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JCO Criticality Accident Termination Operation

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The description focuses on the witness' own behavior, and what he saw and heard, and thus is written from the perspective of action by one individual. This was done simply because it was easier for the witness to write down his memories as he remembers them. Description of the activities of other organizations and people is provided only as necessary, to ensure that consistency in the descriptive approach is not lost. The essentials of this report were rewritten as a third-person objective description in the summary of the report by the Atomic Energy Society of Japan (AESJ).

Since then, comments have been received from sources such as former members of the Nuclear Safety Commission (Dr. Kenji Sumita and Dr. Akira Kanagawa), concerned parties from the former Science and Technology Agency, and reports from the JCO Criticality Accident Investigation Committee of the AESJ, and thus this report was rewritten to correct incorrect information, and add material where that was felt to be necessary.

This year is the tenth year of the JCO criticality accident. To mark this occasion we have decided to translate the record of what occurred at the accident site into English so that more people can draw lessons from this accident.

This report is an English version of JAEA-Technology 2009-073.

Keywords: JCO Criticality Accident, Criticality, Neutron, Exposure

ＪＣＯ臨界事故の終息作業

日本原子力研究開発機構
原子力緊急時支援・研修センター
金盛　正至

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2001 年に、ＪＣＯ臨界事故の臨界事故終息の経緯について、2001 年 12 月 17 日の水戸地裁の証言を基に取り纏めた。同資料は、これらの事故終息に係る作業に関する内容が、今後の原子力防災を考える上で何らかの役に立つものと考え、証言に基づいて整理したものである。

記述した内容は、自らの行動、見聞きした内容が中心となっているので、個人の活動という視点で記述している。これは、単にその方が記憶をそのまま書けるという観点で記述が容易なためにそうしたものである。また、記述の仕方に一貫性がなくなるので、他の機関、人々の活動、等に関する記述については、必要な範囲以外記していない。原子力学会での報告書の取りまとめにあたっては、本報告のエッセンスを客観的記述として取りまとめた。

この間、住田元原子力安全委員、金川元原子力安全委員、旧科学技術庁関係者、原子力学会ＪＣＯ事故調査委員会での報告等でコメントを頂き、不正確であった部分、追加すべきと感じた部分等を追記し再度取りまとめた。

今年は、JCO 臨界事故から十年目にあたり、現場で発生した内容をより多くの方に事故の教訓として汲み取っていただければと思い報告内容を英文化することとした。

本報告書は、JAEA-Technology 2009-073 の英文版である。

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2. Occurrence of the accident

It was a warm, clear day when the JCO criticality accident occurred on September 30, 1999.

Actions of the Japan Nuclear Cycle Development Institute on the day of the accident

At about 12:15 p.m. information was received from Tokaimura that an accident had occurred at JCO. After gathering information on the accident which had occurred at JCO, the Japan Nuclear Cycle Development Institute (referred to below as "JNC") set up an Accident Response Support Headquarters (referred to below as the "JNC Support Headquarters") at its Tokai Works.

At around 12:15, immediately after I (at the time, I was Manager of the Safety Countermeasures

Section) had finished lunch, I was notified that there would be a meeting to set up a JNC Support Headquarters at the Tokai Works because an accident had occurred at JCO, a nuclear power facility in Tokaimura.

The President of JNC was gathering information at JNC Headquarters located adjacent to the Tokai Works, and standing by in preparation for JNC's response. At around 1:30 p.m., the President was instructed by telephone from the Nuclear Energy Bureau of the Science and Technology Agency to cooperate with measures to address the accident. Based on those instructions, the President enlisted the cooperation of other facilities with JNC Support Headquarters at the Tokai Works, and issued instructions for them to provide total support.

I believe it was around 12:30 when I received a phone call from the Site Manager K of JCO. When I picked up the phone, he said, "There's been a radiation accident, and we don't have radiation measurement equipment. Can you bring some over? We're also lacking personnel to do radiometry, so if possible, could you bring over some people who can help us with that?" Personally, I could tell from the content of the conversation that the situation was quite urgent, and I decided to help, but I had to consider whether it would be okay to just rush over and help. That is, this was not an accident at one of our own facilities, and there were many problems involved in providing support for an accident at another organization, such as how to handle it if our workers were exposed to radiation, and how to determine who had the command authority to direct work. I felt that these issues would require a decision at or above the Facility Manager level. I started consultation within our organization, and told the JCO Site Manager that we would have the JNC Support Headquarters in place soon, and to make contact with us formally through that Headquarters. He agreed to do so.

At 12:35, we established the JNC Support Headquarters at the Tokai Works of JNC, and began analysis and investigation of the accident by experts in various fields including criticality accidents, disaster prevention measures, and uranium enrichment. The topics of analysis and investigation were: the accident type and situation, and the best way to respond and provide support going forward.

Later, around 1 p.m., there was a request from the Science and Technology Agency to dispatch experts, provide equipment, and otherwise assist the response effort.

In dispatching experts and providing assistance, there were a number of issues to be considered, such as the rank and role of the people to be dispatched, and how to handle it if they were exposed to radiation. However, since the situation was urgent, it was decided to prioritize emergency action, and, at a minimum, dispatch experts based on requests from the national government to dispatch disaster prevention experts, as stipulated beforehand in laws such as the Disaster Countermeasures Basic Law. At Headquarters, it was decided to dispatch staff including myself and members of the Radiation Control Section. At the time, I was registered as an expert of the Science and Technology Agency.

On the other hand, at around 2:00 p.m., a formal request for assistance including radiometry equipment, and dispatching of experts in radiometry and criticality safety, was received from JCO via the JNC Support Headquarters.

Information sources on the accident at that time included national, prefectural and village authorities, and news reports such as NHK television. NHK news was thought to be providing the most up-to-date information, and at around 13:28, it reported that an accident had occurred at JCO's Tokai Facility, and that it may have been a criticality accident. At the same time, there were also reports that there may have been an explosion, and we could not really determine which information was correct.

(Later, we were notified by the village that the first report from JCO indicated the possibility of a criticality accident.)

The assembled experts in uranium enrichment facilities, criticality accidents and disaster prevention measures were analyzing and investigating the accident in the JNC Support Headquarters at the Tokai Works. At this stage, when we pieced together information obtained from the national, prefectural and village authorities, the dispatched environmental monitoring truck, and news reports, there were two types of information on the accident, i.e., "there was a possibility of criticality" and "there may have been an explosion." Also, gamma ray measurement showed that "radiation continued to be emitted." At the JNC Support Headquarters, we were conducting analysis based on this information by comparing past cases of accidents in uranium facilities and the features of the uranium facilities.

There was information suggesting an explosion accident, and a uranium processing facility such as JCO had established technology to ensure criticality safety. If it were operating normally, the possibility of a criticality accident was extremely low. This was one basis for decision making. Furthermore, speculating based on past accidents at uranium facilities, it was found that although there were criticality accidents involving uranyl nitrate, many reported accidents involved chemical explosions of UF_6. In comparison, there were almost no reports of criticality accidents at uranium facilities. Due to considerations like the above, the opinion of the majority of experts was that a chemical explosion caused by UF_6 was a more likely possibility than a criticality accident.

It was determined that continued measurement of gamma radiation was possible, even in the case where a chemical explosion occurred, depending on the contained amount of radioactive material and how it was scattered by the explosion. In any event, at this stage there was agreement of opinion among the gathered experts that we had to start immediately by checking the radiation situation, and confirming facts such as the situation of chemicals as soon as possible.

We concluded first that environmental monitoring was crucial because it was a form of radiometry which could be measured from the outside without any legal problems, and would also benefit the Local residents. A monitoring car was mobilized from the Health and Safety Division to conduct environmental monitoring at 1:40 p.m.

Based on the results of our investigation and a request from the national government, we decided to dispatch experts to JCO to measure the radiation situation within the JCO site, and ascertain the accident situation.

At about 2:20 p.m., oxygen tank respirators, α ray survey meters, β/γ ray survey meters, and an ionization chamber were loaded into a car, and I and three other Radiation Control staffs of Radiation Control Section No. 2 headed to the accident site as national disaster prevention experts.

3. Ascertaining the situation at the JCO site and evacuating people

We headed to the JCO site by car. Although there was little traffic on Kakeagarisen until we arrived at National Route 6, the road in front of the JCO site is National Route 6, and there was a traffic jam, partly because the Ibaraki Police had established traffic restrictions. The JCO site faces National Route 6, but there were policemen stationed on both sides of the site, and traffic was almost at a standstill. The road from JNC was so slow that stretches which normally took 5 minutes by car took 30 minutes. Therefore, we decided to take a roundabout route along the prefectural highway, turning left on the near side of the JCO site, to see if we could get in on the side of the site. In the end, we were not able to enter the site from the side. However, during this time, we made a full clockwise circuit around the JCO site, and measured the radiation dose due to gamma rays at a number of points. On the side of the prefectural highway, no cars were passing through due to traffic restrictions, but at points where the dose was high, the gamma ray reading was 0.6 mSv. We decided to enter the JCO site by going South on National Route 6 again.

When we arrived at the JCO site after 2:30 p.m., the area around the site was packed with police and news media etc. We completed the procedures to enter the area, entered the site, and when we reached the Administrative Building, there was tremendous confusion. There were over 100 staff and other people inside including women (123 people according to JCO documents) who were unable to evacuate from the facility and did not know what to do.

At the Administrative Building on the JCO site, we confirmed the current status of the accident with the JCO staff there, but at that time the situation at the accident site (the type of accident, current situation) was unknown, and although the gamma dose at that location was known, the situation of other radiation such as neutrons was unknown, and there was almost no overall understanding of the current situation of the accident, including the contamination situation due to other radioactivity. Thus we decided to first measure the radiation situation in and around the Administrative Building. I myself conducted measurements, and I also instructed the Radiation Control staff which accompanied me to conduct measurements.

Shortly thereafter, a second team of Radiation Control staff for conducting radiation control arrived from JNC (thus making a total of 11 staff, including these dispatched staff).

4. Meeting with Site Manager K

Next we went to a room on the first floor of the Administrative Building, and there was a gathering of JCO staff. I quickly approached Site Manager K of JCO (about 15:00) and first asked him to explain the situation of the accident, insofar as he understood. We asked about drawings of the location where the accident occurred, but were informed that there were no appropriate maps. At that point, the Site Manager and other involved parties explained the tank shape, pipe connection situation and other relevant points, and we prepared a drawing by hand. The drawing is shown in Fig.1 (about 15:00).

Instructions were given (about 15:00-15:30) to immediately convey this drawing and the information gleaned from the interview (orally over the phone) to the JNC Support Headquarters, national/Local governments. We felt that it was impossible to deny the possibility that criticality was continuing. It was requested that all information be communicated via the JCO Accident Response Headquarters.

According to the explanation of the Site Manager and others, it was highly likely, judging from the work situation on that day, that the accident occurred in a tank called a precipitation tank. He said that, although only one batch (approx. 2 kg) of uranyl nitrate (chemical systems had not been checked with the Site Manager (about 15:40) and thus were not included in drawings at the beginning stage) was originally supposed to be added, a few batches might have been added. Since the numerical value of the added amount (2 kg, 16 kgU) had not be confirmed at this stage, the Site Manager was requested to confirm this, and it was written into the drawing later. It was explained that a criticality accident may have occurred due to this uranyl nitrate. However, it was unknown whether it really was a criticality accident, or whether the criticality accident was continuing if it indeed was one. At this stage, it was decided to ascertain the general shape of the sedimentation tank. The only points revealed by the explanation were that the tank had a diameter of about 50 cm, a height of about 60 cm, a jacket for circulating cooling water on the outside, and there was a possibility that the cooling water in the jacket was acting as a neutron reflector. (See Fig.1.)

At this time, in speaking with the Site Manager, although it was unknown whether or not the criticality accident was continuing, gamma radiation has high, and thus it was felt that some countermeasures needed to be taken, but it was impossible to investigate such countermeasures. Thus we communicated our thinking that it was necessary to assemble the involved technicians and begin investigation. More specifically, the Site Manager was asked to confirm facts relating to the following points in order to ascertain the criticality situation and investigate countermeasures for termination if the criticality accident was indeed continuing. The first point was to verify the existence of pipe connected to the sedimentation tank, and thereby confirm whether there was a method of draining the cooling water from the outside. The second was whether the ammonia line and air supply line (which were said to be the only pipes available) were usable. The third point was, whether the chemical form of uranium in the precipitation tank (it had not been confirmed with the Site Manager at about 15:40) was indeed uranyl nitrate. It was found that the air supply line could not be used unless it was operated from inside the Conversion Test Building. The ammonia line was supplied from the outside, but the line contained an integrating flowmeter, manual valve and electromagnetic valve. To open this electromagnetic valve, it would be necessary to enter the Conversion Test Building and press the valve switch, and this would be dangerous as described above.

Since more detailed investigation would likely be necessary going forward, we asked the Site Manager to prepare detailed drawings and information on the relevant parts. (About 15:30)(Fig.2)

The Site Manager said that detailed drawings and other documentation on the process could not be obtained without approaching the Conversion Test Building. Also, the process diagrams (process flow diagrams) which were found either were not the latest drawings, or there was a possibility that changes had been made at the construction stage. Therefore, it was pointed out that the actual pipe might not actually be as indicated in the drawings. On the other hand, opinions were exchanged regarding approaches such as supplying a neutron absorber (using the ammonia line), and those results were written into the drawing.

When Fig. 1 was first drawn, the weight of uranium in the precipitation tank was unknown, so that was left blank, and filled in later by asking the Site Manager (my memory is not clear about the stage when that occurred). I believe that around this time it was decided that the chemical form of the uranium in the sedimentation tank could be confidently identified as uranyl nitrate.

Two conceivable countermeasures for the accident were written into the drawing: draining cooling water which might be acting as a neutron reflector, and using the ammonia line to supply water containing a neutron absorber into the tank.

The report of the Accident Investigation Committee indicates that this fax arrived at outside organizations at around 5:00 p.m., and it is contained in the fax received by the Japan Atomic Energy Research Institute (JAERI) (about 18:17). It required a considerable amount of time after requesting that the information be sent until the information actually arrived. There was a feeling that this was unavoidable considering the situation at the time in terms of action and communication of information by the JCO Accident Response Headquarters, but I feel this is an important point requiring reflection for the future.

At this stage, we felt it was necessary to more accurately grasp what was actually happening at the current moment. However, at this time, we were unable to gather any more information likely to be usable regarding the sedimentation tank and the systems including that tank.

There were also problems in the JCO Accident Response Headquarters' system for communicating information to the national and Local government and other involved parties. It was decided to centralize information in the JCO Accident Response Headquarters, and then communicate it from the JCO to the outside, but I felt it would be difficult to improve the confused situation at this stage, with inquiries coming from the outside, and conflicting instructions being made to the inside and so on.

To investigate how to conduct radiometry going forward, we checked the information on radiation meters and similar equipment possessed by JCO. Perhaps because it was thought that a criticality accident would never occur, we found that JCO only had limited equipment for measuring gamma rays, and no equipment at all for measuring alpha rays and neutrons. There were two or three staff from the Radiation Control Section who could do the measurement and were on site, and members of the JCO Radiation Control Section had ascertained the radiation situation by conducting measurement twice (once an hour) only for the gamma dose rate at fixed points.(Fig.3)

To ascertain the radioactive situation, it was necessary to measure the radiation dose rate, radioactive material in the air, and surface contamination density.

Therefore, it was decided to have JNC's Radiation Control Section staff investigate and improve the gamma measurement locations and methods to better ascertain effects on Local residents. They were also instructed to continue periodic measurements together with JCO's Radiation Control Section staff going forward, and to loan measurement equipment and other resources which had been brought in. Fig.4 shows the results of the first measurements after arrival.

5. Issues relating to accident countermeasures

Issues relating to accident countermeasures at this stage were:

・Ascertaining facts such as the accident situation and the radiation situation

・Investigating possibilities for termination of the criticality accident

・Issuing information for the evacuation of residents in the area of the site

・Ascertaining bodily contamination and investigating evacuation for the over 100 employees and other people, including women, still on the site

At this stage, my thinking on each of these issues was as follows.

Ascertaining facts: Although speaking with involved parties suggested there were limits on understanding the accident situation, two points were crucial: continuing efforts to understand the accident, and ascertaining the radiation situation because that was one type of information which could currently be collected. Accurately ascertaining the strength and variation of radiation could lead to an accurate understanding of the situation of the critical accident, and would be the foundation of work going forward.

Terminating the criticality accident: This was an issue to be dealt with promptly after clearly ascertaining the current situation of the accident.

Evacuating residents in the area of the site: It was crucial to ascertain and communicate the most accurate possible radioactivity information to the national, prefectural and village authorities.

Evacuating people on the site: Another issue which was felt to be important was that more than 100 employees and other people, including women, were present on the site, and thus there was a need to take urgent measures to evacuate those people, particularly women, who would not be involved in termination of the accident going forward.

6. Formulation of a specific work plan

The Site Manager K was asked about his thoughts on how to address these issues to be resolved, but he did not have a clear approach. Therefore, I explained my thinking as indicated above on these four issues, and proposed specific actions such as checking the bodily contamination of each person, and carrying out an evacuation. In response, the Site Manager said that he wanted us to proceed in the direction I had proposed.

After this, it looked like the Site Manager would be busy responding to messages and press coming in from the outside, and dealing with other outside parties. Therefore, to conduct work more efficiently, I asked the Site Manager to recommend people to be the technical liaison on the JCO side. As a result, he recommended three engineers (referred to below as "JCO Engineers").

The Site Manager said that any further technical discussions should be directed to the JCO Engineers.

When I had finished consulting with the JCO Engineers, based on the arrangements with the Site Manager, they said "Why don't you discuss these matters with the Operation Control Expert Officer (referred to below as the "Expert Officer") of the Science and Technology Agency?"

I myself was in the position of having been dispatched as a national disaster prevention expert, but as the JCO Engineers said, I felt there was a need to consult with the Expert Officer of the Science and Technology Agency regarding the technical measures to be taken, and when I showed materials such as the radiometry plan to the Expert Officer, and discussed the response going forward, the Expert Officer said "You are the expert in the technology, so please proceed as you have suggested. Report to us appropriately about what you are doing." After this, we acted according to an arrangement where we formulated a plan, and then reported to the Expert Officer at the implementation stage.

7. Radiometry situation

In any case, γ ray measurements with the ionization chamber showed radiation at this time to be about 30-50 μSv/h. Also, Team Leader M conducted measurement of beta and gamma rays in order to measure surface contamination, but because the level of gamma rays was high in the surrounding area, the reading was off the normal scale, and bodily contamination could not be measured under these conditions. Furthermore, when alpha rays were surveyed, there was a count of 200-300 dpm on the surface and in the air. It was thought that this could not be because the surface density was high, but smear sampling was conducted.

It was decided to sample dust in the air at the JCO site, and measure the radioactivity of dust filter paper in the environment. The radioactivity control staff of JNC was extremely worried about whether or not there was radioactive material in the air on the JCO site. This was because, at the stage when we first left JNC, there was a possibility that radioactive material had been scattered by an explosion, and that, due to the effects of that, the alpha ray survey meter was reacting at all locations in the air. If that were assumed to be the case, there was a need to immediately wear respiratory protection masks, but none of the people on the site were wearing masks.

When we looked for locations within the site where measurement could be done, i.e., locations enabling shielding against neutrons and other radiation, we found that there was a ^{60}Co irradiation facility, and decided to conduct measurement at this facility. When it came time to do the measurements, however, we found that, due to the effects of radiation caused by the criticality accident, an interlock was engaged from the inside so that doors would not open, and we could not enter the facility.

Therefore, it was decided to transport smears and dust filter paper to JNC, and conduct measurement and evaluation there (request made at about 15:59; arrived at JNC about 17:25). Measurements showed that radioactive concentration in air, and surface contamination density were at normal levels (about 20:11).

It was also found that surveying JCO employees and other people would have to be done away from the site.

8. Measurement of neutron radiation

Based on previous experience, it was conjectured that the radiation situation of alpha rays and beta/gamma rays in the JCO Administrative Building could be explained by either all of the air being contaminated with alpha rays and beta/gamma rays, or by the formation neutron radiation fields over a wide range. Therefore, we again measured the situation of alpha rays and beta/gamma rays.

The results showed that the alpha ray count was distributed almost uniformly at all locations, including in the air. In this regard, Team Leader M reported that they had found, in previous experience at the plutonium fuel facility of JNC, that contamination in the air exhibited a random count, and thus it was difficult to regard it as in-air contamination, and furthermore that measurement equipment for alpha rays was also sensitive to neutron radiation. It was determined from the state of the alpha ray count that it was more probable that the critical state was continuing and neutrons were being emitted. In order to measure neutron radiation, we requested the JNC Support Headquarters to immediately bring a Rem counter for measuring neutron radiation, and a 3-He neutron spectrometer (about 15:30).

The Rem counter arrived at about 4:30 p.m., and neutron radiation was measured in the Administrative Building. The value on the first floor was 200 μSv/h, and the value on the second floor was 600 μSv/h. The 3-He neutron spectrometer did not arrive.

After that, it was decided that it was crucial to measure the neutron dose at the site boundary in order to confirm the appropriateness of evacuating the national Expert Officer and Environmental Protection Section Manager H from the village who were at the site, and local residents. Therefore staff member K of Radiation Control Section No. 2 was instructed to conduct measurement with the guidance of JCO employees. The measurement results confirmed a value of 4 mSv/h at 17:05 at a location on the prefectural highway side. This was direct evidence indicating that the criticality accident was continuing, and it was the first neutron radiation measurement for determining the appropriateness of the area inhabited by residents. (Fig.5)

9. Ascertaining dose in the surrounding environment

The result of measuring neutron radiation was 4 mSv/h at a location on the prefectural highway side, and this was crucial data for determining matters such as the evacuation plan for the area inhabited by local residents. Therefore, the Expert Officer at the site was notified and he gave instructions to issue data to relevant parties via the JCO Accident Response Headquarters, and notified Environmental Protection Section Manager H from the village who was at the site.

After that, the most important issue for ascertaining the dose to residents in the area was ascertaining the dose in the surrounding environment, and thus it was decided to continue periodic measurements at fixed points.

10. Evacuation from within the site of JCO employees etc.(about 18:30)

There were a large number of people, including women, still within the JCO site, and therefore to reduce their radiation exposure and evacuate them from the JCO site, it was decided to measure the contamination of JCO employees and other people. However, as described above, even though we searched for a location within the site where measurement could be done, i.e., a location enabling shielding against neutrons and other radiation, no suitable location was found. At the ^{60}Co irradiation facility, an interlock was engaged on the door from the inside, and it was impossible to enter the facility. Therefore, bodily contamination measurement could not be done within the site, and thus when we confirmed with Site Manager K the plan of leaving a minimal security staff within the JCO site, and evacuating everyone else to the outside, he replied "Yes, please do that." Therefore Environmental Protection Section Manager H of Tokaimura (Tokai village) was asked to arrange a location with low radiation dose capable of accommodating about 200 people. As a result, it was decided to evacuate all employees and other people to the Ishigami Community Center. (At this stage, it was not possible to use the Funaishikawa Community Center because it was the evacuation point for residents in the area of JCO.)

For the evacuation, we had to arrange vehicles for transport. First, we investigated the method of evacuating everyone in the cars of the employees and so on, but it was pointed out that the cars were located in a parking lot in the direction of the Conversion Test Building and going in the direction of the parking lot was a bad idea from the standpoint of exposure control. Therefore it was decided to arrange a bus. When we started looking under the assumption that the employees and others might be contaminated, one idea that arose was a bus from a nuclear power related organization in Tokaimura, but when that was investigated, it was found that those buses had dedicated uses at each organization, and could not be used at that time. Therefore, although the JNC had already provided a bus to the village, there was no other way than to use the JNC's spare bus. A request was made to the JNC Support Headquarters to cover the inside of a bus with vinyl sheet to prevent contamination, and send it to the accident site. Covering with vinyl sheet took a little more than an hour. We waited for the arrival of this bus, left the security staff needed to ensure safety of the JCO site, loaded the bus with women first, and transported 69 people to the Ishigami Community Center. (I have a vague memory, which I'm not sure about, that there were some ordinary employees who had to return home no matter what. It may have been that they were surveyed and if the reading was not greater than the background level, it was decided to let them go home.)

11. Ishigami Community Center (about 19:30)

At the Ishigami Community Center, there was a possibility of contaminating the area around the center. Therefore, prior to moving everyone, we decided to go investigate the Ishigami Community Center, and establish a zone for controlling contamination. At this stage, it turned to night, and became dark outdoors. The rain had begun to fall.

At the Ishigami Community Center, it was decided to establish a zone covered with vinyl sheet in front of the entrance to the building, and to survey the employees and other people as they entered.

During the survey a situation arose where the background varied due to the effects of a radioactive cloud, but the JNC's Radiation Control Section staff surveyed everyone. For persons who exhibited no abnormalities in the survey, it was decided to have them wait for the time being in the Ishigami Community Center.

This survey discovered seven people who had contamination of their clothing etc. It was decided to measure their WBC in order to check for any internal exposure. When the involved organizations in the village were sounded out about the possibility of accepting WBC measurement, the organizations replied that they could not, and thus, at this stage, we conducted WBC measurement by sending these people to the Tokai Works of JNC where preparations had been made to accept them for WBC measurement. (About 20:00)

Results showed that the bodily contamination was short-lived decay products of noble gas components, and WBC measurement was performed after conducting decontamination of the body etc. When these people were sent out for WBC measurement, it was not thought that Na24 would be confirmed, but the results confirmed Na24 for all seven people. A later survey also confirmed Na24 from 33 employees of JCO. This suggests that, when there is a criticality accident like this, bodily contamination measurement may be a good method of screening for high dose exposure.

More specific investigation for terminating the criticality accident was also begun at the Ishigami Community Center, focusing on measures to terminate the criticality investigated at the JCO site together with employees of JCO, such as the method of draining water, or supplying a neutron absorber (using the ammonia line). Therefore, it was decided through discussion with the Center's Manager to use the first floor of the Ishigami Community Center as a waiting area, and to use the second floor as a conference room for investigating measures to terminate the criticality accident.

First, in order to investigate the procedure for water drainage work, we confirmed the drawings which had been gathered so far, such as process diagrams, pipe installation drawings and building drawings. We gathered two or three drawings of those we could obtain, and investigated them. However, because the drawings might not be the most recent drawings, and there was a high probability that the actual work deviated from the drawings in the construction stage, it was pointed out by the staff of JCO during the investigation that there was a possibility that actual piping might not follow the pipe drawings. It was also found that the part from which water was released would differ depending on whether or not the pump circulating cooling water of the cooling water jacket was operating or not. Therefore, it was thought that, in order to conduct a more detailed investigation, there was no other way than to check the actual site.

12. Off Site Government Accident Response Headquarters (about 20:30)

When we were reviewing the process diagrams and other documents with JCO Engineers in the Ishigami Community Center, there was a request by mobile phone from the senior staff Y of the Science and Technology Agency to come and provide the latest information regarding the accident to the Off Site Government Accident Response Headquarters (referred to below as the "Off Site Government Headquarters") set up at the Tokai Research Establishment of JAERI, and participate in the discussion of accident countermeasures. Therefore, I headed off to the Off Site Government Headquarters together with the JCO Engineers and other involved parties. (About 20:30)

Although there had been inquiries and requests for notification regarding the facts by mobile phone from The senior staff Y prior to this, we could not respond because the situation was such that we had to prioritize the on-site response.

Gathered at the Off Site Government Headquarters were The senior staff Y and other involved persons from the Science and Technology Agency, Director (who arrived about 15:10) and other involved persons from JAERI, and Deputy Director K of JNC and his relevant subordinates.

Later, Parliamentary Vice-Minister Inaba (arrived 19:50), and Nuclear Safety Commission members Sumita and Kanagawa (arrived 21:40) arrived, and there was an explanation regarding matters such as the respective roles of the Off Site Government Headquarters and the Nuclear Safety Commission. (Parliamentary Vice-Minister Inaba: Director of the Off Site Government Headquarters, Nuclear Safety Commission member Sumita: Deputy Director of the Off Site Government Headquarters)

They were investigating methods of terminating the accident at the Off Site Government Headquarters too. I was not there prior to that, so I will let someone else discuss the detailed nature of that investigation.

It was necessary to share information regarding the current situation at JCO among the members of the Off Site Government Headquarters. Therefore, Site Manager K and others explained matters such as the situation of the sedimentation tank at JCO, insofar as they understood it at that time. I reported on the radiation situation at the site, explained that the radiation dose rate was high and that this posed considerable difficulties for work to terminate the accident, and notified them that there was a need to gather more exact radiation data for work, and formulate a work plan suited to the site. There was also a need to continue investigating the feasibility and appropriateness of water drainage and supplying a neutron absorber. Therefore information was shared regarding the content of the investigations at the JCO site and the Ishigami Community Center. Mr. H and others explained the piping situation at the site in particular, insofar as they understood it at this stage. Although there was a possibility of draining water by opening a valve in pipe outside of the Conversion Test Building, there was also a possibility that it would not open easily. Thus, in the end, an understanding was reached that confirmation would have to be done on site.

At this stage, there were a few points which still could not be confirmed. The most important points were the amounts of uranium and liquid in the sedimentation tank.

This was because, at this stage, the critical mass had been calculated from the amount of uranium estimated to have been loaded, and the shape of the sedimentation tank. Calculations by JAERI yielded a value of keff=1.01 indicating conditions at or above the critical point, and even when the water reflection effect due to the water jacket around the sedimentation tank was eliminated, i.e., even assuming the water were drained, the value would be keff=1.004. Committee members stated that there was a 4% difference between the cases with and without water, and that draining water could be expected to have an effect. The results of rough calculations by JNC showed that draining water would reduce keff=1.008 to keff=0.988 and the criticality would terminate. It was decided to proceed with the investigation assuming the JAERI calculation to be correct. These calculation results gave us the impression that there was a 50-50 chance that draining water could terminate the criticality. It was crucial to improve the precision of this calculation, and gain a more accurate understanding of the amount of uranium in order to investigate how to carry out criticality termination work with a lower exposure dose.

In order to gain an accurate understanding of the amount of uranium and other factors, the Senior staff made a phone call to the National Institute of Radiological Sciences, and while discussing the items to be asked in a separate room, a JCO worker with little exposure (Mr. Y) was interviewed. We first confirmed an estimate of the amount of uranium added in the work procedure and other relevant facts. As a result, two points were confirmed: that uranium was added to the sedimentation tank with the aim of mixing, and that uranium solution was placed a few times into 5-liter beakers, and when adding the last beaker of the 40 liters was finished, he saw a blue light. He said that at the final stage of the final batch, the solution went critical, and almost no solution was added after that. Thus it was also possible to take the hopeful view that the supercritical amount was comparatively small. Other information important for the upcoming work was also confirmed, such as that the hand hole was covered with a funnel, that all valves in the ammonia line were closed, and that it was unclear whether or not cooling water was circulating. (Fig.6)

At the Off Site Government Headquarters, opinions were agreed that the highest priority issue was terminating the criticality. To terminate the criticality accident while avoiding excessive exposure, it was decided that we should first drain water, and if the accident still did not terminate, then a boric acid solution should be added.

Taking into account issues such as procuring the boric acid solution and the possibility of work in the Conversion Test Building, we decided to prepare a shield and that JAERI would prepare the neutron shield.

It was decided that since it was impossible to do any more specific planning at the Off Site Government Headquarters, a more specific execution plan would be formulated and implemented at the site. Therefore, I returned to the JCO site with the JCO Engineers.

13. Criticality termination work at the JCO site

13.1 Investigation of work process

I returned to the JCO site at about 10:30 p.m., and resumed work to formulate a plan for draining water together with the JCO Engineers. To do this planning, we needed to know the purpose of work, the dose at the location where work would be performed, the number of workers who could participate in the work, the nature of the protective gear and detailed work procedures.

13.2 Purpose of work

The purpose of the work was to drain water from the cooling jacket containing cooling water which was wrapped around the precipitation tank, eliminate the reflector effect, and thereby make the criticality terminate.

In addition, a neutron absorbing boron solution would be added in case water could not be drained, or to ensure the effectiveness of draining water.

The above were our two goals.

13.3 Work steps

At this stage, we were thinking of conducting the work in the following five stages:

1. Taking Polaroid photographs
2. Valve operation
3. Pipe cutting
4. Hose connection
5. Injection of argon gas

In carrying out each stage of this work, there were closely related items which were investigated at each step, such as investigating specific work procedures, checking the radiation situation at the site, securing workers, investigating protective gear, and consideration of shielding countermeasures.

13.4 Investigation of specific work procedures

In order to investigate the specific procedures for water drainage work, we reconfirmed the drawings which had been collected so far, such as the related process diagrams, pipe installation drawings and building drawings. However, no more drawings could be obtained other than the 2 or 3 confirmed at the Ishigami Community Center. These were not believed to be the most recent drawings, and it was likely that the actual construction deviated from the drawings at the construction stage. Thus it was decided to develop the procedure by assuming that the actual pipe did not necessarily follow the pipe drawings.

In order to confirm the piping at the site, there was no other way than to take Polaroid photographs, and bring them back for review. There was also a need to estimate in a short time the exposure dose received when working around the accident site. Therefore, it was decided to conduct Polaroid photography by approaching from the outside of the Conversion Test Building near the sedimentation tank, and at the same time ascertain the dose during actual work by setting alarms to a dose low enough to ensure a margin of safety. We created a schematic chart of the work procedure to be carried out. (Fig. 7)

This chart was prepared through interviews, where we asked about the situation around the cooling tower which was to act as the work location, the situation of things with potential to function as shielding such as water tanks, other obstructions, and the lighting situation.

First, we reinvestigated whether there was any method enabling water drainage by remote control from outside the Conversion Test Building, but this was found to be impossible.

It was found that there was a possibility of working on pipe from the outside at this cooling tower. There were cocks, and a possibility that water could be drained if the appropriate cock was released.

When the work location and work method were investigated, it was determined that the minimum distance was 2 or 3 m from the sedimentation tank.

We began investigating other approaches to criticality termination more specifically, e.g., supplying neutron absorber (using the ammonia line).

We also found that water would drain from different parts of valves and so on, depending on whether or not the pump was on and circulating cooling water in the cooling water jacket. Therefore, there was thought to be no other way besides checking the actual site to investigate in more detail.

13.5 Securing workers

When the number of employees who could be secured was checked with the JCO Engineers, it was found that there were no other employees on the day of the accident except for the workers conducting work with the sedimentation tank who were taken to the hospital, and thus it was decided to search for other workers who could do the work. The workers conducting work with the sedimentation tank belonged to a different shift and thus about two of them were at home at this time, and it was necessary to search over a broader scope. Therefore, we had to secure about ten people by adding workers who were not working on the precipitation tank but knew the process, and workers who did not know the process, but knew about things such as the location and structure of the Conversion Test Building.

We thought that we should secure even more workers in case of later changes in the content of work and so forth, and asked them to arrange for about 10 more workers. In the end we secured about 20 workers.

13.6 Investigating protective gear

As protective gear, we had already brought Tyvek suits, air-line suits and other gear, but since this was a neutron radiation field, and the radiation concentration in air was not estimated to be that high, and it was likely that the work would only require a short time, it was decided to work with gear that was as light as possible. The basic protection for each worker would be a Tyvek suit, with a vinyl acetate suit on top of that.

It was decided that a full-face mask or air mask would be added if necessary.

We wanted to secure a space to put on this gear, but we were not able to set up a changing area anywhere except the Administrative Building. Thus it was decided to set up the changing area in part of the hall of the Administrative Building.

It was decided to put on the gear indoors, and depart from the entrance of the Administrative Building. Since there was a possibility that the workers would be contaminated after work, we decided to set up an area with vinyl sheet in front of the rear entrance of the Administrative Building for workers to remove their gear. The workers would be surveyed in that area, remove their gear, and enter the Administrative Building. A special area was secured in the hall inside the Administrative Building for final removal of gear.

Due to the high background radiation, Radiation Control staff raised the issue that it might be impossible to carry out the survey, and that it was unclear how to perform the survey. It was decided to rule out major contamination if there was no change in value, even with the high background radiation.

13.7 Consideration of shielding measures

We also investigated shielding measures such as concrete shielding, and using a water tank. Although there was fixed shielding such as concrete or lead at JAERI and JNC, there was no appropriate shielding such as small-scale water shielding. Even if we were to procure such shielding, it would take time, and even if it could be procured, it was likely that workers would be exposed simply by installing the shielding, and there was a possibility that it would put limitations on work at the site. Thus it was decided to control exposure for the time being by limiting work time in the unshielded state.

13.8 Arrival of Deputy Director T, Mr. K and others from JAERI

Deputy Director T, Mr. K and others from JAERI, who had been reviewing the work plan at the Off Site Government Headquarters, arrived at about 11:30 p.m. It was decided to proceed with subsequent work while cooperating as appropriate.

13.9 Radiation measurement and control

We again requested delivery of a 3-He neuron spectrometer, but they said their measuring equipment was not working properly, and they could not provide it.

We discussed whether or not JCO should conduct radiation measurement, but we didn't come to a conclusion, and it was decided to conduct measurement by dividing the work between JAERI and JNC, under the guidance of the JCO Engineers. The Administrative Building was located at a point about 250 m from the Conversion Test Building, but a series of measurements were made at various distances from about 150 m to about 30 m. When taking the measurements, workers departed from the Administrative Building, went around the side of the 1P building, and when they arrived on the side of the Quality Control Building, the readings were 3.35 mSv/hr for neutrons and 350 μSv/hr for gamma rays. It was determined to be dangerous, and they returned to the Administrative Building.

On the 1F of the Administrative Building, we plotted the neutron doses from the sedimentation tank to about 250 m on semi-logarithmic graph paper based on the comments of Mr. K of JAERI, and the points were confirmed to lie almost on a straight line. (Fig.8) According to this line, neutron radiation near the sedimentation tank was about 18 mSv/hr.

However, when this was discussed with Deputy Director T and Mr. K of JAERI, they said they wanted data a little closer to the Conversion Test Building, and measurements were conducted again. (Fig.9)

Measuring again, the neutron reading exceeded 10 mSv/hr when at the side of the Solid Waste Building (16 mSv/hr with another Rem counter), and gamma radiation was 20 mSv/hr at a point about 15 m from the sedimentation tank.

The ratio of neutron to gamma radiation was roughly 10:1, but at a point about 35 m away this dropped to 4:1.

When deciding among these measurements of neutron and gamma radiation, we wanted to ensure maximal safety, so we assumed 20 mSv/hr for gamma rays at a position about 15 m from the sedimentation tank, and a neutron to gamma ratio of about 4:1 for a total of 100 mSv/hr, or a ratio of 10:1 for a total of 220 mSv/hr.

The cooling tower for performing water drainage work was about 3 m along a straight line from the sedimentation tank, and it was thought that we needed to take the dose immediately next to the sedimentation tank as the basis for evaluating the maximum exposure dose of workers. The dose immediately next to the sedimentation tank was thought to be 20 mSv/hr minimum, and 2 Sv/hr maximum. Converted to per-minute values, these would be about 0.3 mSv to 30 mSv. (Fig. 11)

13.10 Arrival of Dr. Sumita, Deputy Director of the Off Site Government Headquarters, and others

Dr. Sumita, Deputy Director of the Off Site Government Headquarters and professor at Kyoto

University, arrived at about 0:30 a.m. on October 1. After that, we proceeded while soliciting the opinions of Dr. Sumita and others on the subsequent work.

13.11 Composition of work teams

By 1:30 a.m., we had taken into account factors such as worker skills and radiation exposure, and decided to conduct the entire work procedure by forming 5 teams made up of 2 workers per team, and forming up to 10 teams in total to provide backup just in case.

While determining who should actually perform the work, the JCO side asked whether the JNC could also cooperate as radiation experts, and whether work might not proceed smoother if JNC staff were included in the work teams.

I confirmed who should do the work with the JNC Support Headquarters and also discussed the issue with Dr. Sumita, Deputy Director of the Off Site Government Headquarters. Dr. Sumita's opinion was that JCO was responsible for conducting the work.

Dr. Sumita's judgment was that the work should be done by forming work teams from JCO staff, because they were the operator personnel, and he himself persuaded Site Manager K. Dr. Sumita asked Site Manager K of JCO to choose the specific individuals and persuade them.

13.12 Work instructions and management

In order to simplify the chain of command and prevent mistakes with unfamiliar equipment, we used a work instruction and management system where we interacted with work teams in a reception room on the 1F of the Administrative Building. In that room, I and the JCO Engineers confirmed the instructions for the each work step and checked work reports, passed out and received alarms to ensure radiation management, and recorded or deleted past data.

Since it was unknown whether or not each operation could actually be carried out, we started with the intention of working by assigning two teams to each procedure.

For the first team of workers, we took into account that the radiation dose was only an estimate, and that work conditions at the actual work location were not completely understood. As a result, we decided on a time control of 2 minutes for work, and a further 1 minute for travel there and back by car, for a total of 3 minutes.

Dr. Sumita, Deputy Director of the Off Site Government Headquarters, and Safety Committee Chairman Sato discussed radiation exposure control, and there was talk that an exposure dose of 100 mSv during an emergency was acceptable. (See reference 11.) It was decided to set the alarms based on this, but some of the workers expressed the view that 100 mSv was too much, and we thought it would be better to avoid excess exposure in case of the need to perform more work. Therefore we decided to lower the value to 50 mSv. We assumed a neutron to gamma radiation ratio of 10:1, set the alarm to 5 mSv for gamma rays, and told workers to evacuate if the alarm sounded. For the purpose of radiation control, it was decided that workers would carry one pocket dosimeter for gamma rays and one pocket dosimeter for neutrons. It would have been better to set the alarm using the pocket dosimeter for neutrons but we adopted the above method because the pocket dosimeter for gamma rays was the only one with an alarm feature.

Workers were instructed to obey three rules: to make the work time a maximum of 2 minutes with an additional 1 minute of movement time for a total of 3 minutes, to evacuate if the alarm sounded, and to turn back in any case when work was finished. After receiving these instructions, they started work.

These three rules were subsequently always communicated at each work step.

13.13 Start of work

1. Departed 2:35 → Returned 2:38 (Fig.10)

The first team returned because the alarm sounded in 2-3 minutes. Their neutron exposure doses were 91.2 mSv and 11.92 mSv. At this stage, the reading for gamma rays was 7 mSv, which gives a neutron to gamma radiation ratio of about 13 for 91.2 mSv, and that seemed to be appropriate, but the meaning of the 11.92 mSv reading was not clear. We determined that the pocket dosimeters for neutrons was unreliable. In retrospect, we found out that the dosimeter had "rolled over" and 11.92 mSv indicated 111.92 mSv.

This work team took three Polaroid photographs, and it was determined from those photographs that the valves around the pump were fully open (i.e., there was no need to operate valves) and there was a union fitting in the line. (Fig.11, 12)

Thus we had to change from pipe cutting to removing the union fitting. At the same time, a worker also confirmed that the on-site indicator lamp of the cooling pump was lit up red, and this indicated that the pump was operating, in contrast to our original expectations.

In any case, the results showed that the dose was higher than we originally expected. According to the workers, the alarm sounded but they had not done any work yet, so they continued, took three photographs, and then had to turn back. When we consider that the entire trip took three minutes, it was likely that the alarm sounded at between 1 and 2 minutes.

Considering the maximum value, this comes to 20 mSv per minute. In other words, converted to dose rate, this seemed to corresponded to an average of 1200 mSv/hr.

Therefore we decided to change the approach to work control. First, since we had determined that the pocket dosimeters for neutrons were unreliable, we decided that the second and subsequent teams would carry two pocket dosimeters for neutrons. It was also decided to set the control target dose to 20 mSv to hold down the dose. Thus the alarm setting for gamma rays was set accordingly to 2 mSv. However, when we consider that the workers barely finished with 100 mSv the first time, there was a possibility that it would be impossible to ensure this dose control. Therefore, it was decided to ensure control by making work time at the site 1 minute, and have the driver of the car signal to the workers to come back by signaling with the horn when 1 minute had passed. With this, we felt that even if 50 mSv was impossible it should at least be possible to ensure that the dose was realistically kept within a limit of 100 mSv.

Later it was determined through irradiation testing at NUCEF of JAERI that the sensitivity of the pocket dosimeters for neutrons was two times too high.

2. Departed 3:01 → Returned 3:03

Workers in the second and subsequent teams were instructed to obey three rules: to make the work time a maximum of 1 minute, to evacuate if the alarm sounded, and to turn back in any case when work was finished. After receiving these instructions, they started work.

The facts confirmed by the first team indicated the possibility that the pump was operating, so the workers in the second team were instructed to confirm the operating status of the pump prior to starting work, and if it was operating, to do nothing and return. To check the operating status, they were told to touch the pump itself, and confirm whether it was vibrating.

When the workers returned, they reported that they had confirmed the pump was operating, and it was decided to change the work steps again. At this time, there was a report that there was an odor like the smell of rubber burning, and we investigated the cause, but it was unclear. There was also a possibility that radioactive material had been scattered, and thus it was decided that the third and subsequent teams would wear full-face masks with iodine filters.

3. Departed 3:22 → Returned 3:25

Since the pump was confirmed to be operating, it was confirmed that cooling water was circulating in the Conversion Test Building. Therefore, for the third team, we changed to the approach of releasing the excess cooling water by closing the water supply valve, and opening the drain valve of the cooling tower while the pump continued operation.

However, it was found that water drainage from the drain valve was not very good, only a trickle. Since there was almost no change in the neutron radiation situation, it was decided to break the drain pipe with a hammer.

4. Departed 3:48 → Returned 3:58

Although the workers of the third team fully opened the drain valve, they reported that water was not draining well, and it was decided to add this work step for the fourth team. From photographs and other information, it was expected that the material of the cooling tower was ordinary PVC, and thus it was determined that the drain pipe at the bottom of the tower could be forcibly broken with a hammer.

The workers of the fourth team were instructed to go to the Construction Section to get a hammer, and also to confirm that water was draining.

5. Departed 4:16 → Returned 4:19

When the workers of the fifth team arrived at the cooling tower, they confirmed that almost no water was coming out, but they reported that they broke the drain pipe at the bottom of the tower with a hammer just to be sure. They also provided information that water seemed to drain out as a result of breaking the pipe with a hammer, or that it had already drained out in the first place.

6. Departed 4:41 → Returned 4:43

The fifth team reported that water seemed to have drained out, but there was also a possibility that the criticality was still continuing, and would not terminate with water drainage alone. As a result, it was thought that perhaps normal cleaning at the bottom of the cooling tower was inadequate, and there was an accumulation of dead leaves or other foreign matter.

However, when drawings and cooling system drawings were reviewed later, it was found that there were cooling water tanks on the top side in the entire cooling system, and equipment for other systems was installed below that. The sedimentation tank was further below that, and the cooling tower was located on the outside of the Conversion Test Building. Therefore, it was thought that a significant amount of cooling water remained.

Water was being circulated by the pump, so we realized that we had to force out the water with air pressure or some other means. Therefore, it was decided to use argon gas due to its lack of reactivity. However, it was determined that blowing in the gas would require close attachment using a fitting such as a flange.

Thus, as a subsequent step, we decided to loosen a flange, bring one half of the flange back, fabricate a flange to fit it, mount it to an argon tank, and perform argon purging.

The sixth team was instructed to remove the union fitting, but while they were loosening it, the alarm rang, so the workers left it in that state and returned. Therefore, the next step was changed to bringing back the bottom of the union fitting for fabrication.

7. Departed 4:59 → Returned 5:02

The seventh team removed the fitting at the bottom of the union which was loosened by the sixth team, and brought it back. After that, hose mounting work was started in the Construction Section. The dosimeter sounded.

8. Departed 5:19 → Returned 5:22

The pump was operating and it was decided that the eighth team would loosen flanges in the line to create outlets for water drainage. Four flanges were loosened and it was confirmed that water came out. The water was reported to be lukewarm.

The dosimeter sounded.

9. Departed 5:44 → Returned 5:46

The ninth team mounted a nozzle for argon purging. They laid out a hose to a location 40 m away which was the position for setting up the argon tank, and they were able to extend it up the side of the Solid Waste Building.

In the beginning, it was envisioned that, because the discharge side pipe would be cut and purging would be done from there, cooling water would drain as is into the cooling tower. But it was found that the pump was operating and that there was a union on the near side of the cooling tank, and thus we changed to the method of purging from there. There was a possibility that, when that was done, water would not drain because the pump was blocking it, and thus it was decided to drain by loosening flanges.

10. Departed 6:00 → Returned 6:04

The tenth team conducted argon purging. The workers doing the purge were instructed to check, if possible, whether cooling water was being forced out. As a result, they confirmed that cooling water was vigorously coming out from the flanges, and returned.

As a result of these work steps, the criticality accident terminated, and that result was confirmed by neutron monitors on the second floor of the Administrative Building. These results were immediately reported to each response site via the JCO Accident Response Headquarters.

The entire work procedure was conducted over the course of about 4 hours from a little after 2:00 a.m. until about 6:00 a.m. on October 1, but in the end, the work was completed with all workers receiving an exposure of less than 50 mSv. (Fig.13)

Due to information that the main constituent was short-half-life radionuclides (e.g., ^{138}Cs) which had decayed from noble gas, each worker wore protective gear consisting of a dust/gas filter with a full-face mask, and a Tyvek suit.

13.14 Adding boric acid solution

Site Manager K of JCO said that perhaps we should speed up the step of adding boric acid solution, but for that task, workers had to approach about 1 m from the sedimentation tank, and there was a possibility of sustaining a lethal dose if the criticality was continuing. Therefore we felt it should be avoided if possible.

When we were deciding who should actually do the work of adding boric solution, the JCO side again suggested to the JNC that perhaps the work teams should be formed with staff members from JNC. Their reasons were that there were already few workers within JCO who could do the work, and only the firefighting team of JNC could operate the fire truck to be used in the work. In this case too, the matter was discussed with Dr. Sumita, Deputy Director of the Off Site Government Headquarters, and his opinion was that we should not change the general rule that work should be done by JCO.

This issue was also discussed with the JNC Support Headquarters. At this stage, water drainage had succeeded and the dose in the field had decreased to less than 1/100th what it was, and since there was little problem in terms of exposure control, and only the JNC firefighting team could operate the fire truck, it was decided to divide the labor, with the JNC firefighting team operating the fire truck, and the JCO workers doing the work of attaching the hose to the sedimentation tank.

Prior to the work, we created a schematic diagram of the Conversion Test Building and the Access Control Building next to it, and investigated the length of the hose. The hand-drawn drawing is shown in Fig. 14. As a result, the length was found to be about 40 m, and we requested Team Leader N of the firefighting team to test the supply of boric acid solution. The test was conducted in front of the Administrative Building. It was found that they could somehow manage to supply the solution, but there were also worries that boric acid solution might be supplied beyond the specified amount. Nevertheless, it was decided to go ahead because we felt that, even if the worst case happened and water overflowed from the tank, it was better than leaving any residual possibility of the criticality recurring.

The fire truck had a water tank, and it was possible to reduce exposure by hiding on the side opposite to the Conversion Test Building. As a result, we were fortunate and this work could be done within a range of exposure of 1 mSv or less.

14. Evaluation of radiation emitted to the surrounding environment

When the entire work process had settled down, we needed to check the soundness of confinement in the Conversion Test Building using negative pressure. To achieve this, we measured surface contamination density, and confirmed the open/closed status of doors and the operation situation of ventilation equipment with the JCO Engineers. However, the various people in charge had evacuated due to the alarm, and thus there were some workers who did not have a clear understanding of the final situation. Therefore, we brought in smoke testing equipment from the JNC, and instructed workers to conduct a check. Considering that we had to deal with the fact that the amount of radioactivity emitted to the surrounding area had not been evaluated, we decided to conduct measurement and evaluation by installing the JNC's dust and iodine sampler equipment onto the stack. Instructions were given to bring the equipment from JNC and start installation and measurement.

15. Sandbag stacking

After termination of the criticality accident, we stacked sandbags to reduce exposure to Local residents. Ninety people from JNC participated in making sandbags, and 110 people participated in the subsequent sandbag stacking work.

Time series showing development of understanding during the JCO criticality accident

Item	Time	Understanding of criticality accident
JCO: Criticality accident occurred	About 10:35	
JCO: Issued 1st report on criticality accident	11:15	
	11:19	・"Possibility of a criticality accident"
Nat'l gov't: Received 1st report on criticality accident	12:15	・ "Possibility of a criticality accident"
JNC: Contacted by phone from Tokaimura	12:15	・Requested "assistance due to radiation accident"
JNC: Contacted by phone from JCO	12:35	・Low probability of criticality accident ・Possibility of explosion involving UF6 etc.
JNC: Investigation by Accident Response Headquarters Results	14:50	・Understood possibility that criticality accident occurred: However, could not completely rule out scattering of radioactive material due to explosion
JNC: Arrived at JCO	15:00 -15:30	
JNC: Created drawing of sedimentation tank	15:00 -15:30	・γ and α ray situation strongly indicated criticality was continuing ・Started investigation of terminating criticality accident: However, still not sure that criticality accident was continuing
JNC: Radiometry (α,γ)	15:30	・Described tank where criticality accident occurred, and part of the method of termination: However, delivery of this information to the involved organizations was considerably delayed
JNC: Issued accident information	15:30	・Neutron measurement equipment was not brought along (although it should have been) so someone was sent to JNC to get it
JNC: Prepared for neutron measurement	16:30	・At the JCO Admin. Bldg., neutron radiation was 200-600 μSv/h: This was evidence that the criticality accident was continuing
JNC: Started neutron measurement	17:05	・4 mSv/h on the prefectural highway outside JCO
JNC: Issued results of neutron measurement		

16. Conclusion

It was truly unfortunate the JCO criticality accident occurred. It is crucial to prevent this kind of accident from ever occurring again, and to definitely terminate any such accident which does occur. We hope that this report will be useful in some way in preventing the occurrence of accidents, and improving termination and disaster prevention activities if an accident does occur.

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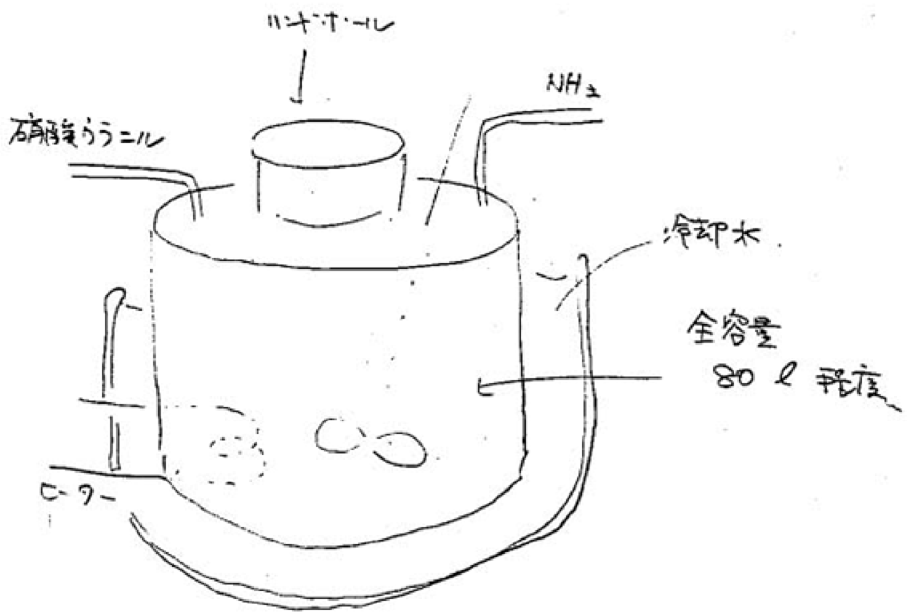


1. タンク内で臨界が起こっていると考えられる。
2. 本来 2kg 投入するところを 16kg 投入した。
3. 流量は不明。
4. タンク周囲の冷却水が中性子反射剤となっている可能性がある。

対策

1. 中性子反射剤である冷却水を抜く。
2. 中性子吸収剤を含む水（ホウ素水）をタンク内に入れる。
3. NH_3ラインから入れることは可能か？

Fig.1 Initially created sketch drawing of the precipitation tank

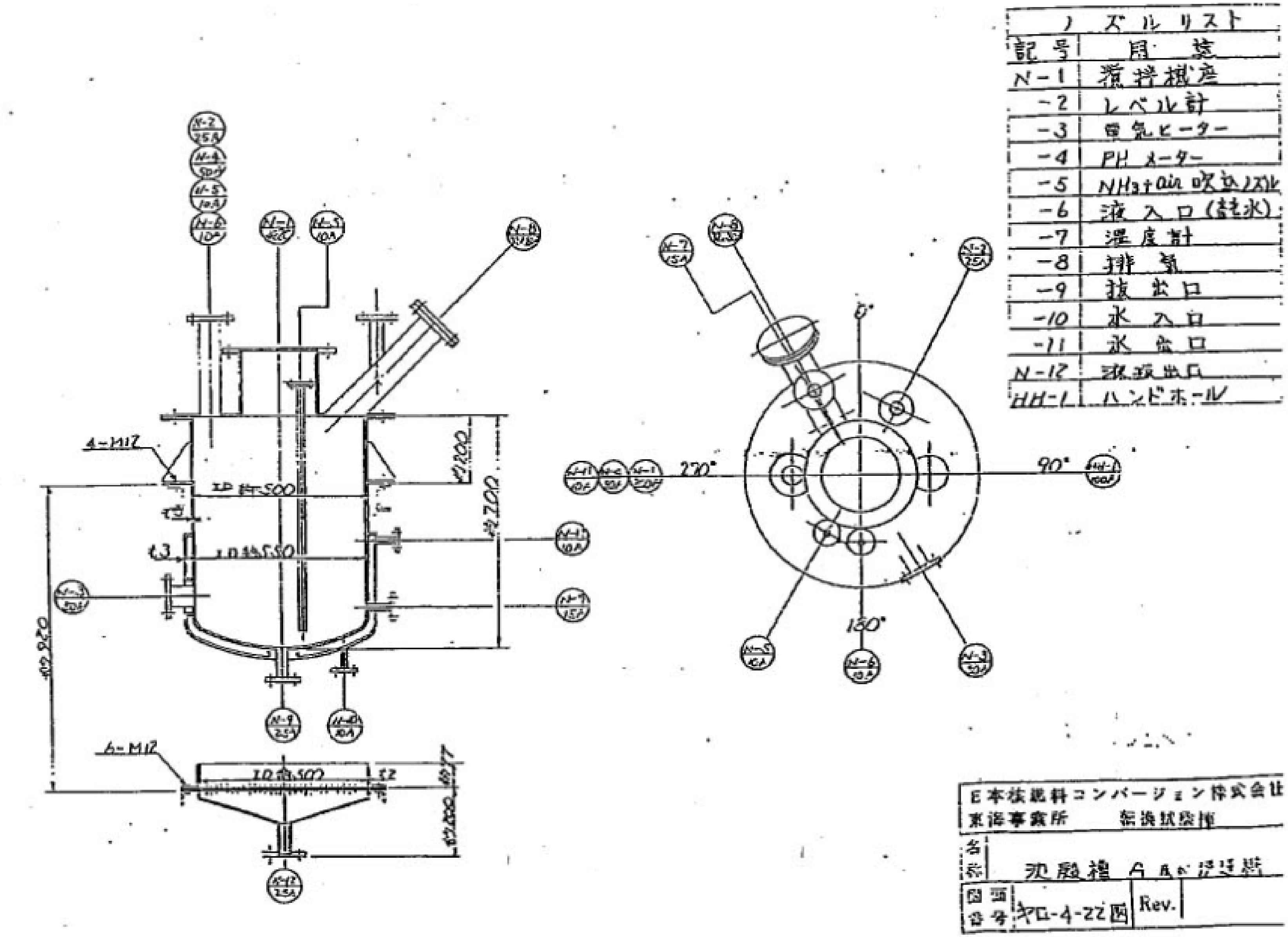
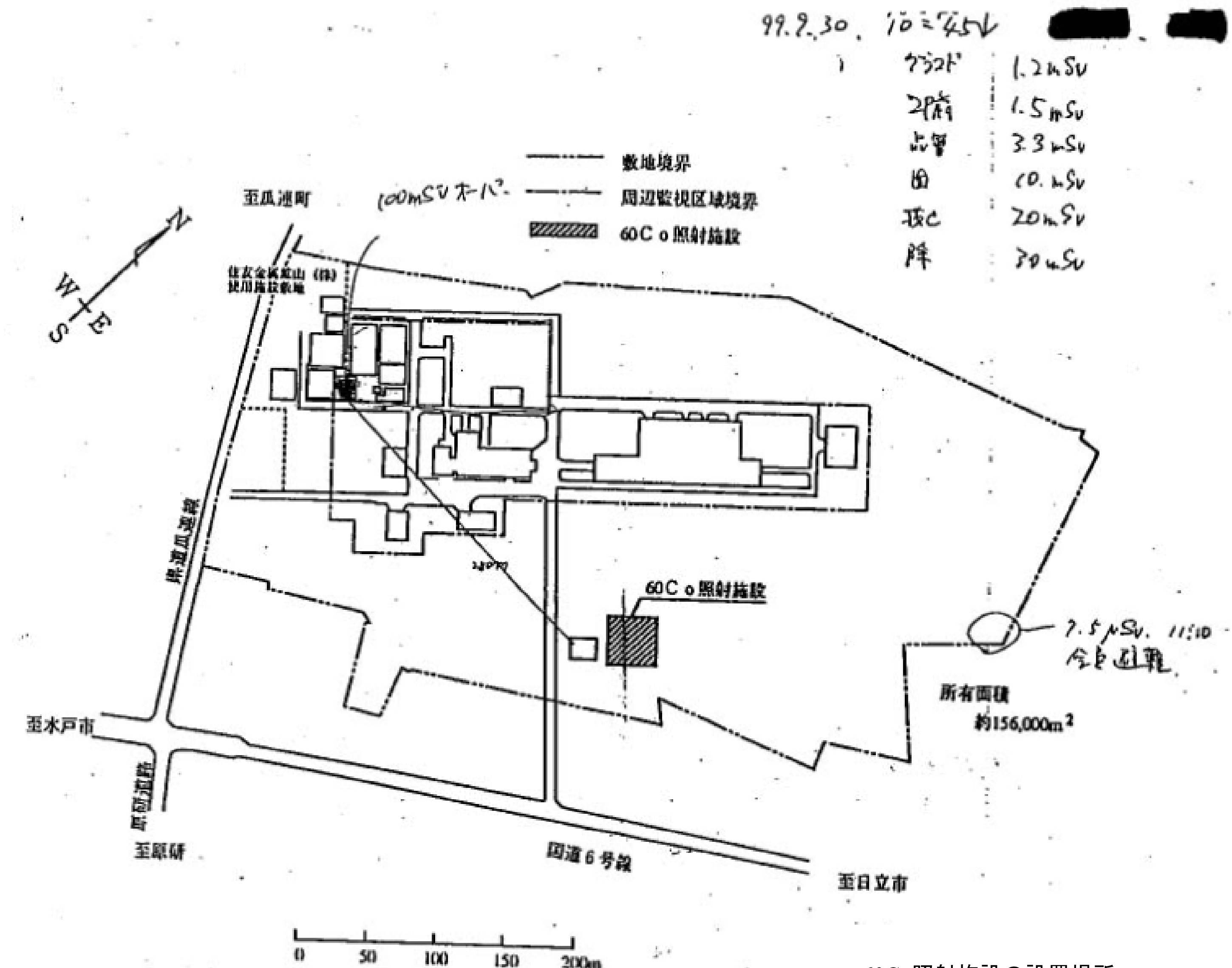
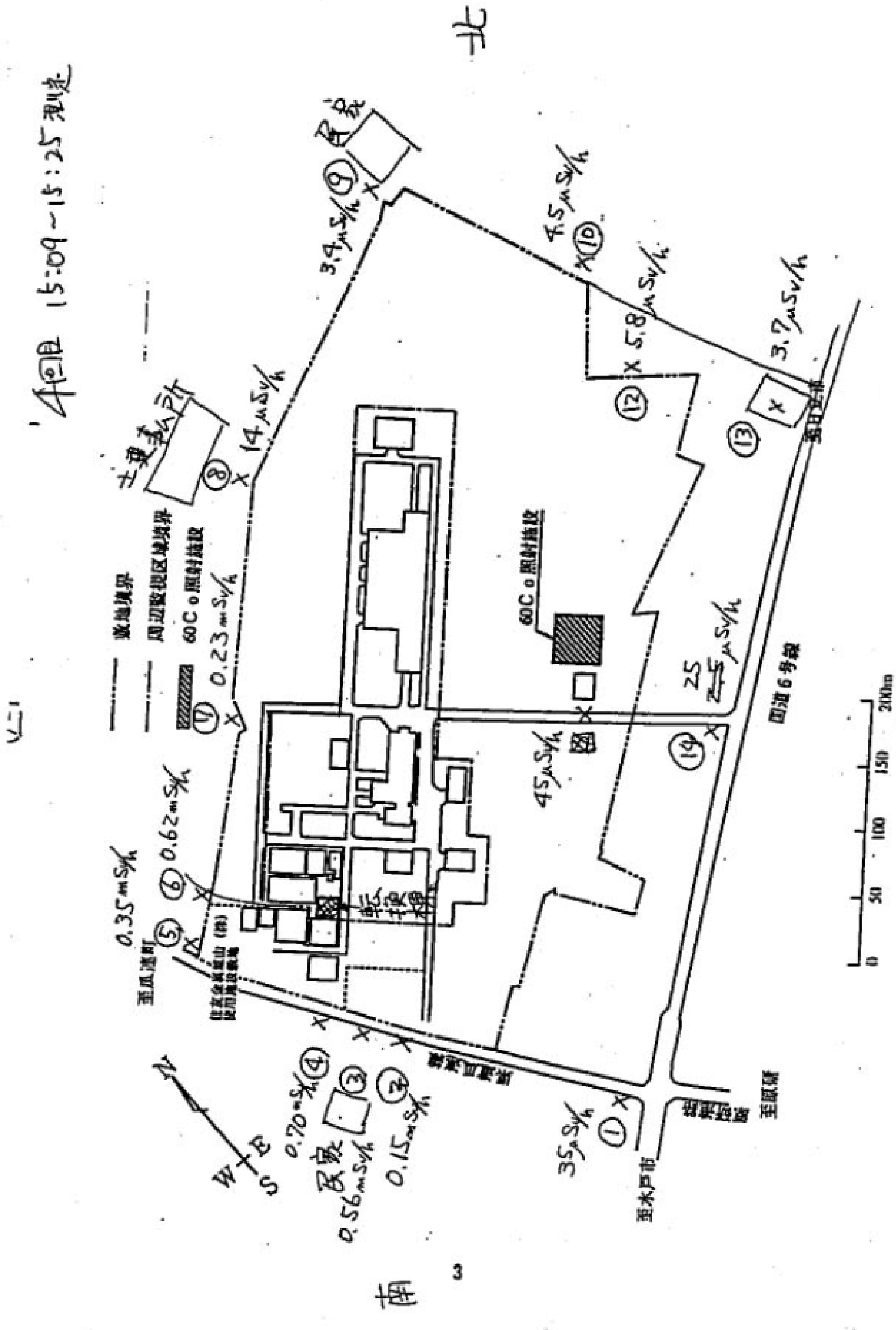


Fig.2 Precipitation tank A and Filtering machinery



60Co照射施設の設置場所

Fig.3 10:45 results of γ ray measurement



60Co照射施設の設置場所

Fig.4 Results of 4th measurement of γ ray

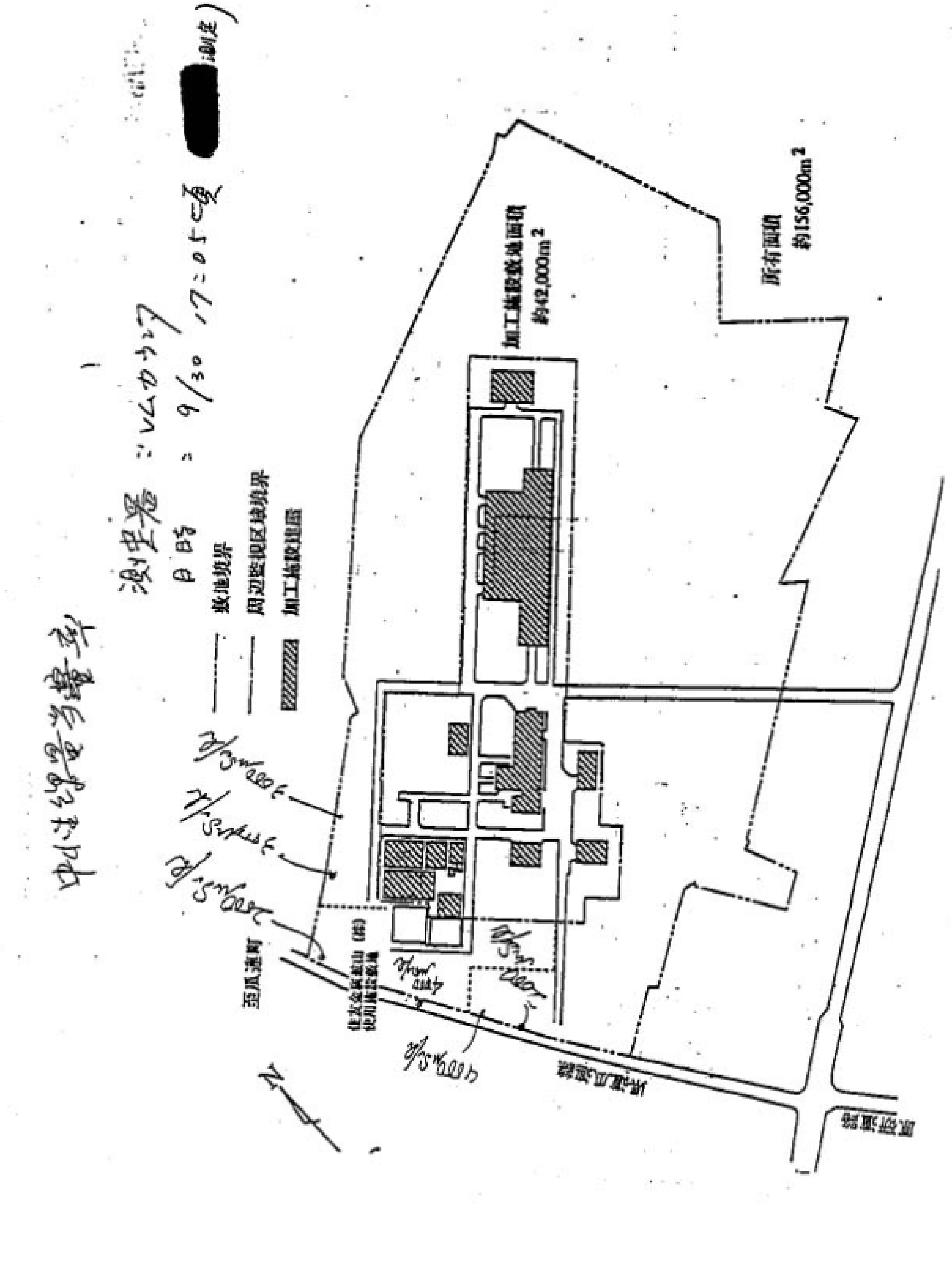


Fig.5 17:05 Results of neutron measurement

ハンドホールから 5ℓのビーカーで、3～4ℓで40ℓ入れた

40ℓ入れたところで起きた。

5ℓの溶液は となりの部屋から(と)の部屋運んで作業した.

・臨界になったときのハンドホール

　フタは開いていたが、ジョーロを入れていたのでふさがっていた。

。バルブの開閉状況 → アンモニアの入る弁の状態

　"全部閉"

。冷却水をまわしていたか → 定かでない.

。沈殿槽には 均一にするために入れた.

。冷却水は入っていたが、循環は定かでない

。ジョーロの材質は → ステンレス

　下5cm 上20cm

Fig.6 Notes from interviews from personnel

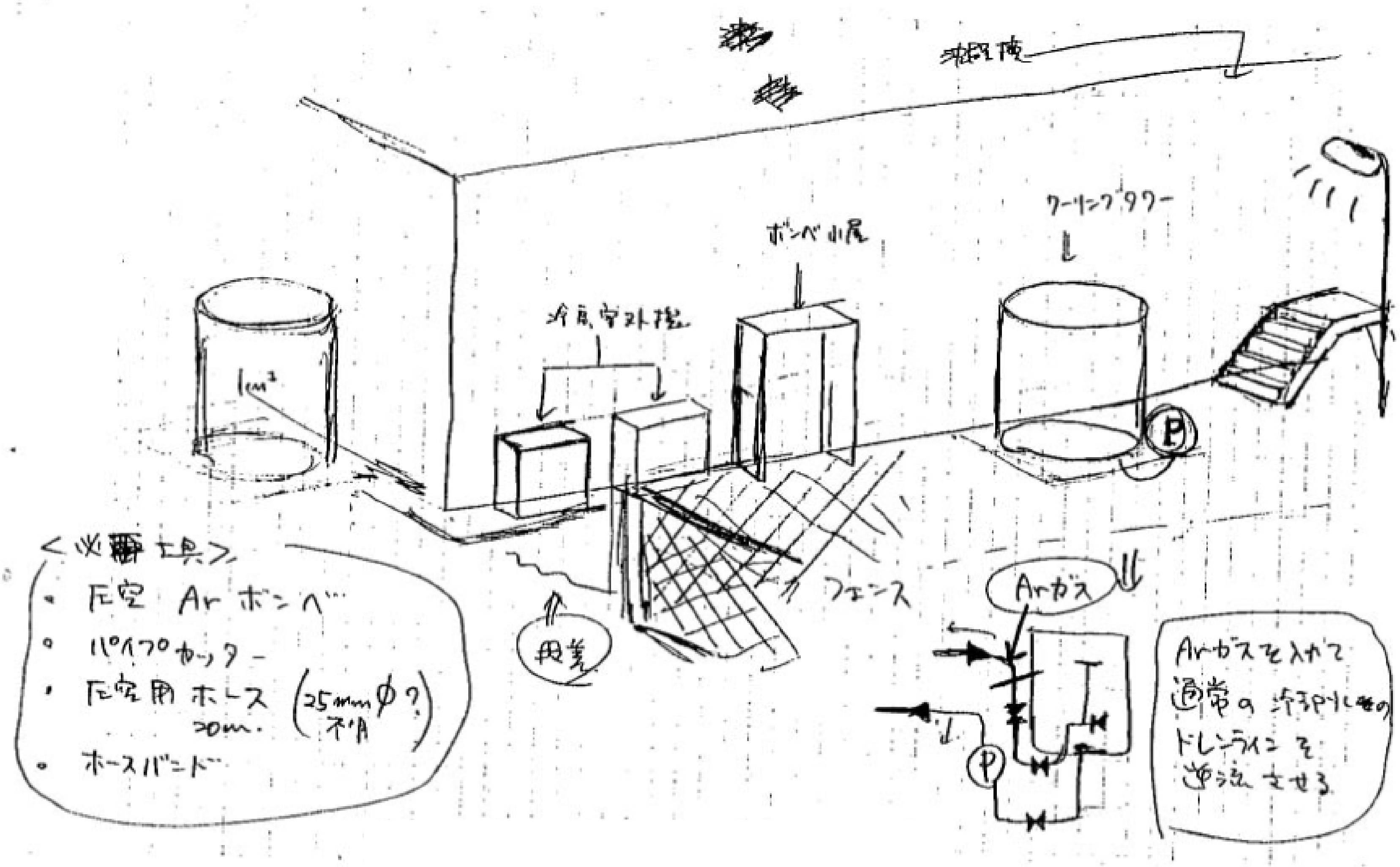


Fig.7 Backside view of Conversion Facilities

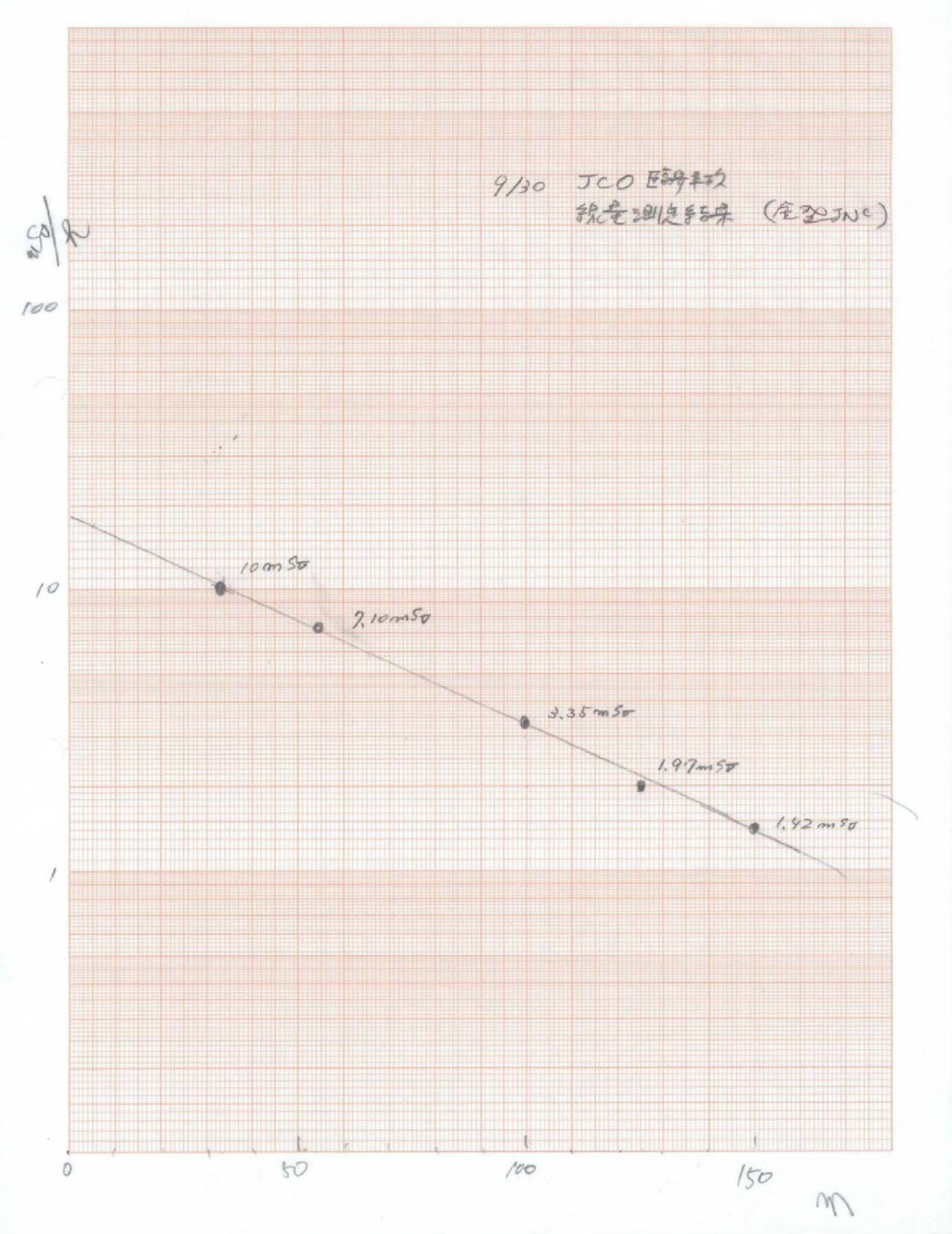
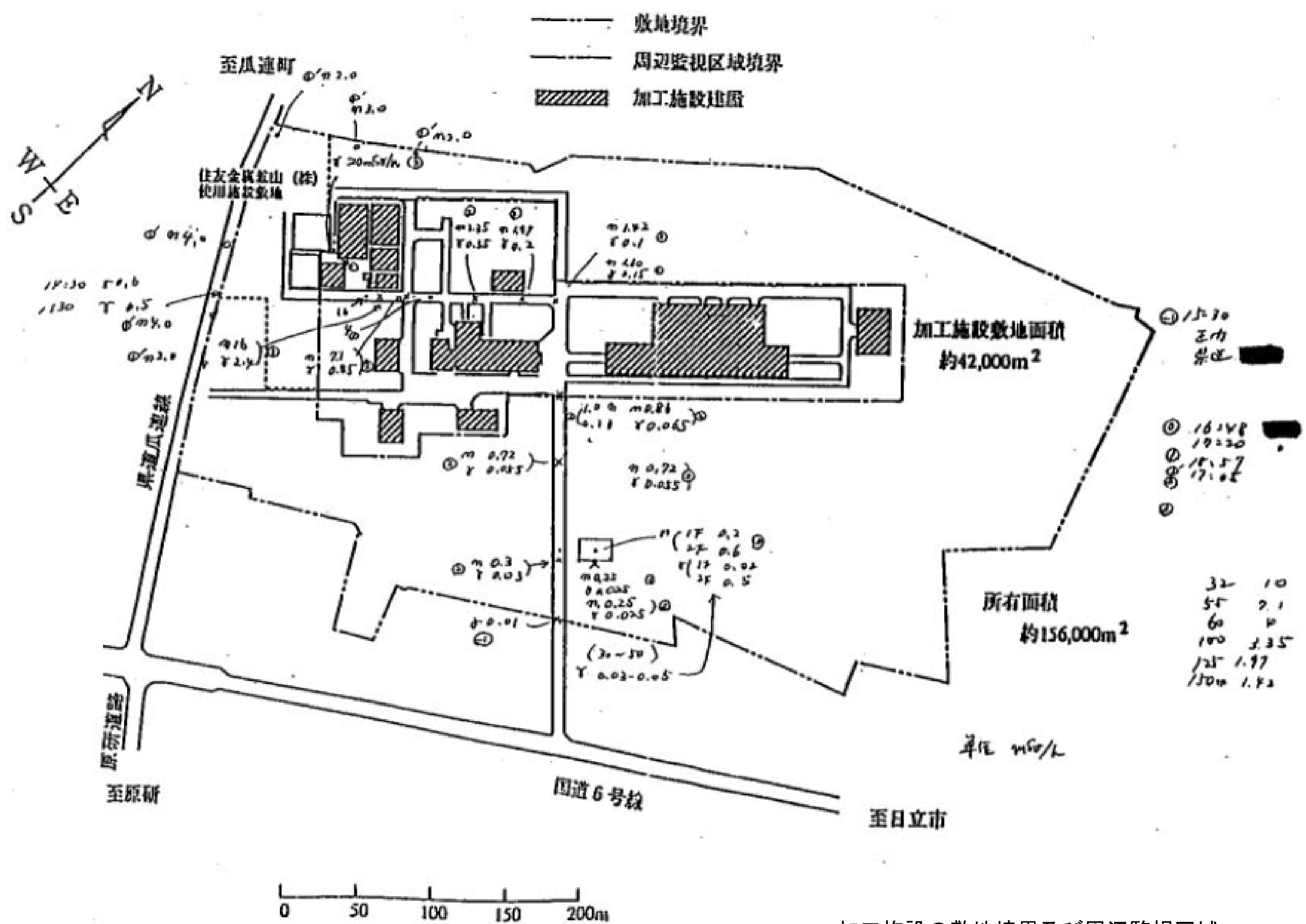


Fig.8 Neutron plot chart



加工施設の敷地境界及び周辺監視区域

Fig.9 Measuring results of radiation dose around the precipitation tank

99.10.1

水抜き手順

（2mSvアラーム，2台用＋1台用（予）3台用）

① ポラロイド写真　2:35発　2:38着

3枚

3/8

[redacted] γ2.15 n 91.2? mSv 12.7

[redacted] γ7.87 n 11.92 mSv 14.2

③ [redacted]

ポラロイド3枚撮影

バルブ全開

→ バルブ操作不要

~~② バルブ操作~~

~~③ カップリング~~

~~④ ホースつなぎ込み~~

~~⑤ Arバルブ操作 予定確認~~

3:01 → 3:03

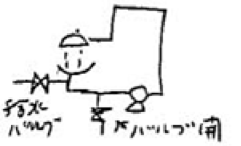
② ユニオン継手外し → ポンプ作動確認　[redacted] 36.20 39.13 γ2.465

・中性子PD2本とする　[redacted] 28.36 27.47 γ2.282

・作業時間1分間とする，（1mSv）

ポンプの動き確認のため，ユニオンとげる要免がする

③ 水抜きバルブ操作（3:22 → 3:25）　[redacted] n(19.49 18.78 γ1.437　[redacted] n(28.42 25.87 γ1.506



バルブ開（DR1），給水バルブws4開

マスクにも異臭あり，車のエンジンか？

[redacted] n(0.04 0.04 γ0.002　[redacted] n(0.05 0.04 γ0.002

工務ハンマー取り（3:48 → 3:58）

（工務課）

④ クーリングタワー下部ドレン配管ハンマー破壊　4:16 → 4:19

[redacted] (49.80 52.21 γ3.835　[redacted] (39.46 36.79 γ4.382　[redacted] ~~(0.05 0.04 γ0.002~~

(0.66 0.56 γ0.025

⑤ ユニオン取り外し → 4:41 → 4:43

ユニオン1インチゆるめたが，アラーム吹鳴でとどまる（40秒）

[redacted] (57.9 52.3 γ5.47　[redacted] 67.7 58.9 γ5.73　[redacted] 0.64 0.62 0.035

⑥ ユニオン下部持ち帰り（4:59 → 5:02）

アラーム吹鳴　[redacted] (61.34 61.06 γ4.24　[redacted] 47.08 49.91 γ6.234　[redacted] 0.60 0.59 γ0.025

⑦ フランジゆるめ（5:19 → 5:22）

([redacted] 入れかえ) 4本ゆるめ，水出てこない，ユニオン側回収，アラーム吹鳴

[redacted] 42.19 45.53 γ3.925　[redacted] (二 γ5.346 手袋汚染確認。[redacted] 0.59 0.57 0.035

⑧ ノズル取りつけ（Arパージ）　5:44 → 5:46

ノズル取りつけ終了，ホース40m，固体廃棄物採取OK.

[redacted] 36.42 34.82 γ3.228　[redacted] (43.17 42.87 γ2.948　[redacted] (0.59 0.51 γ0.024

⑨ Arパージ　6:00 − 6:04

パージOK，フランジより水が勢よく出てくる，内液.

Ar圧力5kg　[redacted] 36.73 37.32 γ2.322　[redacted] 2.13 2.10 γ0.1

6:12 作業班交代　[redacted] 1.38 n0.40 γ0.0016

Fig.10 Work process for working crew

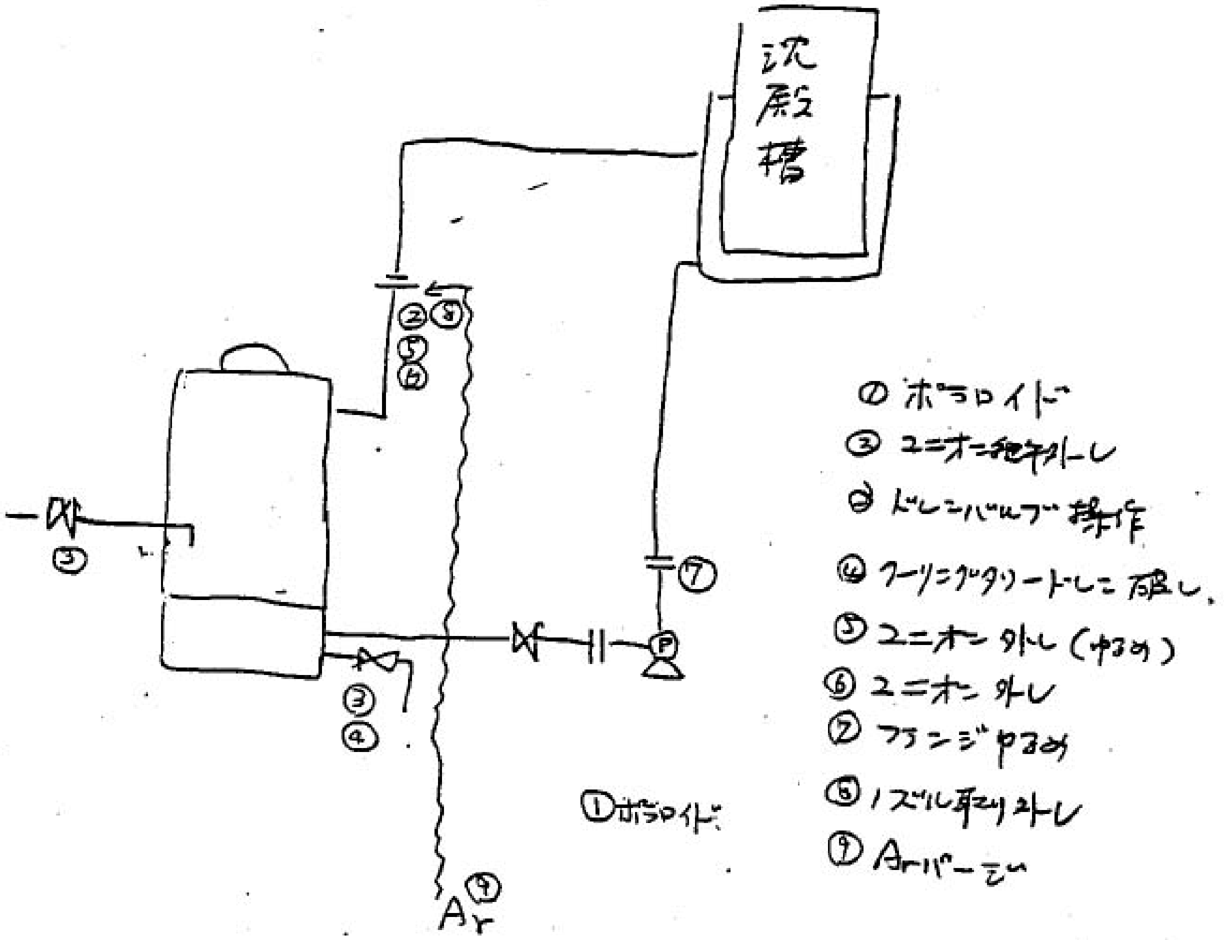


Fig.11 Precipitation tank system diagram

冷却塔

Fig. 12 Polaroid photos

1999. 10. 01 冷却水抜き取り作業について

作成　1999. 10. 01

	時間		作業及び運転者名			作業者1被ばく線量			作業者2被ばく線量			運転者被ばく線量			作業内容
	出発	戻り	作業者1	作業者2	運転者	γ	n1	n2	γ	n1	n2	γ	n1	n2	
1	2:35	2:38	A	B	S	7.15	91.20	／	7.87	11.92	／	0.045	0.55	／	ポラロイド3枚撮影
2	3:01	3:03	C	D	T	2.465	36.20	39.13	2.282	28.36	27.47	0.036	0.81	／	ポンプ運転中を確認
3	3:22	3:25	E	F	S	1.437	19.49	18.78	1.586	28.42	25.87	0.050	0.79	／	水抜きバルブ開、給水バルブ閉
4	3:48	3:58	C	H	G	0.002	0.04	0.05	0.002	0.05	0.04	／	／	／	工務課よりハンマー持ち出し
5	4:16	4:19	I	J	U	3.835	49.80	52.21	4.382	39.46	36.79	0.028	0.66	0.56	クーリングタワー下部配管ハンマーにて破損
6	4:41	4:43	K	L	U	5.47	61.9	52.2	5.73	67.9	58.9	0.035	0.64	0.62	ユニオン継ぎ手部ゆるめ
7	4:59	5:02	M	N	U	4.24	61.34	61.06	5.236	47.06	49.91	0.035	0.60	0.59	ユニオン下部持ち締り
8	5:19	5:22	O	P	U	3.923	42.79	45.53	5.346	表示なし		0.035	0.59	0.57	フランジボルト4本ゆるめ
9	5:44	5:46	H	Q	U	3.228	38.42	34.92	2.946	43.17	42.87	0.024	0.59	0.61	ノズル取り付け
10	6:00	6:04	R	G	U	2.322	35.73	37.32	0.159	2.13	2.30	0.014	0.39	0.40	Arパージ，水抜き確認(Rのみ)

※1　被ばく線量は積算値、単位mSv

※2　n1及びn2は、中性子線を線量計ダブルで測定

Fig.13　Table of dose of each crew member

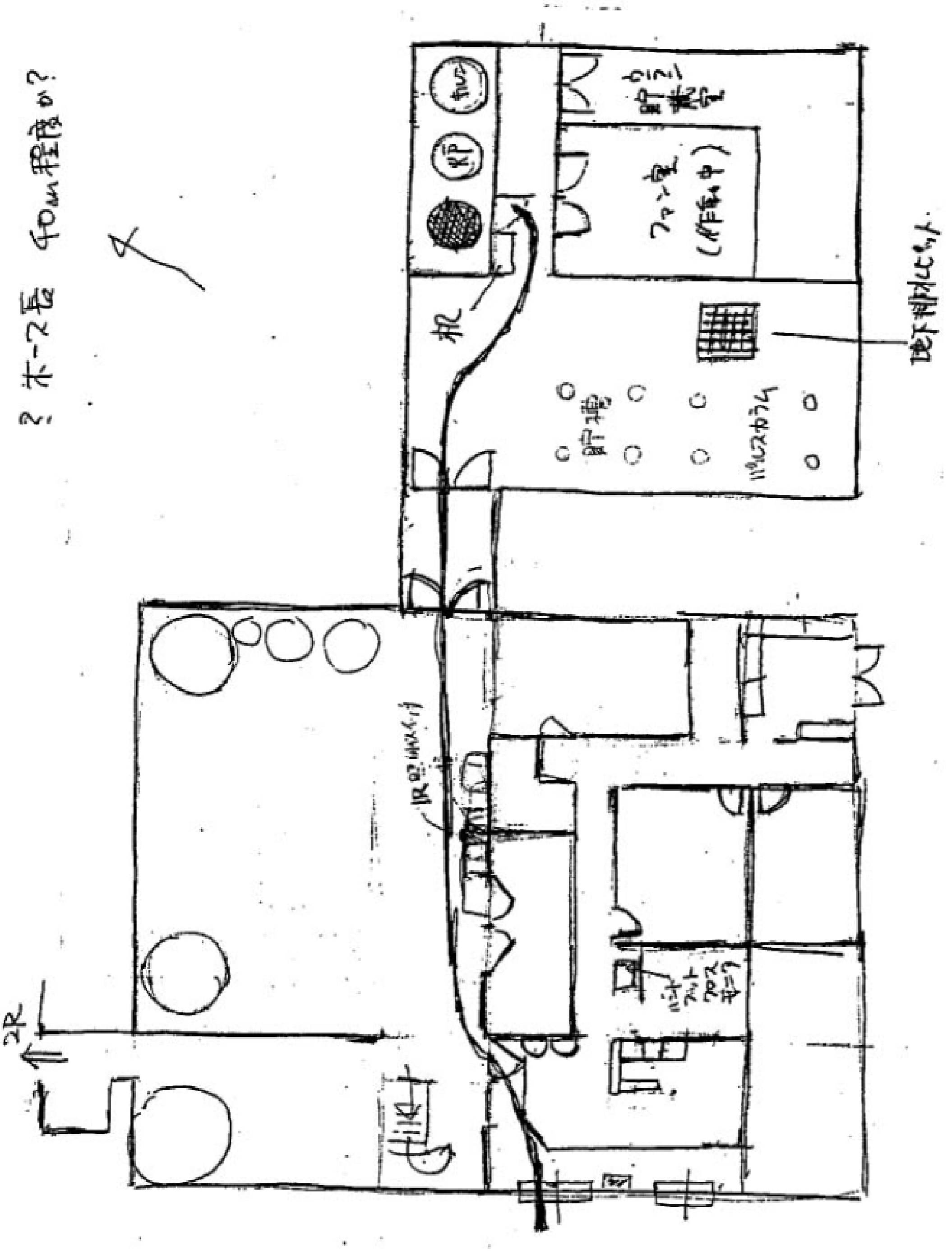


Fig.14 Diagram of infusing route of boric acid solusion

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度(a)，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立法メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率(b)	（数字の）　1	1
比透磁率(b)	（数字の）　1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(b)	rad	1 (b)	m/m
立体角	ステラジアン(b)	sr(c)	1 (b)	m^{2}/m^2
周波数	ヘルツ(d)	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度(e)	℃		K
光束	ルーメン	lm	cd sr(c)	cd
照度	ルクス	lx	lm/m^2	$m^{-2}\ cd$
放射性核種の放射能(f)	ベクレル(d)	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト(g)	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		$s^{-1}\ mol$

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	$m^{-3}\ sA$
表面電荷	クーロン毎平方メートル	C/m^2	$m^{-2}\ sA$
電束密度，電気変位	クーロン毎平方メートル	C/m^2	$m^{-2}\ sA$
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1}\ sA$
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}\ mol$

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	μ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10800) rad
秒	”	1”=(1/60)’=(π/648000) rad
ヘクタール	ha	$1ha=1hm^2=10^4m^2$
リットル	L，l	$1L=1l=1dm^3=10^3cm^3=10^{-3}m^3$
トン	t	$1t=10^3$ kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	$1eV=1.602\ 176\ 53(14)\times10^{-19}J$
ダルトン	Da	$1Da=1.660\ 538\ 86(28)\times10^{-27}kg$
統一原子質量単位	u	1u=1 Da
天文単位	ua	$1ua=1.495\ 978\ 706\ 91(6)\times10^{11}m$

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	$1\ bar=0.1MPa=100kPa=10^5Pa$
水銀柱ミリメートル	mmHg	1mmHg=133.322Pa
オングストローム	Å	$1\ Å=0.1nm=100pm=10^{-10}m$
海里	M	1 M=1852m
バーン	b	$1\ b=100fm^2=(10^{-12}cm)2=10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デジベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	$1\ erg=10^{-7}\ J$
ダイン	dyn	$1\ dyn=10^{-5}N$
ポアズ	P	$1\ P=1\ dyn\ s\ cm^{-2}=0.1Pa\ s$
ストークス	St	$1\ St=1cm^2\ s^{-1}=10^{-4}m^2\ s^{-1}$
スチルブ	sb	$1\ sb=1cd\ cm^{-2}=10^4cd\ m^{-2}$
フォト	ph	$1\ ph=1cd\ sr\ cm^{-2}\ 10^4lx$
ガル	Gal	$1\ Gal=1cm\ s^{-2}=10^{-2}ms^{-2}$
マクスウェル	Mx	$1\ Mx=1G\ cm^2=10^{-8}Wb$
ガウス	G	$1\ G=1Mx\ cm^{-2}=10^{-4}T$
エルステッド(c)	Oe	$1\ Oe \triangleq (10^3/4\pi)A\ m^{-1}$

(c) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	$1\ Ci=3.7\times10^{10}Bq$
レントゲン	R	$1\ R=2.58\times10^{-4}C/kg$
ラド	rad	$1\ rad=1cGy=10^{-2}Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2}Sv$
ガンマ	γ	1γ=1 nT=10-9T
フェルミ		1フェルミ=1 fm=10-15m
メートル系カラット		1メートル系カラット = 200 mg = 2×10-4kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー）4.184J（「熱化学」カロリー）
ミクロン	μ	$1\ \mu=1\mu m=10^{-6}m$

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