Criticality Accident at JCO Uranium Processing Plant

【September 30th, 1999　Tokai, Ibaraki, Japan】

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On September 30th in 1999, a criticality accident occurred at the Tokai Factory of JCO Co. which is a uranium fuel processing facility located in the area where the nuclear energy related facilities gathered in Ibaraki Prefecture. It became the worst accident in the history of nuclear energy in Japan, 150 persons, including three workers, were exposed to radioactive materials, and two of the three workers died.

The accident happened when highly concentrated (U^{235} 18.8%) uranium used for the fast breeder experimental reactor "Joyo" was manufactured temporally using facilities for low concentrated uranium (U^{235} 3-5%). JCO was concentrating uranium fuel, which is a part of the fuel fabrication process. The accident occurred during the equalizing process, in which the equalization of the products of some batches was executed. This process was almost the final stage of JCO operation, it was operated using an illegal procedure throughout the company. According to the statement by a specialist, the direct cause of the accident is that "they injected a uranyl nitrate solution, including uranium that was over critical mass into the precipitation drum that was originally designed for the different purpose and was not designed in the shape that is required for criticality safety".

The critical state continued for several hours without stopping immediately. As it was the first time that a criticality accident occurred in Japan, the Government Countermeasure Headquarters, chaired by Mr. Obuchi who was the Prime Minister at that time, the Accident Countermeasure Headquarters, chaired by the Director General of Science and Technology Agency, and the Government Field Countermeasure Headquarters were organized. The countermeasures for closing the critical state were examined at the Field Countermeasure Headquarters, and it was decided that the water in the precipitation drum jacket that caused the critical state should be drawn off. This is very dangerous work, because it is necessary to approach the precipitation drum in which radiation leaked. Volunteer employees of JCO worked under the threat of death, and the critical state stopped at last after having continued for nearly 20 hours.

The concentration operation was contract work with no profit for the company, and moreover the work was complicated. Therefore, essential safety countermeasures were ignored, and the company allowed too thoughtlessly illegal work methods, which resulted in the occurrence of the accident. The problems were that not only the occurrence of the accident but also a lack of prior preparation for countermeasures in the event of a criticality accident and the fact that a basic part of nuclear energy policy was left in the charge of a private enterprise and concrete operation procedures had not been checked by the government.

A large number of criticality accidents at nuclear fuel facilities have been reported. Many of these criticality accidents happened in the U.S.A. and the former Soviet Union during the initial stage of nuclear energy development in the 1950's to 1960's. A criticality accident at nuclear fuel facilities was supposed to be the accident that human beings had overcome in the past. The impact of the criticality accident that occurred in Japan was very strong as it was generally considered that “Japan is the most advanced nation in atomic energy where nuclear accidents are very few”.

This accident and the leak accident of metal sodium at the prototype fast breeder reactor “Monju” made a difficult state for continuing the nuclear energy policy of Japan as before.

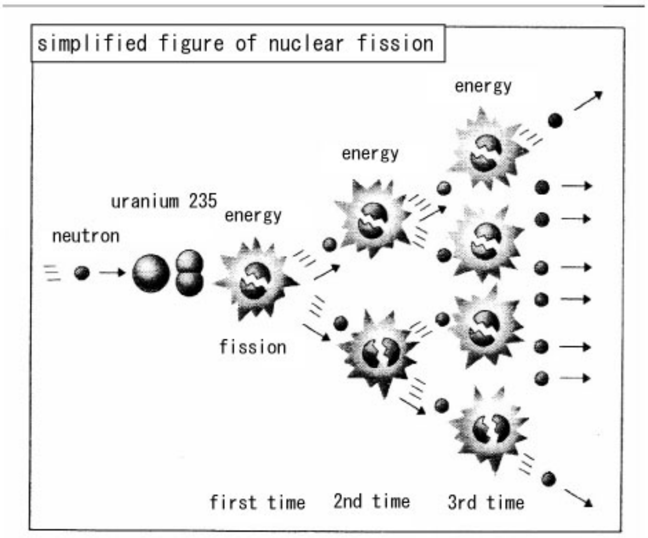

Fig.1 Simplified figure of chain reaction

Although there were some excellent countermeasures such as the order of evacuation of inhabitants living within 350 meters of the facilities by the village leader, the decision to organize the Government Countermeasure Headquarters beyond the sectionalism of each government department, and the actions of the Field Countermeasure Headquarters that accurately instructed the measures to stop the critical state, the overall impression of the countermeasures was a little confused.

The description of this paper will be limited to only technical aspects such as the cause, countermeasures and the background of the accident, and nuclear energy policies, medical cure of the victims, actual conditions of the rumor damage, and so on will not be mentioned.

1. Event

To begin with, the manufacturing of uranium fuel for nuclear energy generation is simply explained. The manufacturing operation consists of three processes. The first process is the conversion process of producing uranium hexafluoride UF_6 gas from uranium raw ore. The next process produces a powder form of triuranium octoxide U_3O_8 from the gas. The final process removes impurities and adjusts the concentration by dissolving triuranium octoxide powder in nitric acid. In JCO, this final process was undertaken. (although some reports indicated that JCO conducted the entire operation from the production of the uranium hexafluoride). The quantity of highly concentrated uranium fuel to be manufactured was small because there was only one user, the experimental reactor Joyo. Therefore the highly concentrated uranium fuel was produced by using the facilities installed in the conversion test building, since it could not be processed in the production facilities designed for producing low concentration uranium fuel.

The processing method is as follows. To begin with, triuranium octoxide is dissolved in nitric acid. Impurities are extracted by the solvent and then separated in the precipitation drum. After that, the solution is made into solid purified triuranium octoxide in the calcination furnace. The solid purified triuranium octoxide is then dissolved again in nitric acid in order to equalize the properties of the product, and it is made into uranyl nitrate containing 18% U^{235}. After mixing and equalizing the product in some batch processes, the product is shipped as a liquid containing 18% of U^{235}. The criticality accident happened during the process of re-melting and equalization.

Like other processes, permission from the Science and Technology Agency is necessary for the facilities and operation methods for this final process. The formal operation working paper is called the "official manual". However, JCO changed facilities and operation methods according to the "JCO company manual" without obtaining permission from the Science and Technology Agency, since the work involved in the re-melting and equalization process took a lot of labor and time.

The production operation in which the accident occurred was a temporary operation that was started several months after the previous run. The production operation for the process of re-melting and equalization was always a temporary work, because the amount of the order for the highly concentrated product was so small. In this operation, the facilities and working methods were changed again because it was still troublesome to carry out the operation even using the re-melting and equalization process in the JCO company manual. The comparison of these three processes is shown in Fig.2.

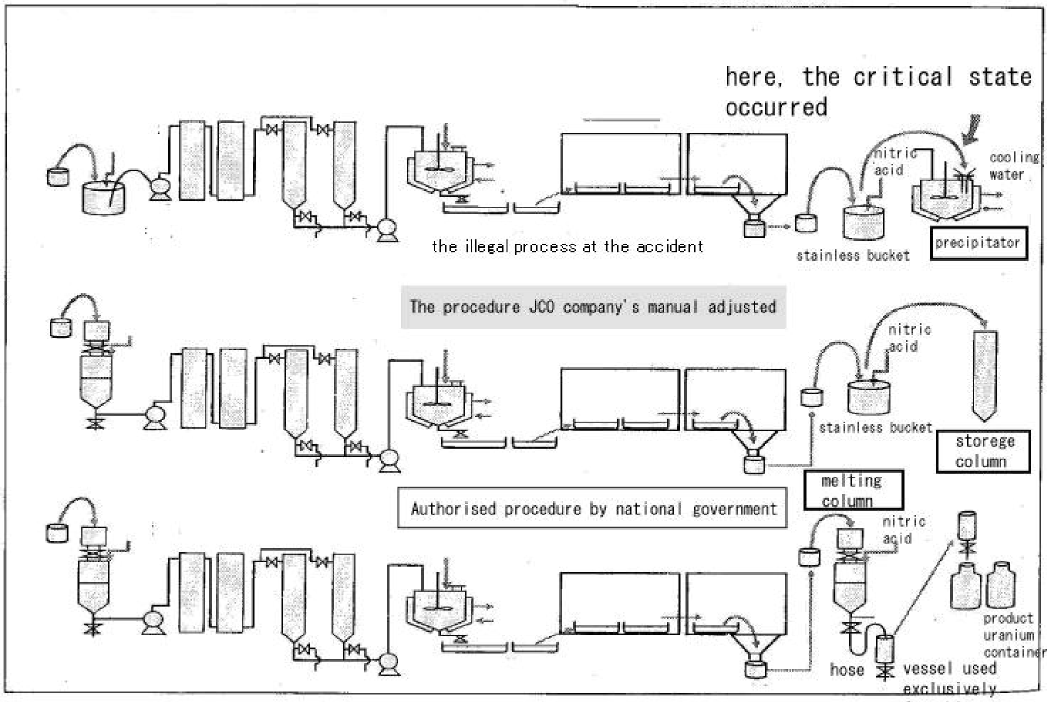

Fig. 2 changes of uranium solution processing

The final process is labeled as the "illegal process at the accident" in the figure. In the official manual, re-melting work is required to be done in the dissolution tower, and the subdivision is required to be done using a specially designed container. In the JCO company manual, the re-melting work was done using stainless steel buckets and the subdivision was done using a normal storage tower. The storage tower was 3. 5m height and 17.8 cm in radius, and the bottom valve used for supplying the liquid to the stainless steel bucket was mounted only 10 cm above the ground. The operation using the storage tower was very difficult. Therefore, in the operation that led to the accident, another change was made to use the stainless steel buckets and the precipitation drum. Even worse, the precipitation drum was attached to a water jacket. The image of the precipitation drum is shown in Fig. 3.

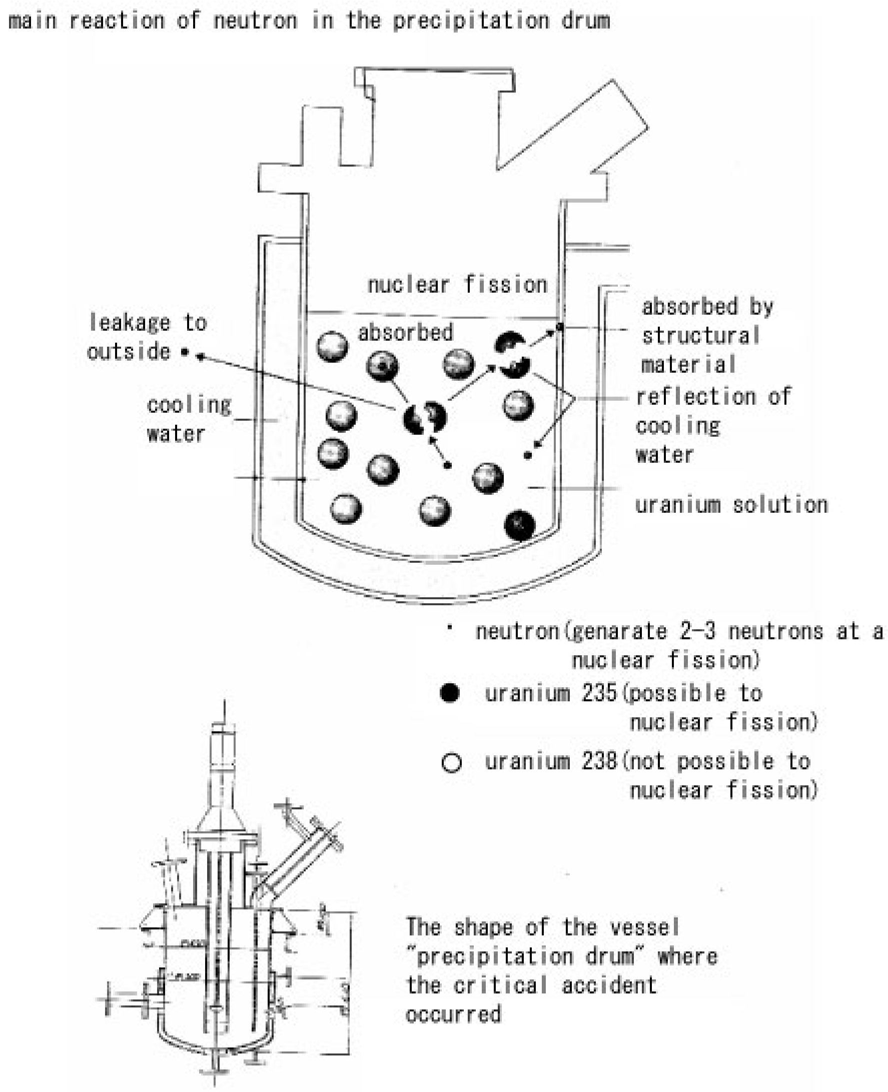

Fig. 3 image figure of the precipitation drum

There were some absurd misunderstandings in the operation. It had been specified that 2.4 kg of uranium should be processed in a single batch from solidification to re-melting in nitric acid. Only for the equalizing operation using the storage tower, the volume treated during equalizing, which had been called "a lot", was seven batches. As it was the first operation to using the precipitation drum for equalizing, the operators requested the permission to mix seven batches from the supervisor. The supervisor consulted with a colleague who had finished the master's course in the nuclear engineering department. As the colleague assured the supervisor that it will be safe, the supervisor permitted the work. However, the colleague had a misunderstanding about the concentration. He thought the concentration was about 5%, the level of the low-concentration product that was generally manufactured, and made his evaluation without doing any confirmation or special calculation. As a result, after several batches of the nitric acid solution were added to the drum, a critical state was caused, and the uranium in the drum started a runaway chain reaction. It was as if a small nuclear reactor suddenly appeared very near the workers. A report described that the accident was like an explosion of a miniature atomic bomb with a large emission of radiation at the beginning of the accident. The critical state continued without stopping, and the radiation kept leaking around the facilities.

After receiving the research results for stopping the critical state from the Government Field Countermeasure Headquarters, JCO decided to organize suicide squads who had to work very near the precipitation drum from which radiation kept leaking. The suicide squads succeeded in drawing off the water from the precipitation drum jacket, and the critical state stopped. The complete end of the critical state was assured by injecting a boric acid solution of a neutron absorber into the precipitation drum. The drawing-off of the jacket water helped the critical state stop because some of the neutrons, which were created by nuclear fission, were rebounded by the water into the precipitation drum and kept the nuclear fission occurring. If the shape of the precipitation drum had been nearer to a circle and if the temperature and/or concentration conditions were more likely to cause a critical state, it would have been necessary for JCO to destroy the precipitation drum itself or inject a boric acid solution into the precipitation drum in order to stop the critical state. These two actions were more dangerous than drawing-off work of the water from the jacket. The water drawing-off was an effective measure, because the rebounding of neutrons occurs even in a water layer of only 2.5cm thick, and when the neutrons return into the drum, the probability of a collision with the atomic nucleus of U^{235} rises.

Besides, radiation kept leaking while the critical state continued. Three operators who were working near the precipitation drum were exposed to a heavy dose of radiation; they had to be hospitalized, and in the end two operators died from the radiation exposure. In addition, employees of the facilities and about 150 neighboring inhabitants were exposed to harmful radiation. The influence to the society was also large. For instance, the inhabitants living within a radius of 350m from the factory were evacuated, and traffic regulation was executed within a radius of 10km.

2. Course

2.1 Course of the critical state and surrounding situation

At JCO, purification work of solid triuranium octoxide started in the middle of September, and it ended on September 28th. The triuranium octoxide was dissolved in nitric acid for purification on September 29th, and the work to produce a uranyl nitrate solution was started. At this time, stainless steel buckets were used instead of the dissolution tower that was specified in the manual.

Equalizing of uranyl nitrate also started on September 29th. Four batches of the uranyl nitrate solution were injected into the precipitation drum. The quantity of uranium in a 6.5 liters batch was 2.4 kg.

On September 30th, three more batches of uranyl nitrate were added into the precipitation drum. At 10:35, a criticality accident happened, and three operators were exposed to radiation. At 10:43, a JCO employee made an emergency call to the fire station and requested an ambulance for patients who showed "the epilepsy symptoms ". When the emergency team arrived at the site, they collected information, as they felt something strange in the surrounding state. Through the collected information, they determined that the patients with epilepsy symptoms had been exposed to radiation.

At 11:19, JCO made the first report to the Science and Technology Agency (the governing agency for nuclear fuel processing at the time) and at 11:22, JCO made the report to the Ibaraki Prefecture. The Tokai Village Office received a facsimile from JCO at 11:34.

The ambulance took the radiation victims to National Mito hospital at 11:49. They were transferred to the National Institute of Radiological Sciences in the Chiba, Prefecture, and they arrived there at 15:23.

At 12:15, the Accident Countermeasure Headquarters was established in Tokai village. At 12:30, the Tokai village headman requested that the nearby inhabitants stay indoors. In addition at 15:00, he decided to evacuate the inhabitants within a 350m radius of the facilities.

At 14:30, the Accident Countermeasure Headquarters was organized in the Science and Technology Agency. At 15:00, the Government Countermeasure Headquarters was organized. At the beginning, the Director General of Science and Technology Agency was its chairman, but later the Prime Minister became the chairman of the Headquarters.

At 22:30, the Governor of Ibaraki Prefecture made a recommendation that the inhabitants within a 10km radius of the facilities stay indoors.

At around 22:30, the Government Field Countermeasure Headquarters decided to draw off the water in the precipitation drum jacket. At 02:35, according to the decision, two persons of JCO started the draw-off work as the first suicide squad. At 06:04 in the following morning, the critical state ceased due to the successful drawing-off of the drum jacket water by the tenth JCO suicide squad, and the criticality stopped.

At 08:39, the injection of a boric acid solution into the precipitation drum finished and the critical state ended at last.

At 16:30, the Governor of Ibaraki Prefecture cancelled the recommendation to stay indoors for inhabitants in a 10 km radius. Afterwards, investigations and health examinations related to radioactive contamination were carried out.

2.2 History of high concentrated uranium fuel processing in JCO

JCO received a license to manufacture powder uranium with a 12% concentration in November 1980, and received permission to manufacture liquid products with a 20% concentration in June 1984. JCO manufactured the liquid products using the permitted manufacturing method until around 1986.

Around 1993, JCO stopped using the dissolution tower for the re-melting process and started to use stainless steel buckets instead. As for the equalizing operation, the first single batch liquid in a stainless steel drum was divided into subdivision containers and the next single batch liquid was also divided into the subdivision containers. The same operation was repeated, and the equalization was performed in such a way. This method was the same as the licensed method.

In the operation around 1995, the storage tower was used for the equalizing process. It seemed that this choice was an attempt to improve the efficiency of work. In the year of 1999 when the accident occurred, JCO began using the precipitation drum instead of the storage tower in the equalizing process. This seemed to be an attempt to further improvement in efficiency.

The course of events surrounding the accident is described in detail in "The blue flash, Tokai criticality accident document" published by Chuou Koron New Company and edited by the Yomiuri Shimbun editorial office.

3. Cause

As described in the outline, the cause is that “they injected a uranyl nitrate solution, including uranium that has over critical mass, into the precipitation drum that was originally designed for a different purpose and was not designed in the shape that is required for criticality safety”. However, this is too ridiculous a reason from the viewpoint of a specialist on nuclear energy.

U^{235} is a radioactive material that generates three or four neutrons when it decays. If more than one of these three or four neutrons causes another U^{235} atom to decay, the number of nuclear decay will increase rapidly in geometric progression. The generated energy becomes enormous, and many neutrons are radiated. This is called a "critical state". If the critical state is controlled, it can be used for nuclear power generation, and if it is not controlled, it can become an atomic bomb or a disaster like Chernobyl or Three Mile Island. These matters are all well understood at least by persons related to the nuclear power industry.

In order to reach the critical state, two conditions are needed. First the number of U^{235} atoms must exceed a certain limit. Second, the probability of a collision of generated neutrons with an atom of U^{235} must be high. Considering that neutrons escape from the surface of the fuel canister, a critical state is hardly generated with a container with a big surface area, in other words a slender container.

Even though it was at the request of the working operators, the accident was triggered by the decision of the manager to change from a slender container to a stumpy container with a small surface area, and to conduct equalizing work with uranyl oxide with critical mass without any confirmation, or calculation, based on the wrong conviction that the concentration of the material was 5%, though actually it was 18%.

Basically, illegal changes were executed by the company, and the constitution of the corporate must be a true cause of the accident.

1) The illegal work change in the company seemed to be the primary cause of the accident. Although the permission of the governing legal authorities was required for any changes concerning the facilities and operation methods considering the danger in handling the nuclear reactor fuel, they changed the operation without any permission. Though JCO recognized this illegality, it had hidden the fact.
2) The final change that led to the accident was the result of the opinion of an engineer who seemed not to have a direct responsible to the operation. He said that it was "maybe safe" without confirmation of the site and without proper calculations. Based on his recommendation, the permission to use the drum was decided by the manager on the lower management level, not the top of the facilities, who did not have a right to decide the change of operation manuals. It is too careless a decision, which must not be made in any industry.
3) There was no consciousness of the possibility of creating a critical state in the whole facilities. It is necessary for the nuclear industry to have the consciousness from the beginning to the end, because a critical state can cause a fatal accident.

Some people say that the proposal from the site must be regarded as important because the improvement from the site is the biggest power in Japanese industries. However, safety must be prior to other items. There must have been both lowering of morals and a decline the safety consciousness.

There are some arguments that the instructions and the supervision of the governing legal authorities are the problems, which cause common use of the facilities and existence of different kinds of facilities in the same building.

4. Process of the cause elucidation

The injuries were of radiation burns, and it was confirmed that the neutron beam had sufficient strength to cause the burns. The causes will be clarified if the working conditions at the accident place are shown by hearing investigation.

5. Immediate action

1) An ambulance carried the three injured persons to an emergency hospital after confirming the radiation damage. After that, they were transported to the National Institute of Radiological Sciences in Chiba City by helicopter.
2) The following regulations were carried out: evacuation of the inhabitants within a 350m radius of the facilities, recommendation for the inhabitants within a 10 km radius to stay indoors, stopping of various kind of local traffic facilities, and changing of the source of water supply.
3) The critical state was stopped by drawing off water from the precipitation drum jacket and by injecting a boric acid solution into the precipitation drum.
4) Decontamination work and so on.

6. Countermeasure

The way to prevent recurrence of the accident is “to operate the manufacturing process according to the prescribed work method at the prescribed facilities”. Since one of the causes of the accident was that the facilities were difficult to run, it is desirable that the facilities be remodeled. However, as nuclear energy is one of the most dangerous technologies in the history of human civilization, the design, the construction, and the operation of the facilities must be executed with most careful attention and established techniques. Not only operators but also engineers and management staff should realize again the basic of the nuclear industry.

“Back to the basis”; this is the only countermeasure to prevent recurrence of the accident. (Other countermeasures, such as countermeasures for inhabitants are were not described here.)

7. Knowledge

1) A thoughtless change of work devices and work methods may cause the danger. Not only at JCO but also at other places, similar thoughtless changes are repeated.
2) Safety confirmation of a work method change just before the accident was done easily by analogy without any confirmation of the situation or calculation. The supervising officer gave permission for the work method change based only on the analogy. Such a thoughtless action must be avoided, not only in the nuclear energy industry that handles enormously dangerous materials but also in all other industries.
3) From the various reports, it appears that JCO did not have the basic minimum level of risk management and of crisis management, which means preparing for the worst case before an accident, taking countermeasures, and after the accident, rapidly transmitting information. It is important to notify the highest-ranking person who is related to the accident without reconfirmation or detailed information, if the accident is predicted to cause serious damage.

8. Influence of the Failure

As for the human damage, three workers were hospitalized for serious radiation damage, and two of them subsequently died. The total number of persons exposed to radiation was 150. Furthermore, the inhabitants within a 350m radius were ordered to evacuate, and the inhabitants within a 10 km radius had to stay indoors.

As for the social influence, just after the accident, traffic was restricted such as the JR train system, the expressways, and other traffic systems within a 10 km radius. Also, facilities such as schools and day care centers were temporarily closed. In the medium term, rumors of radioactive contamination caused sales of Ibaraki-made agricultural products to decrease. Finally, the failure had a major effect on the national nuclear energy policy.

Although the monetary damage to JCO for the compensation for the deaths and the injured as well as for the economic damages caused by rumors was large, losses in both the social status and economic valuation to both JCO and its parent company cannot be measured.

9. On the side

This accident originated from the careless management of a change. There is a change of the situation when something is modified, but this change of the situation was not recognized. Unlike the accident of the bituminized material in the old Power Reactor and Nuclear Fuel Development Corp., this failure was the result of problems that could solve only by the technology of the nuclear industry. Moreover, the accident appears to have occurred as a result of a concession by an unskilled engineer to operators who wanted working methods easier. There is no doubt that proposals from the operators such as " Kaizen (improvement)" or "5S" are one of the sources of the power sources of the Japanese enterprises. However, it must not be forgotten that it is the duty of the engineers and the task for the management supervisors to avoid theoretically dangerous situations and to make improvements in technical studies.

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