe geometry, to make sure there was no risk of criticality a limit of 2.4 kg was placed on the mass of uranium (figure 1B). In fact, the two operators filled the tank using 7 buckets, each containing 2.4 kg of uranium powder dissolved in nitric acid. While emptying the last bucket, an operator saw a blue flash characteristic of a criticality accident (the **Čerenkov effect**): the tank then contained 16.6 kg of uranium (figure 1C).

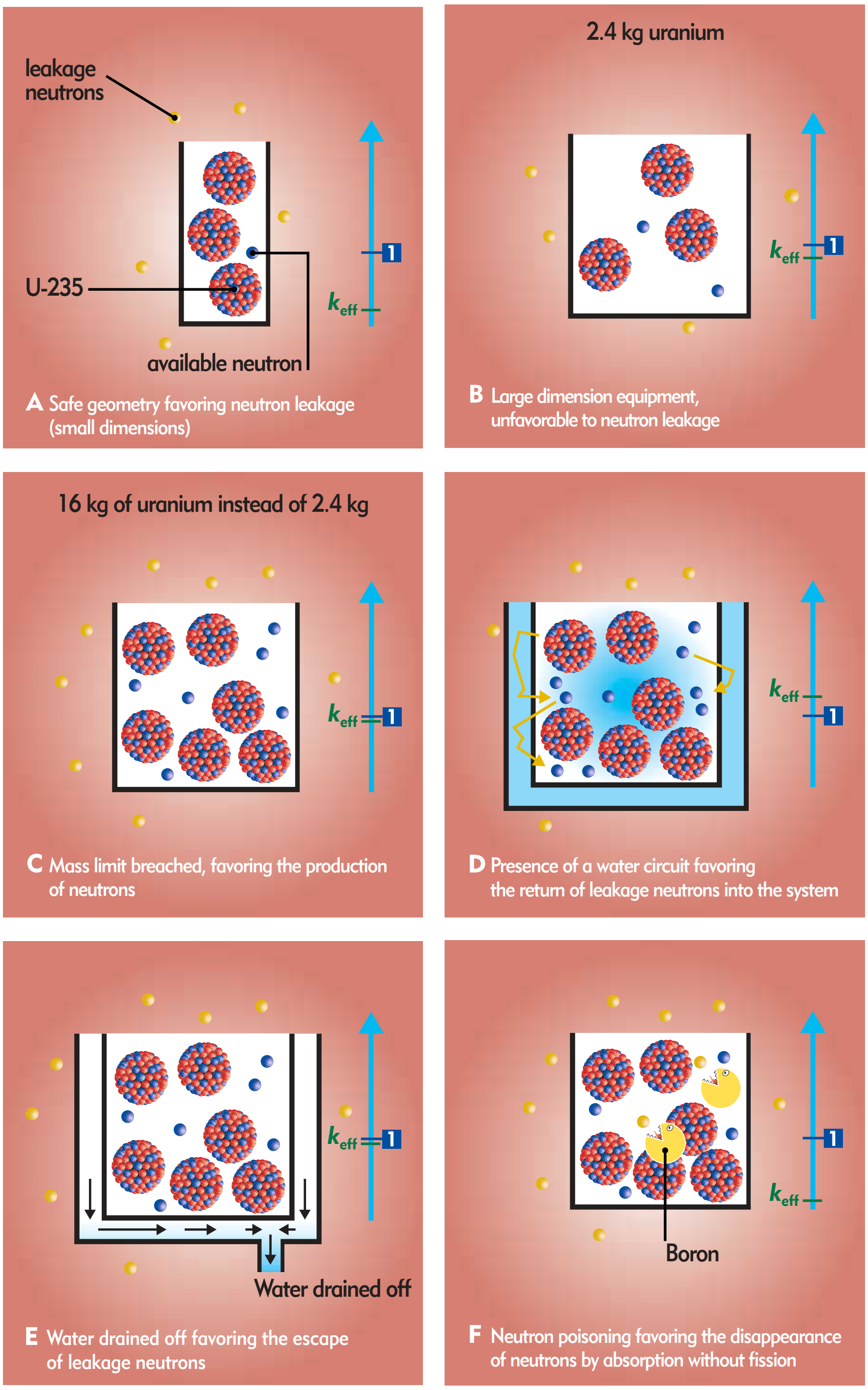

Figure 1. The different fissile medium configurations involved in the 1999 accident. Figure 1A shows the safe geometry equipment with capacity judged to be too small. In figure 1B, the equipment is of large dimensions where the system would remain non-critical if the mass had remained below 2.4 kg. Figures 1C to 1F show how the situation developed, with the k_{eff} value relative to 1 shown on the right hand side.

Several factors

Technically, three factors led to the accident. The first was replacing safe geometry equipment with larger equipment, resulting in a much lower number of **neutrons** able to escape from the equipment and so an increase in the value of the **multiplication factor k_{eff}** (figure 1B). Secondly, the mass limit of 2.4 kg was not complied with in the large dimension equipment.

If this limit had been observed, the operation could have been carried out

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Full scale model of the settler-precipitator produced for the accident enquiry.

without risk of criticality with a large safety margin. As the production of neutrons increases with the number of **fissile** nuclei in the medium (and thus with the mass of fissile material), the presence of 16.6 kg of uranium increased the value of k_{eff} significantly. Finally, the presence of a water cooling circuit (acting as a neutron reflector) brought neutrons which would have escaped in the absence of water back into the fissile medium, so they could also take part in the production of neutrons (figure 1D). The presence of water around the tank increased the value of k_{eff} to over 1. Again, respecting the 2.4 kg mass limit would have enabled the operation to be carried out without risk of criticality (see *The risk of criticality and its prevention* and inset F, ***Criticality accident: a question of neutron balance***).

The accident lasted 20 hours, a characteristic length of time for a criticality accident occurring in solution. The formation of **radiolysis** gas bubbles resulting from the irradiation of water molecules combined with bubbles of steam due to the heat released caused a local reduction in the density of fissile material and thus a drop in k_{eff}. The medium thus returned to a subcritical state, causing the bubbles to disappear. But the

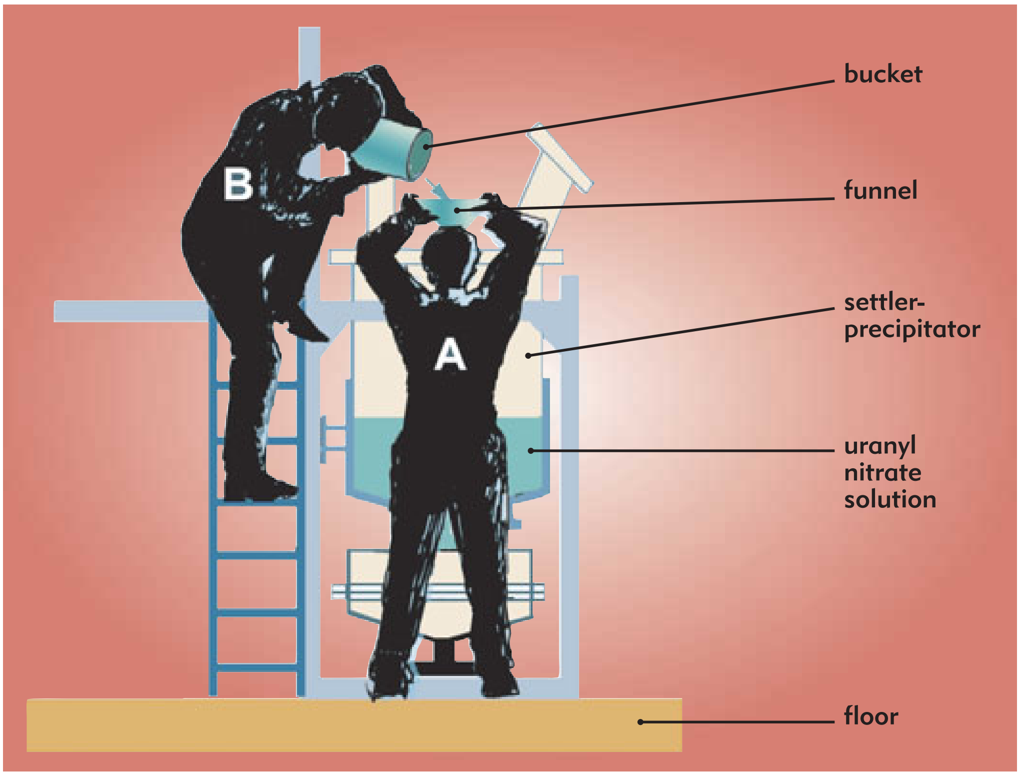

Figure 2. Position of the two most exposed operators relative to the settler-precipitator when the Tokaï Mura accident started.

fission chain reaction could then start up again with the medium returning to supercriticality. In the particular case of Tokaï Mura, the continuous supply of water in the cooling system interfered with the thermal exchanges, preventing the fissile medium from becoming subcritical for long enough to allow any intervention.

The operator then tried to drain the cooling circuit. This attempt failed, so the workers acted to break the pipework, thus stopping the accident (figure 1E). Without water around the tank, the accident would not have happened for 16.6 kg of uranium, but would have required a larger quantity to become critical (see *The risk of criticality and its prevention in nuclear plants and laboratories and during transportation*).

Next, boron, a nuclear poison which absorbs neutrons (see *Control and operation of pressurized water reactors*), was introduced into the tank, reducing the k_{eff} value significantly and definitively (figure 1F). Emergency teams could then get access and place biological barriers (including sandbags) against the walls surrounding the equipment concerned in order to reduce the ambient radiation near to the tank.

The consequences

During the accident, 136 people on the site were irradiated at very variable doses, three of them seriously. Two employees involved in the operations and located next to the tank died, after three and seven months of intensive care respectively. The worse affected of the two (operator A in figure 2) received a dose of 9.1 Sv, almost twice the lethal dose (corresponding to 50% deaths in an irradiated population without special medical treatment, 5 Sv), while the second operator (B) received a dose of 5 Sv. The supervisor, located in an adjoining room, about 5 meters from the tank, received a dose of 1.2 Sv and may in the long term develop cancer. The other 133 people (emergency personnel, operators acting to stop the criticality accident, government advisors) suffered much less severe exposure and most will certainly have no directly observable effect on their health. They received doses estimated at between 0.1 and 50 mSv. An investigation by the operator revealed that about a hundred other people on the site may potentially have received doses estimated at between 0.01 and 21 mSv. In the vicinity of the site, 160 people living within a radius of 350 meters of the building containing the tank were evacuated, while 320,000 others in a radius of 10 km were advised as a precaution to stay at home until the accident was over. Measurements taken in the air, water and on vegetable products only revealed intermittent trace levels of iodine.

The lessons

The organization set up by JCO and approved by the safety authority was not satisfactory. In particular, the company's organization chart had a production department and a technical department in parallel with each other; the technical department included the managers responsible for safety and production quality assurance. The company manual specified that in the case of changes to procedures by the production department, the opinion of the safety and quality assurance managers was only consultative. This consultation, which was optional, was not judged necessary by the production engineer when asked by the supervisor before implementing the change in procedure which led to the accident. Moreover, the instructions to be observed to ensure that no criticality accident could take place were not displayed (in particular the mass limits as a function of the uranium-235 isotope enrichment). There was no criticality expert at the center, nor were regular inspections carried out by the safety authority.

The operators were not aware of the risk of criticality. The supervisor and the operators had many years of experience of operations involving uranium enriched to 5% of ^{235}U, for which the mass limit was 16 kg. The operators had thus transposed their experience to 18.8% enriched uranium without knowing the risks they were running. For the equivalent mass of uranium, the presence of the fissile ^{235}U isotope in greater quantity (4 times as much in this case) increases the value of k_{eff} (because there are more neutrons produced by the greater number of fissile nuclei present causing fission reactions: see figure 1C).

The seriousness of this accident prompted all the safety authorities and operators in all countries using nuclear facilities to undertake a review of current procedures and practices concerning the prevention of risk of criticality. ●

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