LESSONS LEARNED FROM THE JCO NUCLEAR CRITICALITY ACCIDENT IN JAPAN IN 1999

FOREWORD

Since the tragic Chernobyl accident in 1986, many improvements have been made in nuclear installations and in radiological protection. The state of nuclear and radiation safety has been very much enhanced in the last two decades by accumulation of experience and knowledge, and improvements to relevant technology and the global nuclear safety regime.

However, in recent years some reoccurring significant events in many parts of the world have been experienced. It can be said that such accumulated experience and knowledge is neither being adequately shared nor fully utilized. What has really been learned is that another significant event can still happen anywhere and at anytime if a strong vigilance of maintaining safety is not exercised by highest priority. We are all literally 'in the same boat'.

Considering the limited resources of the world nuclear community, the experience and knowledge need to be better shared as a global common asset. It can be said that experience and knowledge are significantly increased rather than decreased through wider sharing and utilization.

In such a context, this report will extract lessons learned from a criticality accident that occurred at a chemical processing facility in the conversion test building of JCO in Tokaimura, Ibaraki Prefecture, Japan on 30 September 1999, at 10:35 local time (01:35 GMT) in order to make the lessons adequately shared and fully utilized.

Although investigations of the accident have already been carried out and their findings are broadly disseminated (the IAEA dispatched a fact finding mission to the site in October 1999 and made a preliminary report; the investigative committee under the NSC of Japan made an official report in December 1999), and in accordance with aforementioned official report of NSC, the regulatory bodies of Japanese government took actions to newly enact or revise relevant laws, governmental structure and regulatory programs in Japan by the beginning of the 2001, the JCO accident is still worth while recalling and paying attention, and there is still high need to compile a report because of below mentioned reasons.

One of the reasons is that, in addressing nuclear safety issues, it is meaningful to globally share lessons learned from the JCO accident with more technical perspective of why and how such an accident had been caused, what had actually happened in the accident, and how the accident had been dealt with. It is envisaged that detail documented experiences and a set of data acquired through and based on various objective researches can actually serve as a quite practical and technical guidance for assuring robust safety of nuclear activities as well as a reference. Until recently some close technical researches, analyses and evaluations, that do not intend to revise relevant laws and regulations but specialized in a technical viewpoint, have been continued by various private groups including the Atomic Energy Society of Japan (AESJ), and some are now continuing. The AESJ had complied its findings and published a report in February 2005. Besides these reports, there are some reports by radiological experts that specialized in dose evaluation to victims of the accident, dose assessment in the surrounding area of JCO facilities, emergency medical response, and subsequent remedial measures. These existing reports, including the official report of NSC, which have been written in line with their respective objectives are still having very valuable information. However, since a lot of them are written in Japanese only, therefore, it is regrettably still hard to internationally share these valuable lessons and technical information gained from the accident. Based on above mentioned circumstances, it is unprecedented and valuable undertaking to consolidate many topics on the accident ranging from fact finding, analysis of causes, amendment of legal framework, dose assessment, emergency medical response to remedial procedure, etc. in addition to the latest technical views expressed by contributors and to offer them in a comprehensively and globally accessible form.

Another reason is that the accident still can be referred and lessoned as a typical example of deterioration of the safety culture and the management system that lead to fatal consequences. Deterioration of the safety culture and the management system has been globally recognized as a generic and crucial issue for nuclear safety through the worldwide shared experiences: the Three Mile Island (TMI) accident and the Chernobyl accident.

This report was drafted and finalized through face-to-face meetings at the Agency and web-based iterative exchanges by which valuable comments from contributors, whose names are included in the list, were yielded during the period 2005–2008. Particular acknowledgement is paid to the contributions made to the preparation of this report by members of the AESJ.

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1. INTRODUCTION

1.1. Background

On 30 September 1999, at 10:35 local time (01:35 GMT), a criticality[1] accident occurred at a chemical processing facility in the conversion test building (CTB) of JCO in Tokaimura, Ibaraki Prefecture, Japan. A solution of enriched uranium (U(18.8) or 18.8 wt.% ^{235}U by mass) in an amount reportedly about seven times more than the specified mass limit had been poured into a precipitation tank for homogenization purpose. This action was reported to have been in violation of the legally approved criticality control measures. It resulted in three JCO workers suffering acute radiation syndrome and a number of workers and members of the public receiving radiation doses. Some 161 resident people were evacuated from within about 350 m from the CTB in the JCO site, and some 310 000 people were advised by the governor of Ibaraki Prefecture to stay indoors for about 18 hours as a precautionary measure.

This accident aroused large concern worldwide. Although the accident did not result in an international trans boundary radioactive release and therefore Japan had no obligation to notify the IAEA or other States, the Emergency Response Centre set up by the IAEA pursuant to its obligations under the Convention established and maintained contact with the relevant competent authority in Japan to ascertain facts in order to respond to the many requests for information from official Contact Points under the Convention arrangements. Reports had been sent to the IAEA's contact points in Member States and to Permanent Missions in Vienna. At the 43rd regular session of the general conference of the IAEA held on the day, the Director General, Dr. Mohamed ElBaradei, drew attention to the IAEA press release on the accident issued on the same day and offered the Japanese government the services of an expert team to be dispatched immediately. The IAEA dispatched three experts of its Secretariat, specializing in the nuclear fuel cycle and its regulation, emergency response and accident consequence assessment, and environmental monitoring and dosimetry, on a fact finding mission to Tokaimura from 13 to 17 October 1999. Based on the key technical information obtained during the mission, a preliminary report was made to assist in the dissemination of information on the accident and its consequences, and to set out established facts [1].

The Japanese governmental investigative committee, "the JCO Criticality Accident Investigation Committee", was organized under the Nuclear Safety Commission (NSC) which is advisory to the Prime Minister. The committee undertook its own investigation into the accident and in December 1999 made a official report, which analyses causes of the accident, evaluates emergency actions performed in response to the accident, and gives recommendations on necessary improvements in the government and relating industries [2]. The laws, governmental structure and regulatory programs concerned were recently enacted or revised in accordance with the official report of NSC at the beginning of 2001.

Even after completion of the above-mentioned intensive investigations and the government's launching of new regulatory programs, the JCO accident still draws broad attention, and there is still high need to compile a report because of below mentioned reasons.

One of the reasons is that, in addressing nuclear safety issues, it is meaningful to globally share lessons learned from the JCO accident with more technical perspective of why and how such an accident had been caused, what had actually happened in the accident, and how the accident had been dealt with. It is envisaged that detail documented experiences and a set of data acquired through and based on various objective researches can actually serve as a quite practical and technical guidance for assuring robust safety of nuclear activities as well as a reference. Until recently some close technical researches, analyses and evaluations, that do not intend to revise relevant laws and regulations but specialized in a technical viewpoint, have been continued by various private groups including the Atomic Energy Society of Japan (AESJ), and some are now continuing. The AESJ had complied its findings and published a report in February 2005 [3]. Besides these reports, there are some reports by radiological experts that specialized in dose evaluation to victims of the accident, dose assessment in the surrounding area of JCO

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[1] The state of a nuclear chain reacting medium when the chain reaction is just self-sustaining (or critical), i.e. when the reactivity is zero.

facilities, emergency medical response, and subsequent remedial measures. These existing reports, including the official report of NSC, which have been written in line with their respective objectives are still having very valuable information. However, since a lot of them are written in Japanese only, therefore, it is regrettably still hard to internationally share these valuable lessons and technical information gained from the accident. Based on above mentioned circumstances, it is unprecedented and valuable undertaking to consolidate many topics on the accident ranging from fact finding, analysis of causes, amendment of legal framework, dose assessment, emergency medical response to remedial procedure, etc. in addition to the latest technical views expressed by contributors and to offer them in a comprehensively and globally accessible form.

Another reason is that the accident still can be referred and lessoned as a typical example of deterioration of the safety culture and the management system that lead to fatal consequences. Deterioration of the safety culture and the management system has been globally recognized as a generic and crucial issue for nuclear safety through the worldwide shared experiences: the Three Mile Island (TMI) accident and the Chernobyl accident.

1.2. Objective

The objective of this report is to introduce not only existing information but also later information, such as regulatory measures taken after the accident, technical consideration provided in the AESJ report in 2005 [3], and latest views expressed by contributors, including radiological experts, and to make them shared in the international arena in a comprehensively and globally accessible manner for further safety enhancement of nuclear activities.

This report will:

- Overview the environment surrounding the JCO accident such as nuclear fuel cycle development, the nuclear fuel industry and the regulatory system in Japan,
- Provide technical detail of the facilities and activities of JCO,
- Provide a detailed sequence and evaluation of the criticality event and measures taken for mitigation, as well as an evaluation of the characteristics of the criticality event,
- Provide detailed dose evaluation
- Provide detail of emergency response actions, including medical treatments
- Analyze causes and background of the accident,
- Take an overview of legislative and regulatory reforms carried out after the accident, and
- Extract lessons learned which are worth sharing by the Member States.

It is unprecedented and valuable undertaking to consolidate all these topics at once in addition to the latest technical views expressed by contributors and to offer them in a comprehensively and globally accessible manner.

1.3. Scope

This report places priority on extracting and helping worldwide sharing of lessons learned from the JCO accident based on information provided mainly by the private research groups such as the Atomic Energy Society of Japan (AESJ) [3], the latest views expressed by contributors as well as existing information including the official NSC report [2], and on being a technical reference material for helping further enhancement of nuclear safety. The report describes practical lessons and examples learned from the accident that can be used to ensure nuclear safety. It does not establish requirement or make recommendations.

This report is intended to be one of the many technical references for not only operators of nuclear installations but also the regulatory bodies of the Member States can refer to address nuclear safety issues at their own discretion. In particular it may be of interest from technical point of view to operators of nuclear installations, regulatory bodies and those agencies delegated with fostering safety culture in the nuclear industries, emergency preparedness for nuclear accidents, including preparedness for medical response.

This report does not address questions of responsibility, legal or otherwise, for acts or omissions on the part of any natural persons, legal persons, and organizations. Therefore this report itself neither intends to review the Japanese regulatory system nor to verify the legitimacy of administrative decisions and acts made by Japanese authority.

This report itself does not review, authenticate nor finalize any other existing report and information sources with regard to the accident. Facts and findings revealed in this report does not aim to verify, revise, correct, deny, confirm or certificate any of those written or implied in any other reports. In addition, the views expressed in this report are those of the contributors only, and neither representing nor authorizing those of the IAEA and any of its Member States.

1.4. Structure

The report consists of 12 chapters. Chapter 1 provides the overall framework for the report. It covers the background, objectives, scope and outlines the structure.

Chapter 2 contains an overview of the fuel cycle development, fuel industry and regulatory system in Japan at the time of the accident.

Chapter 3 provides a technical specification of the JCO site and facilities.

Chapter 4 provides a history of facilities and activities of the JCO. It covers licensing history and operational history.

Chapter 5 examines the criticality accident in detail. It covers the sequence of criticality accident, activities taken for mitigation, and evaluation of nuclear characteristics of the criticality accident.

Chapter 6 provides information on emergency response actions.

Chapter 7 examines dose assessment and health effects in detail. It covers dose assessment for main victims of the accident, for other employee of the JCO, for emergency response personnel and for local residents.

Chapter 8 provides information on medical treatments as well as medical and public health actions taken for three highly exposed victims of the accident, for other JCO, employees for emergency response personnel and for local residents.

Chapter 9 analyses causes and background of the accident.

Chapter 10 provides an overview of amendments to legislative and regulatory framework after the accident.

Chapter 11 derives and summarizes lessons learned from the accident.

Chapter 12 gives conclusion of the report.

2. OVERVIEW OF FUEL CYCLE DEVELOPMENT, FUEL INDUSTRY AND REGULATORY SYSTEM IN JAPAN AT THE TIME OF ACCIDENT

2.1. JCO in LWR fuel material processing market

In 1979, the Japan Nuclear Fuel Conversion Co., Ltd. was established as a subsidiary of the Sumitomo Metal Mining Co. Ltd. (SMM) to take over the uranium conversion business from SMM. It was renamed “JCO” in 1998. The principal involvement of the company was converting low-enriched UF_6 into UO_2 powder (re-conversion) for commercial light water reactor (LWR, both BWR and PWR) fuels. JCO also provided a uranium re-conversion service to the national fuel cycle program as described in the next section. JCO was a unique company in the world’s fuel industry in that its principal involvement was solely UF_6-to-UO_2 re-conversion. The company used a “wet” re-conversion technique developed by SMM, which consisted of the solvent extraction method utilizing precipitation method for solidification.

Until 1999, the role of JCO in the Japanese fuel industry was to provide, in competition with foreign industry, uranium re-conversion services to domestic fuel companies, who were also in competition with each other, and to foreign industry. The production and sale of JCO peaked in 1993 (540 t U and 3,276 million yen), but had decreased to 68 % and 53 % respectively of the peak values in 1998, prompting rationalization. In 1999, JCO was preparing for introduction of a “dry” re-conversion technique for better competitiveness in the LWR fuel material processing market.

2.2. JCO’s involvement in the Japanese fuel cycle program

In addition to the businesses with the LWR fuel companies, JCO had an exclusive relationship with the Japan Nuclear Cycle Development Institute (JNC) in re-conversion of uranium for fabrication of mixed oxide (MOX) fuels and uranium oxide fuels for development reactors operated by JNC. The reactors included the fast experiment reactor JOYO, the fast breeder reactor (FBR) prototype MONJU, and the heavy-water moderated, light-water cooled reactor FUGEN, all constructed and operated as part of the national fuel cycle program. The 18.8 wt.%-enriched uranium solution that reached criticality was being processed for use in fabrication of JOYO fuel.

The company’s involvement in the national fuel cycle program dates back to 1972, when SMM received an order from the Power Reactor and Nuclear Fuel Development Corporation (PNC, renamed to JNC in 1998) for conversion of 23 wt.% enriched uranium for the initial core of JOYO. The contracts since then were affected by the progress in the fuel cycle program, in particular the commissioning of the PNC Tokai reprocessing plant in 1977.

Until 1978, the role of SMM was to supply UO_2 powder at various enrichments, to be mixed with PuO_2 that was transported from foreign reprocessing plants, to produce MOX powder in PNC. This SMM role could have been unchanged if the PNC reprocessing plant had replaced the foreign plants by producing PuO_2 powder, as originally planned. This, however, did not happen because the U.S. administration opposed, under a new nuclear nonproliferation policy, the PNC production of PuO_2 from spent fuels that included U.S.-enriched uranium. The Japan-U.S. negotiation on this issue took years (1977-1980), but reached an agreement on the use of a proliferation-resistant method developed by PNC. In this method, termed Pu-U co-conversion, the plutonium extracted in the form of nitric acid solution (PuNH) is mixed with solution of uranyl nitrate hexahydrate (UNH, $UO_2(NO_3)_2{\cdot}6H_2O$) before denitration into powder form.

The adoption of the co-conversion method led PNC to a decision to outsource the production of uranium solution, needed for co-conversion, to SMM. The first order in 1979 concerned the solution of purified natural uranium, which was used for fabrication of FUGEN fuel. Later, in 1984, PNC made a decision to outsource the production of 19 wt.%-enriched uranium solution for the fabrication of JOYO fuel to JCO, which had replaced SMM in the contractual relationship with PNC. The first order was placed in 1986.

The demands for the uranium conversion by SMM/JCO were subject to progress and events in the national fuel cycle program operated by PNC/JNC. The program consisted of the reprocessing project, the MOX fuel fabrication project, and the three reactor projects, all running in parallel. The three reactors demanded uranium of different enrichments. Only JOYO (first criticality was reached in 1977) required intermediately enriched uranium (IEU) to have a high fissile content, necessitated by the small size of the reactor core. FUGEN (1978) used natural and low-enriched uranium. MONJU (1994) used depleted uranium.

The fuel fabrication in PNC/JNC had to accommodate different demands for uranium and plutonium from these reactors, concurrent with a non-straightforward transition in the plutonium supply. The PNC reprocessing plant did not become the sole source of plutonium even after the end of the testing phase in 1981. There were surplus amounts of irradiated LWR fuel to be processed, and the delivery from foreign reprocessing plants until 1993.

The form of product (UO_2 powder or solution) ordered by the PNC/JNC from SMM/JCO depended on the origin (foreign or domestic) of the plutonium to be mixed with, and on the stage of fuel fabrication where the product was used (in the Pu-U co-conversion, or in the adjustment of the plutonium content of MOX powder). The orders for solution of IEU started in 1986 and continued intermittently until the accident in 1999.

2.3. Regulatory system related to JCO licenses for re-conversion of intermediately enriched uranium for JOYO fuels

The safety regulation of the fuel material processing facilities is performed pursuant to the provisions set forth in the Law for the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors, subordinate to the Atomic Energy Basic Law. According to the license classification in the law, SMM/JCO was engaged in:

- Utilization of nuclear fuel materials, and
- Nuclear fuel fabrication.

The distinction between the two classes above is not defined explicitly, while it is generally understood that the former applies to activities on an intermittent or temporary, developmental basis, and the latter applies to those on a regular, continuous, industrial basis. Accordingly, the latter class practically covers a broad range of fuel businesses, from enrichment to fuel assembly fabrication. The re-conversion of IEU by SMM/JCO was first licensed as a “utilization” of uranium for a period of about twelve years (1972 -1984), and then licensed as “fuel fabrication” after 1984 until the accident in 1999.

The licensing flow diagram for a “utilization” application, before the governmental reorganization in 2000, is shown in Figure 2.1. The responsible regulatory body was the Nuclear Safety Bureau (NSB) of the Science and Technology Agency (STA)[2], the Office of Prime Minister. The legal basis included a ministerial ordinance, which stipulated the general rules applicable to “utilization” including requirements for prevention of criticality. However, there was no specific regulatory guide applicable to “utilization” applications.

In 1972, SMM was granted a “utilization” license for re-conversion of 23 wt.% enriched uranium. The license was updated in 1979 for processing of 12 wt.% enriched uranium, in a new plant to be built in the CTB. The plant and CTB were transferred to JCO in 1980.

In 1984, JCO was awarded a license for re-conversion of 20 wt.% enriched uranium in a renewed CTB plant, as an additional coverage of the “fuel fabrication” license that SMM/JCO held since 1969 for re-conversion of low-enriched uranium, the principal involvement of the company.

The licensing flow diagram for a “fuel fabrication” application is shown in Figure 2.2. The responsible regulatory body was the same as in the case of “utilization”, but the basic design review conducted by STA was reexamined by the NSC. Once NSC advised the Prime Minister of the approval of the application, STA started the review of detailed design and construction plans. The regulatory requirements were, in general, more formalized and stringent for “fuel fabrication” than for “utilization”, throughout the licensing and the operational phases, e.g. the “fuel fabrication” license required the engagement of a nationally certified staff member as the Chief Engineer of Nuclear Fuel Materials for the facility.

Figure 2.3 shows major legislations and guides governing the safety regulation of fabrication business or utilization of nuclear fuel material. There was no specific regulatory guide applicable to “fuel fabrication” facilities dealing with IEU (more than 5 wt.% ^{235}U) when JCO submitted an application for the modification of its “fuel fabrication” license for inclusion of the new 20 wt.% enrichment facility, as

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[2] STA was merged into Ministry of Education, Culture, Sports and Technology (MEXT) on 6 January 2001 when Central Government Reform was executed. The duty of NSB was taken over by Ministry of Economy, Trade and Industry (METI) and MEXT.

advised by STA in the pre-application review [3]. While the Basic Regulatory Guide for Nuclear Fuel Facilities issued by NSC stipulates the general requirements for the basic design review, applicable to the "fuel fabrication" facilities, the specific requirements and criteria were provided only for low-enriched uranium facilities. This may have reflected that processing of IEU was rare in the Japanese fuel industry; no other company than SMM/JCO was involved in such a task.

The Basic Regulatory Guide for Nuclear Fuel Facilities stipulates for consideration of the occurrence of criticality in the safety design of those facilities where the possibility of criticality exists. However, JCO did not assume the occurrence of criticality in the design of the facility, on the grounds that the possibility of criticality could be eliminated by appropriate operation. This logic and the facility design were judged to be adequate by STA and NSC, after JCO committed itself to implementing an additional rule for the operational management of criticality safety.

The first regulatory requirement, in written form, for particular precaution against criticality of IEU. (more than 5 wt.%) was put forth in a ministerial ordinance on the technical standards for detailed design and construction plan of "processing" facilities, issued in 1987, three years after the JCO facility was licensed. The standards included a provision requiring an a priori assumption of the occurrence of a criticality accident in the safety design of facilities handling more than the minimum critical mass of IEU. The JCO facility was the sole facility pertinent to the above requirement in the standards.

The issuance of the standards in 1987, however, did not lead to any regulatory actions against the detailed design of the JCO facility in its configuration as licensed in 1984. There was no occasion where the design of the JCO facility was officially reviewed in accordance with the standards (JCO made no licensing application after 1984 relating to the chemical processes of the facility). According to the STA's answer to a question in the Diet after the accident in 1999, STA made an informal review of the JCO facility sometime after the issuance of the standards, and concluded that the facility satisfied, in effect, the requirements of the standards.

<<Figure 2.1 – 2.3 will be inserted.>>

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[3] JCO initially intended to file the application for updating the contents of its "utilization license".

3. JCO SITE AND FACILITY

3.1. Location of the JCO site

The accident took place in a chemical processing facility in the CTB in the JCO site in Tokaimura, a large village 120 km northeast of Tokyo in Ibaraki Prefecture (Figure 3.1). The JCO site was also close to the town of Nakamachi. At the time of the accident, there were nine municipalities and about 310,000 inhabitants within a 10 km radius (Figure 3.2), and around 150 people lived within 350 m from the CTB in the JCO site. The nearest residence was within 200 m from the CTB. There were many nuclear installations operating in Tokaimura (Figure 3.3), including a BWR nuclear power plant of Japan Atomic Power Company (JAPCO), nuclear fuel manufacturing plants of Mitsubishi Nuclear Fuel Co., Ltd. (MNF), Nuclear Fuel Industries Ltd. (NFI) and JCO, research reactors of the Japan Atomic Energy Research Institute (JAERI), and a fuel reprocessing plant and fuel fabrication plants of the Japan Nuclear Cycle Development Institute (JNC).

3.2. JCO facilities

The operating company, JCO, wholly owned by SMM, operated three re-conversion facilities at this site (Figure 3.4):

1. No.1 processing facility: This had an annual production capacity of 220 tons of uranium (t U/a) for low enriched uranium (LEU) (with enrichment less than 5 wt.%) for commercial LWR power plants;
2. No.2 processing facility: This had an annual production capacity of 495 t U/a for LEU (with enrichment less than 5 wt.%); and
3. Conversion test facility: This was located in the CTB, where the accident took place, with a licensed annual production capacity of 3 t U/a for IEU (not more than 20 wt.%) for the production either of uranium dioxide (UO_2) powder or of uranyl UNH, from uranium hexafluoride (UF_6), uranium yellow cake or scrap.

The CTB was located on the western side of the site, near the boundary between the municipalities of Tokaimura and Nakamachi.

3.3. JCO Conversion Test Building (CTB) and process

The modified CTB, where the accident occurred, was commissioned in 1984, particularly for processing of IEU for JOYO, with a licensed capacity of 3 ton U per year. Similar services had been provided since 1972 by SMM and after 1979 by JCO to PNC.

The plant had been processing raw-material uranium oxide (U_3O_8) powder, rather than UF_6, of 18.5 wt.% to 19.75 wt.% enrichment into UO_2powder since the first contract in 1985. The U_3O_8 powder was supplied by PNC/JNC and the UO_2 powder was delivered to the PNC/JNC fuel fabrication plant in Tokaimura. Starting from the contract in 1986, the same plant produced UNH solution of about 370 gU/L, in addition to the UO_2 powder, to accommodate the PNC/JNC demand. The UNH solution was delivered to the PNC/JNC Pu-U co-conversion plant within the reprocessing installation in Tokaimura.

Figure 3.5 shows the equipment layout in the CTB. In the name of the building, “test” was used to imply that the work there was of developmental nature rather than commercial. The precipitation tank was located at the end of the area in line with the calcination and reduction furnaces. The building was connected by an entrance/exit control room or passage way to a neighboring building owned by SMM. The building was equipped with a ventilation system. Air from the building and/or its equipment passed through a pre-filter, an activated carbon filter, and then a HEPA filter before being discharged to the outside atmosphere from an exhaust stack on the roof of an adjacent building of SMM.

In the calcination and reduction room within the CTB, there was the precipitation tank into which much more amount of UNH than the regulated criticality safety limit was poured and criticality occurred. The drawing of the precipitation tank is shown in Figure 3.6.

Figures 3.7 and 3.8 show the licensed conversion process and system. The process flow chart of producing, UO_2 or UNH by JCO was a rather common (general) process in the three facilities of the JCO, except for the production of UNH. The process is called the Sumitomo ADU (ammonium diuranate) method which had been developed by SMM. A unique feature of the process is the additional extraction process utilizing TBP (tributyl phosphate) to the conventional ADU method.

The purification steps include:

- Dissolution of a single batch (less than 2.4 kg U) of U_3O_8 powder in nitric acid using a steam-heated dissolution tank, mixing materials by pumping,
- Extracting impurities in the extraction and counter-extraction pulse tanks using TBP and nitric acid or water,
- Storing purified UNH in a storage tank,
- Bubbling ammonia gas into the solution in a precipitation tank, to precipitate ADU, $(NH_4)_2U_2O_7$, mixing with a mechanical stirrer, and
- Separating the ADU precipitate from the solution using a pan filter.

The precipitate in trays is heated in a calcination furnace to produce U_3O_8. When the required product is UO_2 powder, the purified U_3O_8 is to be reduced in a reducing furnace into UO_2. When the required product for delivery is UNH solution, the purified U_3O_8 powder is to be re-dissolved in the dissolution tank.

According to the licensing condition, the plant was to be operated in batch mode under the maximum batch mass limit of 2.4 kg U for enrichment of 16 wt.% to 20 wt.%. This limit had been supposed to be applied to the work since the commissioning till the accident. However, JCO actually processed more than 15 kg U of UNH solution (more than six times as much as the maximum batch mass limit) per lot in order to obtain homogenized delivery lots. JCO started such operations beyond limit from the first contract for production of UNH solution in 1986, in complying with PNC's request to shorten the time taken for pre-delivery examination of the solution. The homogenization step initially followed the "cross-blending" procedure agreed between JCO and PNC. It used ten 4 L product delivery bottles, placed in line on the floor of building hallway in front of the calcination and reduction room. Solution was transferred from a product storage container for each batch holding about 2.4 kg U or 6 to 7 L solution, to each bottle so that the ten bottles received the same amount of solution from the container. This process was repeated for 6 or 7 containers (i.e. batches) to fill the bottles. The homogenization step was not included in the conversion process approved by STA and NSC in the license issued in 1984, but was introduced by JCO without application for amendment to the license.

The procedure was changed in 1995 by JCO, again without STA approval, to lessen the work load. In the new procedure, a pure UNH storage tank was used for homogenization of a whole delivery lot, at one time, by circulating and bubbling nitrogen through the solution instead of "cross-blending" with ten 4 L product delivery bottles. The solution was suctioned from the storage tank through a plastic tube attached temporarily to a temporary line at the bottom of the storage tank.

The final and fatal modification to the procedure was making use of the precipitation tank for homogenization instead of the pure UNH storage tank. The modification was introduced on the day before the accident. The workers poured solution through a funnel inserted into a handhole opening on the top of the tank.

The criticality accident occurred as a result of multiple decisions relating to facility operation. Three of them are most crucial and immediate causes:

- The precipitation tank was used for homogenization. The tank was the sole exception in the conversion process equipments in that it had unsafe configuration (e.g. geometry and capacity) from a view point of prevention of criticality.
- JCO and PNC agreed on a concentration of solution (about 370 g U/L) which minimized the critical mass for enrichment of about 19 wt.%.
- They also agreed on making a homogenized lot amounting 14.5 kg U, which is a little more than 6 times as much as batch mass limit. JCO actually processed 7 times as much as batch mass limit at one time after they started using the pure UNH storage tank for homogenization. The accident occurred when the mass in the precipitation tank reached about 6.9 times as much as batch mass limit (16.6 kg U).

More detailed chronicle of the change in the production process in the CTB is described in Chapter 4.

<<Figure 3.1 – 3.8will be inserted.>>

4. CHRONICLE OF JCO ACTIVITIES

4.1. Licensing History

In 1969, SMM obtained a license for processing nuclear fuel material, especially for re-conversion of low enriched uranium (LEU) (with enrichment less than 5 wt.%) mainly for commercial LWRs.. Construction of a plant was completed, and production of UO_2 production of low enriched uranium started in 1973.

In addition to the above mentioned license, SMM obtained another license in 1972 for “utilization” of nuclear material, which was meant especially for re-conversion of IEU (less than 23 wt.%). The material was intended for preparation of MOX fuel with 18 wt.% $PuO_2$to be loaded into the MK-1 core of the experimental FBR JOYO of PNC. Production began in 1972. Corresponding to the modification of the JOYO core into the MK-2, SMM updated the license in 1979. The CTB was designed for re-conversion of IEU with enrichment less than 12 wt.% (IEU). The Pu content of the MOX fuel of the JOYO MK-2 core was 30 wt.%. The uranium enrichment was changed from 23 wt.% to 12 wt.% because importing uranium with enrichment more than 20 wt.% became difficult from the view point of physical protection. The CTB was transferred in 1980 to Japan Nuclear Fuel Conversion Ltd. (JCO), which was established in 1979 and wholly owned by SMM. JCO obtained the license for “utilization of nuclear fuel materials” immediately in 1980.

In 1984, JCO updated the license for processing of nuclear fuel material, including re-conversion of IEU with less than 20 wt.% for the JOYO MK-2 J2 core fuel in the CTB. The enrichment was increased in order to extend the fuel burn up and to compensate the decrease of the fissile Pu ratio due to higher burnup of LWR fuels to be reprocessed. The licensed product forms were UO_2 powder and UNH solution.

To modify the facilities in the CTB for increased uranium enrichments, JCO had originally intended to submit an application for updating the CTB license obtained in 1980. However, the STA did not agree because the modified facilities would allow JCO to routinely operate with large amounts of uranium. This was outside the criteria for utilization of nuclear fuel material. A new license for “nuclear fuel fabrication” was required. An audit of STA’s review of the basic design by the NSC and reviews of the detailed design and construction plans by STA were required. The reviews were conducted as follows.

On November 22, 1983, JCO officially submitted the application for updating the license. STA completed the review by the end of January, 1984 and NSC completed its audit of STA’s review at the end of April, 1984. The license was issued by the Prime Minister on June 20, 1984. The detailed design and construction plans were submitted by JCO on July 6, 1984, and were approved by STA on July 26. After construction work was completed, the facility inspection was carried out, and its result was approved by STA on December 10. The operational safety program was approved by STA on December 21, 1984. The operation test with water was carried out in January, 1985 and the first campaign of UO_2 production for JOYO MK-2 J2 core fuel was begun in August, 1985.

In relation to licensing activities there were several problems as follows.

In the process of safety reviews by STA and NSC, the following two kinds of mass limit for criticality safety control had been imposed:

(a) Total mass from dissolution (or hydrolysis) process through precipitation process should be no more than the maximum mass limit per batch (2.4 kg U), and

(b) No more than 2.4 kg U should exist in each vessel or facility even if it had been designed with favorite geometry for criticality safety control.

However, these licensing conditions were not appropriately described in JCO’s safety related documents for operation. The condition (b) had never been described in the operations safety program or in its subordinate criticality control criteria. The condition (a) had also never been described, until it appeared in the criticality control criteria in 1995. The criticality control criteria had not been updated until 1988.

The option of UNH production was not noticed in the safety review by STA. .It was found in the audit by NSC. However, the process was not investigated in detail even by the NSC. Specifications for UNH, such as concentration and annual production rate, and the production process were not investigated in detail by the STA and the NSC. The need of a homogenization process was not noticed either.

After the modification of the CTB was licensed and the production had been begun, the Technical Standards on Design and Construction Method of Manufacturing Business of Nuclear Fuel Material was enacted in 1987. It required that “appropriate measures including a criticality alarm system should be implemented with the assumption of the occurrence of a criticality accident" in manufacturing facilities processing uranium with enrichments higher than 5 wt.%. Although the existing gamma radiation area monitors were regarded as virtually a criticality alarm system, no means were requested for terminating a criticality accident or for mitigating its consequences.

The history of contracts JCO had been awarded is shown in Appendix I.

4.2. Changes in facility and operation

The production system in the CTB,which was licensed in 1984, is shown in Figure 3.8. Variations of the UNH solution production process with regulatory implications are shown in Figure 4.1. Concerning the re-dissolution process, stainless steel buckets were introduced in 1993, replacing the licensed dissolution tank. Furthermore, although there was no homogenization (mixing) process for purified UNH in the licensed process, such a process was introduced without modification of the license. For the homogenization, a cross-blending method using 4L product delivery bottles was utilized at first. Another method, utilizing a storage tank intended for pure UNH, was introduced in 1995. Finally, a method utilizing the precipitation tank for this purpose resulted in the accident.

Changes in the whole process and in the facility are described as follows.

From the commencement of the production of UO_2 in the modified CTB in 1985 to the accident in 1999, there had been seven types of production system (facilities and process) which were planned and/or carried out. The last production system resulted in the criticality accident.

Production system (1): *UO_2* ***production system in the period 1985-1991 (Figure 4.2)***

The first campaign in the modified CTB was to produce UO_2 from U_3O_8 powder. The utilized facility was in accordance with the license. However, the actual operation process was different from the license in the mixing process for homogenization. Although the licensed process consisted of only one step for mixing with a mixing can, the actual mixing process consisted of two steps. The first step of mixing was to mix five batches of UO_2 in a mixing can, and the second step of mixing was a 10 x 10 cross-blending with ten mixing cans. The second step of mixing using the cross-blending method had not been mentioned in the licensed documentation, but had been regularly carried out since 1974.

In the 3rd and 4th campaigns from 1985 through 1988 (see Appendix I), the purity of the material U_3O_8 had already satisfied the product specification and then the extraction process for purification was bypassed. Namely, intermediate product UNH was transferred directly from the dissolution tank into the pure UNH storage tanks bypassing the extraction columns.

Production system (2): UNH production system plan agreed by PNC and JCO on 1986/06/25 (Figure 4.3)

Before the production of UNH solution began in October 1986, a new objective was set to homogenize UNH solution over a lot of about 40 L (15 kg U). This required processing seven batches of 2.4 kg U. In order to comply with the objective, a cross-blending method utilizing 20 of the 4 L product delivery bottles was proposed by JCO and agreed by PNC. The cross-blending method of this homogenization process required 10 x 10 times of measuring precisely 0.4 L of UNH and transferring it from a product vessel to another product vessel.

This homogenization process with cross-blending method was proposed by JCO to extend the delivery lot size. This complied with PNC's request to shorten the time taken for pre-delivery examination of the solution.

The criticality safety related implication of the process was not investigated at the time.

Production system (3): UNH production system in the JOYO 4th campaign in 1986-1988 (Figure 4.4)

Although the planned 10 x 10 cross-blending method had been agreed for homogenization, it was not actually carried out. Instead of delivering one batch of UNH (2.4 kg U) into the first 10 product vessels, the workers delivered one batch of UNH into a dedicated stainless steel vessel and carried out 7 x 10 cross blending.

Ten product vessels were located on the floor in front of the calcination and reduction room as shown in Figure 3.5. However, neither marking to support locating product vessels nor measures to prepare them were implemented at that time. This means that the facility and procedure of the cross-blending were not in accordance with regulatory requirements for criticality safety control for plural units. Furthermore, the whole cross-blending process could be regarded virtually as one batch for the workers.

The process might have exposed workers to a high risk of chemical hazard due to their direct contact with liquid or vapor from toxic nitric acid and UNH. The process also introduced the burden of a heavy workload. Workers therefore probably wished to improve these stressful working conditions. It should be noted that beside the occupational radiation health hazard of a criticality accident, internal exposure through the inhalation of uranium oxide powder was also a key concern. However, the risk of such internal exposure was rather small if the worker was equipped with a mask.

As already mentioned above, in the 4th campaigns in 1986 through 1988, the purity of theU_3O_8 had already satisfied the product specifications. The whole purification process was then bypassed. U_3O_8 was put into the dissolution tank for producing UNH product with a concentration of 350 gU/l.

Production system (4): UNH production system in the JOYO 6th campaign in 1993 (Figure 4.5)

In 1993 a stainless steel vessel was introduced for the re-dissolution process, replacing the dissolution tank in order to make the process more efficient. The changewas proposed by the head of the production division in JCO. The procedure of the cross-blending method for homogenization was 7 x 10 which was similar to that of the 4th campaign.

The stainless steel vessel was not designed with favorable geometry for criticality safety control. Only mass limitation was a valid control to avoid criticality.

Production system (5): UNH production system in the JOYO 7th campaign in 1995-1996 (Figure 4.6)

In 1995, the pure UNH storage tank was utilized for the homogenization process, replacing the cross-blending method. This change was intended to bring about greater efficiency, a lighter workload, and less occupational risk of chemical hazard. The change was proposed by the chief engineer of the CTB team and was approved by the technical division in JCO. The stainless steel vessel was also utilized for the dissolution process in the uranium oxide purification process. This decision was a result of a misunderstanding of the new chief engineer of the CTB team who orally communicated with the predecessor when taking over the duty.

The change of the process which allowed seven batches of UNH to be put into a pure UNH storage tank was extremely unfortunate because the mass limitation within a single unit was largely violated. It finally led workers to put a large amount of UNH into the precipitation tank on the day of the accident in 1999.

Production system (6)**: UO_2 **production system in the period of 1996-1998 (Figure 4.7)

The stainless steel vessel was utilized for the dissolution process in the uranium oxide purification process also in the UO_2 production.

Production system (7): UNH production system in 1999/09 (Figure 4.8)

The accident occurred when this system was applied. The workers began to utilize the precipitation tank for the homogenization process, thereby replacing use of the pure UNH storage tank. The change was proposed by the workers themselves for more efficiency without enough consideration of criticality safety control. They wanted to complete the campaign as fast as possible because they were busy with other missions.

Causes and background of the change are discussed in detail in Chapter 9.

4.3 Criticality risk in the production system in the CTB and its cognition

The criticality risk of the facility in CTB was judged to be small enough in the licensing process. This regulatory judgment was unchanged until the day of the accident, and the risk which had actually been growing in proportion to the modification of the facility was not noticed in any safety assessment.

The criticality risk in the production system for conversion of IEU in the CTB had been escalated by producing UNH solution with high concentration in addition to UO_2, introducing a homogenization process of the UNH solution over an amount much more than the regulatory mass limit for criticality safety and changing homogenization method from cross-blending with product delivery bottles into a method utilizing a pure UNH storage tank. The final modification of the production system, i.e. utilization of a precipitation tank for the homogenization of the UNH solution instead of the pure UNH storage tank, resulted in the criticality accident.

In the homogenization process using the cross blending method with product delivery bottles, each bottle had two independent criticality safety properties: its geometry with a short diameter which could prevent its content from reaching criticality and the capacity less than the regulatory mass limit for criticality safety (2.4 kg U). Accordingly, the criticality risk was rather small due to this double safety control. However, in the modified method utilizing the pure storage tank for homogenization, the tank had only a geometric property to prevent criticality but could be filled with an amount of UNH solution beyond the regulatory mass limit . The workers did not understand that criticality was barely prevented with the small diameter. The management people thought that criticality risk was small as long as the pure UNH storage tank was utilized for homogenization.

The involvement of JCO in conversion of IEU was little known outside the company, although it had continued for twenty seven years. It was not so much regarded as safety-significant that there was a precipitation tank without favorable geometry for criticality control in the CTB, and that converted uranium was shipped to JNC in the form of solution in addition to powder after1986. The regulatory review for licensing the facility design and the operational safety program (1983-1984) did not explicitly address the risk associated with the production and handling of IEU solution. Although the occurrence of criticality was not sufficiently taken into consideration, the review concluded that the hazard analysis was adequate.

The uranium solution for shipment had a high concentration and was homogenized over an amount more than criticality mass limit before the shipment. In JNC, only a limited number of staff members who were involved in the contracts with JCO knew these facts. STA had chances to be aware of the concentration and the quantity of the solution through the licensing process of the shipment casks and the uranium receiver tanks in JNC. However, STA may not have fully recognized the implication of these specifications in the light of criticality safety, because the license applications were submitted by JNC, the owner of the casks and the receiver tanks, after the JCO facility had been licensed. Finally, STA stayed unaware of the existence of the homogenization process. The process was introduced in 1986 without regulatory approval, and was not detected by STA through the operational phase.

<<Figure 4.1 – 4.8 will be inserted.>>

5. CRITICALITY EVENT

5.1. Occurrence of Criticality

From the morning on September 29, 1999, just the previous day of the accident, three workers of the special crew had started production of homogenized solution, so-called "JOYO 9th Campaign" in the CTB (Photo 5.1, Figures 5.1 and 3.5). The aim of this campaign was to manufacture 57 kg U of UNH solution for the fuel processing, which was to be used in JOYO, the fast experimental reactor at Oarai. The handled solution contained 18.8 wt.% enriched uranium and its concentration ratio was about 370 g U/L.

The jobs of the campaign was started on September 10, and they had already got purified U_3O_8 powder by September 28. As mentioned in Chapter 4, the processes for manufacturing the solution had been developed without enough consideration to criticality safety control in those production stages. The workers were only cautious of avoiding the sedimentation of solution, without any consideration of a "supercritical mass" problem. There was a mass limitation, the so-called "one batch restriction", which strictly restricted the mass to less than 2.4 kg U for each step of all production processes.

In this procedure, powder of U_3O_8 equivalent to the mass limit for one batch was dissolved in nitric acid in a stainless steel bucket with 10 L of capacity. Then the filtered UNH solution was moved into a 5 L stainless steel beaker (Photo 5.2) and was poured into the 95 L precipitation tank (Photo 5.3) through a funnel inserted into a hand hole (Figure 5.1). In each step, homogenization using a mixing fan driven externally was required. Finally, well homogenous UNH solution, equivalent to 7 batches in total, was expected to be inserted into the large precipitation tank.

By the end of September 29, the workers had finished 4 batches (9.71 kg U) and started to repeat the same process for the remaining 3 batches (7.06 kg U), starting around 10:00 in the morning of September 30. When dealing with the 7th batch, one of the three workers tried to pour the latter half of the 7th batch to the precipitation tank through the funnel which was held by another worker. The third worker, the senior group leader of this working group, was sitting outside of the room and was to begin the related paper work.

While pouring the solution, the workers felt a strong shock and heard a strange sound that they had never experienced before. According to an unconfirmed report from one of the workers, he had observed a blue light flashing. They immediately stopped pouring and escaped out of the room. The stainless steel beaker in which a small quantity of the solution still remained. Simultaneously a gamma ray monitor, installed at the ceiling of the room triggered an alarm to indicate a very high dose rate (Figure 5.2). According to a record, it occurred at 10:35 on September 30. It is memorized as the moment of the first, and hopefully the last, fatal criticality accident in Japan.

Three workers were exposed severely, but managed to escape to the decontamination room in the adjacent building connected to the CTB by themselves. One of them fainted near the door in the room. They were carried out from the building by other colleagues working at other places near the CTB where the criticality occurred. It is presumed that those colleagues were not quite aware of the workers' suffering from the criticality accident. The senior group leader of this working group reported that he immediately recognized the unusualness of the situation. After helping the two workers to escape to the decontamination room, he returned to inspect the inside of the room where the accident happened. He could not find any visible change near the working space.

Because of unavailability of information on neutron dose rates at an early stage, the continued criticality excursion was not immediately recognized by the staff in other nuclear facilities near the accident site either. After the distinguishable first transient sequence was terminated, it was later understood from several observed neutron dose rate sources that the criticality excursion had not terminated after this first shock.. Several fission peaks occurred within about 25 minutes. Gradually the power (fission rate) got closer to a constant level and continued to stay at quasi-steady delayed critical state in the following 19 hours.

5.2. Recognition of Criticality Continuation

Observation of environment gamma dose rates, after the occurrence of the accident, showed that quite high gamma dose rate continued after the initial burst of indications. The termination of the criticality was doubted. Indication of high alpha monitoring values might also have had sensitivity to neutrons. Though neutron data from JCO and other monitoring spots in the neighboring area were still unavailable, possibility of the continued criticality was indicated in the early afternoon by several specialists in other organizations (including JAERI and JNC), dealing with nuclear material in the vicinity of the JCO site. Immediate initiation of neutron monitoring and gathering of neutron information near the accident site were suggested.

Before starting neutron monitoring, the specialists had asked JCO about the accident situation, and about the physical structure of the facilities used in the process, including the precipitation tank. Though JCO could not supply detailed structural and operational information on the precipitation tank where the criticality had occurred, some voluntary calculations to evaluate the criticality were undertaken by specialists at JAERI and JNC. The simplified calculation model was based on a sketch (Figure 5.3) provided by JCO at that time, roughly showing the situation of the tank. JAERI and JNC, which were both under the jurisdiction of STA, had been requested by STA to support accident relief activities. However, they were not given detailed instructions and therefore established their own supporting centers around 13:00 and sent supporting staff members to local governments by their request (Figure 5.4).

An official report from the NSB of STA presented at 14:00 to NSC still did not clearly mention the criticality situation. However, the commissioners of NSC had recognized the possibility of a continued criticality excursion.

From about 16:30, JNC health physicists started neutron monitoring at the JCO site boundary and in some buildings in the JCO site. They observed a few mSv/h at several spots (Figure 5.5) which definitely gave indication of an on-going criticality event. The data were officially reported to relevant authorities including STA at nearly 18:30. STA immediately recognized it as an obvious evidence of an on-going criticality and asked all related organizations to prepare for actions to terminate the event. It was shown later that the neutron monitors (2 km and 1.7 km away from JCO) at the JAERI Naka site (Figure 5.6) had recorded direct neutrons from the accident spot in JCO and also the time dependent neutron level variation in the whole accident period, including during the initiation moment (Figures 5.7 and 5.8). The data exactly show the accident progress and allow the determination of the ratio of peak to background in the neutron level due to continued delayed criticality (Figures 5.9). However, the staff in the JAERI Naka site was not clearly informed of the possibility of a criticality and could not recognize the relevance of the recorded neutron data at the moment of the accident. The data were handled as a general background reference, without special remarks (they were piled up on a desk with many other documents at the JAERI Tokyo Office).

Between 17:00 and 18:00, most of the specialists from organizations involved in the response in Tokaimura had confirmed the on-going criticality and started to investigate release scenarios from the delayed critical state. Several investigations were carried out separately in each involved organization, without appropriate coordination, until the Government Accident Countermeasure Local Center (GACLC), an authorized supervising on-site committee, was established in accordance with the Disaster Countermeasures Basic Act.

About 20:00, the deputy director general of STA arrived at Tokaimura as the head of the GACLC. The GACLC was then established with headquartered in a building in the Tokai Research Establishment of JAERI. Most of the key specialists joined in the GACLC and provided their findings of the investigations in each organization.

The on-going criticality event was announced to the public around 20:00. Fortunately, the announcement did not cause severe public reactions.

5.3. Preparation Steps for Release from Delayed Critical State

The general assembly of the GACLC was assembled about 21:00 and was chaired by the deputy director general of STA who had the authority to command on-site emergency operations as the head of the GACLC. Before his arrival, a provisional on-site emergency operation center, headed by the deputy director of the NSB in STA, had already been established. This was combined with the GACLC. The NSC commissioners, accompanied by specialists from Tokyo, joined in the discussion about 22:00. Almost all specialists who were expected to contribute to practical discussions to deal with the criticality accident had assembled at the GACLC from relevant organizations in Tokaimura.. Many organizations related to the handling of the criticality accident from various aspects had sent their own staff to the meeting.

A provisional calculation of the criticality event was provided for the GACLC by specialists from JAERI and JNC. The calculation was based on pre--distributed nuclear and structural data from JCO (Figure 5.10). Rough information on the mechanical and material structures of the precipitation tank and on the conditions of auxiliary supporting tools and parts were briefed, but detailed information on the facility and its actual operation was not available. All workers who were concerned with the accident conditions had been already transferred to a hospital in the Chiba Prefecture, more than 100 km away from Tokaimura.. Inquiry by telephone was allowed only for a very short time. Detailed drawings and specifications were kept in the premise of the JCO site, where high dose rates were expected due to the on-going criticality. JCO could therefore not supply such essential information (Figure 5.11) before 20:00.

However, from a nuclear engineering point of view, the water cooled tank system was a very simple system which could be recognized as an aqueous homogeneous cylindrical geometry system filled with fresh fuel material and surrounded with a light water reflector. For such a simple system, calculation models for thermal reactors were expected to give good results. Fortunately, JAERI had operated the NUCEF (Nuclear Fuel Cycle Safety Engineering Research Facility), a very flexible critical assembly with similar characteristics, and had nuclear data libraries and calculation codes for criticality calculation corresponding to various situations, including time-dependent characteristics (Figure 5.10).

Several methods to reduce reactivity from the established delayed critical system were evaluated. One method, draining water from the cooling water jacket surrounding the tank, was considered to be feasible because it could be completed outside of the CTB, without too much exposure dose. The observed neutron flux, which had indicated nearly constant level, meant that the system was very close to a delayed critical state. A calculation by JAERI showed that removing the reflector (estimated -5 $) was expected to easily terminate the delayed critical state. This calculation was based on more reliable information additionally supplied from JCO between 20:00 and 21:00. Applied conditions for the calculation made in the first night after the accident were also indicated in Figure 5.10. This urgent estimation was compared with results of accident condition confirmation experiments using the NUCEF and nuclear data shown in Section 5.6, and was verified.

Several other ways to reduce reactivity of the system were also considered but difficult to carry out. Putting nuclear poisoning materials into the tank might be very effective, but there was no practical way to put the poisoning materials into the tank, considering the allowable total exposure dose of the personnel who were assigned to the operations. Breaking the tank wall to release the solution outside the vessel seemed to be feasible by remote gun shooting, but might spread solution contaminated with fission products.

Finally, draining water from the cooling water jacket surrounding the tank was selected by the GACLC as the measure to terminate the criticality event. Furthermore, putting poisoning materials into the tank after termination of criticality was strongly recommended by the GACLC to keep the system subcritical. The GACLC also requested a confirmation that the kinetic behavior of the system would not quickly recover the reduced reactivity by the decrease in temperature and the ceasing of bubbling which would be caused by the termination of the self-sustaining nuclear fission chain.

Based on the above mentioned decision, the GACLC requested a small working group consisting of representatives from NSC, STA, JAERI and JNC to investigate each step of draining water in detail, taking health physics aspects into consideration. After some discussion, the working group suggested that, for each step of the operation, a leader who was appointed by the deputy director general of STA be sent to the JCO site with a few supporting staff from each special field. This suggestion was approved by the GACLC, but actual nomination of the members who would carry out each operation was subject to negotiation between the organizations concerned and also within each organization. Especially, the JCO management needed to spend a rather long time to discuss responsibility for carrying out operations in high-exposure areas. The general agreement finally reached by the organizations after more than one hour of negotiation was as follows: JCO employees would handle the facilities, staff from JAERI and JNC would be in charge of assisting work like health physics service, and staff from STA would be in charge of information exchange between the inside and the outside of the JCO site. JCO management called their employees back from their home. Operation work was initiated about 2:00 on October 1.

Meanwhile, Ibaraki Prefecture officially announced a recommendation for residents living within a radius of 10 km from the JCO site to stay indoor at 22:35. This recommendation had been authorized in accordance with the Disaster Countermeasures Basic Act which is a general law for preparedness for natural disaster and agreed by the Emergency Technical Advisory Board (ETAB). However, among nuclear specialists there had not been any common agreeable technical evaluation, on which the evacuation could be based.

5.4. Termination of Criticality

To drain water from the cooling water jacket of the precipitation tank, the easiest way was to cut a cooling water pipe connected to the cooling tower. This was located outside the CTB (Photo 5.4 and Figure 5.12). The path to get access to the pipe was very narrow and very poorly paved. Possibility of introducing shielding materials between the building wall and the space where the operation would be performed was investigated. However, it was concluded that it was less effective, i.e. it might reduce exposure per unit time but force the operation members to stay in the place longer because the shielding material would make the working space narrower and thus reduce efficiency of the operations.

In order to reduce exposure of each member, presence in this high-dose area was limited. In addition personal neutron dosimeters were supplied to the members. The dosimeters supplied to the first group indicated quite varying values, and after that each member carried two dosimeters.

On the occasion of the serious accident, the maximum planned exposure was allowed to be no more than 100 mSv by the law and ordinances at that time. The aim when planning the operation was to keep the exposure below one half of that. Based on the dose limit, a time limit for each step of the operation was preset. After the first step of the operation, the time limit was reduced from three minutes to one minute. Each step of the operation was required to be followed by a time keeper. An operation member could be asked to stop working and to escape from the working place to the standby car. Each operation member wore a protection suit and used an air mask (Photo 5.5).

The operation to drain water was divided into the following ten steps that were undertaken by ten groups that were organized with a total of 21 members (note: less exposed members joined again in later steps). In the original plan, the whole operation was supposed to be divided into five steps and to be undertaken by five groups each of which consisted of three members. However, while putting it into practice, it was recognized that more steps were required to terminate the criticality in practice. Therefore the plan was revised as seen appropriate at that moment. Around 2:30 the first group started from the preparation building. Each time in the bracket shows when a group carried out an operation step in the JCO site. The modification of the system to drain cooling water was made through the operation shown in Figure 5.12.

1. **Visual and sound checks of pump and valves**
   Some photos around the cooling tower were taken (Photo 5.6) and the normal working sound of the circulation pump was checked. This was the pump which made the cooling water circulate through the cooling system including water jacket. (2:35-2:38)
   Three of the photos showed that the valves near the pump were open.
2. **Recheck of pump by sound and vibration**
   The condition of the circulation pump was rechecked by sound and vibration. (3:01-3:03)
3. **Valve operations**
   The cooling tower feed valve was closed. The drain valve from the tower was opened. (3:22-3:25)
   It was expected that the cooling water would be drained off, but it did not drain sufficiently. The neutron monitoring indicated a tendency to decrease.
4. **Effort to break pipe**
   The 4th group tried to break the pipe connected to the cooling tower but did not succeed. They searched a hammer to break the pipe. (3:48-3:58)
5. **Pipe breaking**
   The pipe connected to the cooling tower was broken with a hammer by the 5th group. A low-level water flow from the broken part was observed (4:16-4:19).
6. **Effort to separate pipe components from each other**
   The 6th group tried to loosen a union joint in the pipe between the cooling tower and the circulation pump, but failed to take it off. (4:41-4:43)
7. **Separation of pipe components**
   The 7th group succeeded to take the union joint off. (4:59-5:02)
8. **Connection of new pipe and opening of flange**
   A new pipe to send purging gas was connected to the part where the union joint was removed.

The 8th group loosened four bolts at a flange in the pipe connected to the cooling water and confirmed that water was running. (5:19-5:22)

9. **Connection of drain pipe**
   The 9th group connected a nozzle of a drain pipe to the flange. (5:44-5:46)
10. **Argon gas injected**
    The 10th group sent purging argon gas and confirmed that the cooling water ran out. (6:00-6:04)
    Neutron level rapidly decreased at many monitoring points within and near the JCO site. (Figure 5.13)

To keep the system in subcritical state, boric acid solution was poured into the precipitation tank, startingfrom 8:40. 200 L of boric acid solution, with a density of about 20 g/L was prepared at JAERI and stored in a water tank of a fire engine at JNC. About 17 L of solution were poured from the hand-hole of the precipitation tank through a hose connected to the water tank (Photo 5.7).

All of the operation steps to terminate the criticality were now completed. Investigation of the inside of the CTB, including surface contamination survey of the floor and other parts, and pressure maintenance of the CTB to control release of fission products, were carried out. Dust and iodine samplers were newly installed at the stack of the building.

5.5. Nuclear Characteristics of the JCO Criticality Accident

The nuclear transient during the JCO accident consisted of two phases: an initial power excursion caused by prompt criticality, and a subsequent quasi-steady phase with delayed criticality at low power in balance with the heat loss from the UNH solution. The latter phase continued for almost 20 hours, until it was terminated by the draining of the cooling jacket water, as described in section 5.4. This sustained criticality characterized the accident and enhanced the social consequences of the accident by necessitating the evacuation of the nearby residents.

Following the NSC investigation that was conducted immediately after the accident, extensive evaluation of the nuclear processes, including the initial criticality, and the solution kinetics during both of the two phases, was made by JAERI[4] and JNC for better understanding of the event. Code analyses, transient criticality experiments with use of the NUCEF/TRACY (Transient Experiment Critical Facility) [5, 6, 7], and heat loss experiments with a full-scale mock-up were conducted. The major outcomes from these studies are summarized in Appendix II. Some important results derived in these studies are shown in Table 5.5.1.

- Table 5.5.1. Numbers characterizing the nuclear transient in the JCO accidentTotal number of fissions: 2.4×10^{18}
- Number of fissions in the initial portions of the accident
    - First pulse: $5\text{x}10^{16}$
    - "Burst" phase (initial 25 min.): 2 to 5×10^{17}
- Excess reactivity: less than 3 dollars
- Reactivity due to neutron reflection by water in the cooling jacket: about 5 dollars
- Solution temperature coefficient of reactivity: -3 cents/℃
- Average solution temperature during the sustained, delayed criticality phase: about 70℃

<<Photo 5.1 – 5.7 and Figure 5.1 – 5.13 will be inserted.>>

6. EMERGENCY RESPONSE

This chapter provides the legislative and administrative framework of the response established at the time of the accident, a chronicle of response actions to the accident mainly taken by JCO, the government and organizations including JAERI and JNC which supported mitigation actions of JCO and the government, and social impacts observed after the accident. Detailed medical treatment given to the three workers at NIRS and other medical facilities is described in Appendix IV.

6.1. Legislative and Administrative framework of the response

The Disaster Countermeasures Basic Act stipulates that the national government, prefectures and municipalities shall develop and carry out emergency preparedness and response plans and basic policies for emergency measures to deal with natural and human-induced disasters. The Central Disaster Management Council, which consists of the Prime Minister as the chair and other Ministers concerned, had prepared the national Basic Disaster Management Plan in which the chapter of "Nuclear Emergency Preparedness" clarifies roles and responsibilities assigned to the national government, local governments (prefectures and municipalities) and operators and prescribes arrangements for preparedness, response and recovery regarding nuclear accidents. The NSC had also issued a Guideline on Nuclear Emergency Preparedness which specifies technical matters including definition of emergency planning zones, criteria for protective measures, etc.

Such legislation for nuclear emergency preparedness in Japan had been developed step by step since the accident at the Three Mile Island (TMI) nuclear power plant in 1979. The NSC Guideline was issued in 1980 as one of the measures to maintain preparedness for accidents like the TMI accident. The guideline naturally therefore mainly focused on power reactor accidents. In the following years, prefectures and municipalities in the vicinity of power stations had established their own emergency plans in accordance with the Guideline.

The chapter of "Nuclear Emergency Preparedness" was added to the National Basic Disaster Management Plan as the 1995 South of Hyogo Prefecture Earthquake prompted the government to incorporate specific plans for each kinds of hazards including nuclear accidents to the national plan. Legislation in local governments (prefectures and municipalities) followed in accordance with the updated national plan.

The fire and explosion accident in the JNC low-level waste solidification plant in March 1997, causing a release of a small quantity of radioactive materials, also resulted in several changes of legislation. An official was placed in Tokaimura for close surveillance of the operational practices in the nuclear fuel facilities in Tokaimura, and for liaison between Tokaimura and Tokyo in unusual situations. The first official, on duty since April 1998, had visited the CTB in the JCO site twice, however the facility was out of operation at both times.

On September 13, 1999, seventeen days before the accident, the NSC Guideline was revised and a position paper on steps to be taken toward reinforcement of institutional countermeasures against nuclear hazards was issued by NSC. The steps included development of a new special law for nuclear emergency preparedness, which had been an issue for years and was realized shortly after the JCO accident (see Chapter 10).

These legislative and administrative actions mainly focused on the preparedness against a postulated release of radioactive material from a power-generating or reprocessing plant. The possibility of a radiation accident due to criticality in a fuel material processing plant like the JCO accident was not specifically taken into account in the national or local emergency plans.

6.2. Response actions

6.2.1 Chronology of response actions

The uranium solution in the precipitation tank of the CTB reached prompt criticality at 10:35 on September 30, 1999. Emergency response actions taken after the occurrence of the criticality are chronologically described in the following subsections.

(1) 10:45 - 11:00 at JCO

In about 10 minutes after the alarm went off, about fifty of the site workers were evacuated to a muster area, which was an open, unshielded ground about 150 m away from the CTB. It took some more time for the JCO safety control section to recognize that the accident occurred in the CTB, because the alarm was triggered at all three uranium processing facilities in the JCO site. A total of 121 workers at 11:00 moved to the south-east side of the administration building, about 280 m away in a straight line from the CTB, after high dose rates were measured at the first muster area.

The three overexposed workers were found incidentally by an SMM employee who showed up at the CTB to shut down the machines there. He called the fire department of Tokaimura for an ambulance at 10:43, without recognizing that the symptoms were due to radiation exposure. The ambulance crew arrived at the building at 10:56, but was unprepared for this kind of accident. The JCO safety control team found the radiation level in the CTB to be particularly high, and urged the ambulance crew to leave the site with the overexposed three workers.

The foreman reported the occurrence of an accident to his supervisors. (Discrepant testimonies have been made on what he reported and to whom.) While the three workers were kept in the JCO site for more than one hour before the ambulance left for the hospital (Chapter 8), the JCO management apparently did not take the opportunity to ask the foreman for detailed information on the operation that caused the accident. The information obtained from the workers was not much more than a few words and numbers: “CTB; the precipitation tank; the three workers’ names; 18.8 wt.%; 360 g/L; 16 kg; and 2.3 kg mass limit”, which were left on a whiteboard in a conference room of the administration building and found after the departure of the ambulance.

(2) 11:15 - 12:15, JCO, Ibaraki Prefecture

JCO sent the first report to STA, and the offices of Ibaraki Prefecture and Tokaimura, by telephone and FAX, more than 40 minutes after the onset of the accident. (The municipalities surrounding Tokaimura received the alert even later, about 13:30.) The FAX report stated briefly that two (rather than three) workers had been exposed to radiation and transported to the National Mito Hospital, with an additional remark that read “Possible occurrence of a criticality accident.”

One of the monitoring stations of Ibaraki Prefecture (about 1400 m away from the JCO site) had detected an increase in the gamma dose rate at 10:38, but the cause and the source were unknown until the initial alert from JCO was received. Upon receipt of the alert, the Prefecture started an extensive monitoring in anticipation of radioactive material release. The prefecture police department blocked the public roads around the JCO site at 12:15.

The STA resident official (see Section 6.1.1) entered the JCO site after 12:00 for fact-finding. Prefecture officials also did this nearly at the same time.

JCO started measurements of the gamma dose rate on the site boundaries after 11:36 and reported by FAXes at 12:01. JCO had no neutron survey meters. From this time on, the measured dose rate on the nearest site boundary (~90 m from the precipitation tank) indicated almost constant values between 0.78 and 0.84 mSv/h until 15:30, as shown in Figure 5.4.

(3) 12:30, Tokaimura and Ibaraki Prefecture Offices

The office of Tokaimura informed the residents via public loudspeakers and an emergency radio broadcast of “an accidental release of radioactive material” in the JCO site, and advised school children and personnel as well as the nearby inhabitants to stay indoors.

Ibaraki Prefecture issued a press release on the initial alert from JCO. An observation was presented that the accident was seemingly terminating because the signals from the prefecture’s monitoring stations had returned to the normal values.

(4) 12:30, STA

The NSB and the Atomic Energy Bureau (AEB) in STA instructed JAERI and JNC to nominate experts of health physics, dosimetry and criticality for technical assistance and advisory to the municipalities. Follow-up instructions regarding the expert nominations were not given by STA to JAERI and JNC through the whole period of response to the accident. “The possibility of a criticality accident” at the JCO site was informed orally by NSB to these two institutes, and this oral information was not necessarily retransmitted in writing even when the institutes requested monitoring of radiation levels to their concerned sections.

(5) 12:40, Prime Minister Office

STA reported the initial report from JCO to the Prime Minister. A government-wide action was not taken until the government emergency headquarters (EHQ) in Tokyo was established at 15:00

(6) 14:00, Nuclear Safety Commission

An official report from the NSB in STA to NSC presented at 14:00 still did not clearly mention the situation of criticality. However, the commissioners of NSC had recognized the possibility of an on-going criticality event. NSC decided to convene a meeting of ETAB in order to prepare for the situation at 15:30. ETAB consisted of about 20 leading specialists in nuclear safety fields. The members of ETAB had started working and discussion around 17:00. Even after 18:00, when the first meeting of ETAB was officially started, information to figure out the whole situation of the accident was still not fully available. ETAB therefore decided to dispatch two commissioners of NSC to Tokaimura in order to collect relevant information directly. The two commissioners left Tokyo for Tokaimura around 19:00.

(7) 14:08 - 14:40, Tokaimura Office

JCO asked the Mayor of Tokaimura twice (14:08-14:40) for evacuation of the nearby residents within a radius of 500 m, as a necessary step to be taken before the off-site evacuation of the JCO employees. The company representatives reported that the site-boundary gamma-ray dose rates kept almost constantly high values, and that most of the JCO employees had evacuated to the administration building about 280 m away from the facility, while the nearest residence was about 150 m away (Chapter 3). The office of Tokaimura asked the Prefecture and STA for advise by telephone. The Prefecture advised against evacuation on the ground that the dose (gamma ray) was still much lower than the criterion of 50 mSv, and recommended indoor sheltering. The STA authorities were unavailable on telephone.

At 15:00, the Mayor, however, decided to evacuate 47 households within a radius about 350 m from the JCO facility. The evacuation zone was determined based on gamma dose distribution as measured by JCO at the community block boundaries. The evacuation started about 15:30 and was completed about 20:00.

(8) - 15:00, JCO

In response to direct requests from JCO to JNC, four JNC engineers entered the JCO site about 15:00 to provide dosimetry instruments and technical support. The JNC engineers were prepared for a possible release of radioactive material. After the arrival in the JCO site, they found high readings on the alpha survey meters, in addition to that of the gamma meters, and suspected that the high alpha readings might have been caused by neutron radiation. Since they had not brought instruments for neutron, they asked JNC for delivery of such neutron survey meters.

About 15:40, JCO briefed the JNC engineers on the internal configuration of the precipitation tank, the amount and concentration of uranium in the solution, and the possible influence of the water jacket on reactivity. A sketchy drawing of the precipitation tank was made based on the briefing. A criticality specialist of JNC joined about 16:40, and discussed possible ways for termination of the criticality event with JCO staff members. No information on the operational situation at the occurrence of criticality nor the precise drawings of the precipitation tank was provided by JCO until about 19:00, except for the site-boundary dose rates.

By 16:00, JAERI and JNC nuclear experts who were informed of gamma dose rates at the site-boundary suspected the ongoing criticality. Neutron measurement was performed at different places.

The JNC engineers started neutron measurements in the JCO site at 16:30 and found high neutron levels that evidenced the sustained fission reaction. The site-boundary dose rates (up to 4 m Sv/h on the nearest site boundary) were reported to STA and to other organizations involved in the response by 18:30. By the same time, JAERI at its Naka site had measured neutron dose rates, which provided another evidence.

JCO employees started evacuating from the site about 18:15. Seven of them indicated contamination during the pre-evacuation survey and were sent to JNC for measurements by a whole-body counter.

Meanwhile, STA officials, headed by the NSB vice director, arrived in Tokaimura at 15:34, and moved to the JAERI Tokai site about 16:30 to establish an STA local EHQ there. The EHQ, however, was not provided with the detailed information from JCO. JCO started communicating with the STA EHQ about 18:10, providing the sketchy drawing of the precipitation tank which was made in the discussion between JCO and JNC.

(9) - 20:00, STA and Governmental EHQ in Tokaimura

The STA EHQ in Tokaimura was chaired by the STA parliamentary vice minister and consisted of government-wide staff members including representatives from other ministries. After arrival of the STA vice minister at 20:00, government-wide discussion and decision-making with advice and support from Tokyo could be started. The EHQ thereafter served as a de facto Governmental EHQ (GEHQ).

Measures to terminate the criticality had been investigated and prepared since about 15:00 by JAERI on its own initiatives.

Such information as a detailed drawing of the precipitation tank became available to the GEHQ only after the JCO management joined the GEHQ about 20:40. About 21:00, STA officials by telephone interviewed the concerned workers' foreman, who had been air-lifted to the NIRS hospital (chapter 8) to get detailed information on the work that caused the accident. During the interview, it was revealed that the workers poured the solution into the precipitation tank using a “bucket” or beaker through a hand-hole. The foreman was uncertain whether the cooling water was circulating or not.

It was reported to the GEHO by JCO engineers that no line was available for boron injection into the precipitation tank, nor for drain of the solution in the precipitation tank by remote operation from outside the CTB. To drain the cooling water from the water jacket, by modifying the cooling water line connected to a cooling tower outside the CTB, was considered as a feasible method to terminate the criticality, i.e. it was considered that the drain would remove the reactivity representing the neutron reflection from the cooling water. However, it was still not known whether the line had a valve that could lead water out from the water jacket. Also, the steady-state reactivity decrease (the reduction in the excursion power level will compensate at least for some of the negative reactivity) due to the planned drain had to be determined in order to evaluate the effectiveness of such an operation.

JAERI started a quick analysis of two-dimensional (r-z) neutron transport in the precipitation tank to evaluate the reactivity effect of water drain from the water jacket. According to the analysis, done by JAERI in 2 or 3 hours, a negative reactivity of 4 % (5 $) could be obtained. JAERI also had started the preparation of boric acid solution to be injected into the precipitation tank to keep the system permanently and safely subcritical after the termination of the criticality. Two hundred liters of 20 g/l solution was prepared and loaded on a JCO fire engine at 24:00.

(10) 21:41 -, GEHQ in Tokai

Two NSC commissioners, including the Vice Chair of NSC, arrived at the GEHQ at 21:41. The measures to terminate the criticality were discussed by the national authorities, relevant nuclear experts and the JCO managements. JAERI reported on the code-predicted reactivity effect of full drain of cooling water from the water jacket on reactivity. The water pipe connected to a cooling tower outside the CTB was expected to drain the cooling water, but it was not known whether the water pipe outside the building had a valve leading water out from the water jacket. The accessibility to the water pipe outside the CTB, and the method for draining the cooling water from the water jacket by modifying this pipe, were discussed. It was decided that the draining of water drain was to be tried first. Boron injection into the precipitation tank would be considered in case the water drain failed to terminate the criticality. The JCO management, bearing the responsibility for the facility, was then advised to perform the necessary operation to drain the cooling water, indicated strong hesitation at first.

In the meantime, Ibaraki Prefecture at 22:35 advised the residents within a radius of 10 km from the JCO site to stay indoors. The decision on this advice was made independently from the GEHQ on the grounds that there was no indication that the criticality would terminate by itself, and the dose rates were still high on the site boundary.

Nuclear experts from JAERI and JNC left the GEHQ for the JCO site, at 22:30 to 23:00, to support the JCO operation to terminate the criticality. The Deputy Chair of NSC also entered the JCO site at 24:00 to take the lead in the operations. NSC was an advisory committee for the prime minister rather than an administrative authority. However, the chair of the GEHQ, the STA parliamentary vice minister, entrusted the NSC Deputy Chair and asked him to take the administrative lead in the cooperative operation by JCO and nuclear experts from JAERI and JNC, for which negotiation with the JCO management was still required.

The operations to terminate criticality were described in detail in section 5.4.

6.2.2 Availability of Nuclear Expertise for Response

Nuclear research institutes (JAERI and JNC), fuel fabrication and reprocessing factories, and a power station were located in Tokaimura (Section 3.1). Therefore, expertise on criticality, neutron kinetics, shielding, radioactive material transport, health physics, dosimetry and emergency management was fortunately at hand for this accident.

JAERI and JNC played important roles in the termination of the criticality. The two institutes, however, had to take response actions on their own initiatives and responsibilities, because the instructions for them to provide response actions were not sufficiently specified by the regulatory body (NSB of STA). The locus of responsibility remained unclear in the early stage of the accident. The primary information from JCO was not transferred by NSB to the institutes. JNC, which had a long relationship with JCO, was informed of the content of the accident directly from JCO, but JAERI was not. The AEB of STA, the supervisory authority of the two institutes, requested the institutes early after the occurrence of the accident (about 13:30) to support the response actions.

6.2.3 Evacuation and Sheltering

It was the first time in Japan that the protective measures for the public were implemented in response to a nuclear accident. The mayor of Tokaimura requested residents within about 350 m of the facility to be evacuated, and the Governor of Ibaraki Prefecture advised residents within a 10 km radius of the facility to take shelter indoors.

Article 60 of the Disaster Countermeasures Basic Act prescribes in general the responsibility of the mayor of a municipality for recommendations or instructions on residents' evacuation from the affected area. In accordance with the Basic Disaster Management Plan, however, the national government was expected to give instructions or advice for the local governments' implementation of protective measures based upon the technical recommendations by ETAB which NSC establishes in accordance with the Basic Disaster Management Plan. The local governments, therefore, had responsibilities for arrangements of protective measures such as sheltering and evacuation according to the instructions or advice given by the national government.

At the time of the JCO accident, both of the local emergency plans prepared by Ibaraki Prefecture and Tokaimura specified that the Governor of Ibaraki Prefecture was to give instructions to the mayor of Tokaimura for taking protective measures, including the specification of the response area according to the instructions and advice by the national government, and the mayor of Tokaimura was to take appropriate arrangements for protective measures.

The mayor of Tokaimura had decided independently to evacuate residents living within a radius of about 350 meters from the accident site (Figure 6.1) at 15:00 and started executing it effectively at 15:45. The decision was based on the following three factors:

- The γ dose rate had not decreased, although there still considered to be a time before reaching the prescribed limit (50-100 mSv) for evacuation.
- JCO's request to evacuate the local residents within a specified area (especially JCO wanted their female personnel to be evacuated outside the site.)
- The monitoring data were available to determine the region of evacuation area

Those actions were based on suggestion of the mayor's supporting staff in the office of Tokaimura and repeated requests from JCO. Evacuation transport of the residents was supported by courtesy buses from other nuclear facilities such as JAPCO. The mayor had expressed his strong discontent with having received no suggestion nor support from the nuclear regulatory authorities for his urgent decision-making. Evacuation of 161 people was completed at midnight.

At 22:30 the Governor of Ibaraki Prefecture recommended the residents living within a radius of 10 km from the JCO site (about 310,000 people) to stay indoors as a precautionary measure on the grounds that:

- The dose rates measured 7 km from the site were still above the normal background level.
- The neutron dose rates were measured and therefore the criticality was considered to be still continuing.
- It was considered that the response actions should be sufficiently conservative regarding safety of the residents.

This decision was based on the advice from the Director General of STA (22:20) and the ETAB judged that the advice was adequate (22:50).

The Governor of Ibaraki Prefecture requested the government to give advice on early lifting of the recommendation to residents within a 10 km radius of the facility to stay indoors around 06:30 on Friday 1 October. This was after the water had been drained from the cooling jacket of the precipitation tank. There are no specific criteria for lifting protective measures such as sheltering and evacuation in the Guideline on Nuclear Emergency Preparedness issued by NSC. The GEHQ decided to measure γ dose rates by monitoring cars at 115 points in 16 directions within a radius between 0.5 km and 10 km from the JCO site. ETAB gave advice to lift the recommendation after completing γ dose rate measurements at 84 points (about 80 % of planned points) at 14:25 and the recommendation was officially lifted by Ibaraki Prefecture around 16:30.

On the other hand, since a gamma dose rate of 4.1 μSv/h was still measured at a part of the area around the facility, the cessation of evacuation for residents within a radius of 350 m from the JCO site was delayed. On 2 October at around 18:30, after placing sandbags and other shielding material around the facility to reduce gamma dose rates, it was decided by the mayor of Tokaimura that the evacuation was ended for residents within a radius of 350 m from the JCO site. The decision was based upon consultation with the GEHQ and the ETAB on the following grounds that;

- a survey showed no contamination of radioactivity in soils or well-water,
- a survey of window glass in dwellings within a radius of 350 m from the JCO site showed no radioactivity that could be associated with the accident, and
- the projected annual dose after accounting for shielding was expected to be less than 1 mSv.

The survey and dose estimation were carried out by voluntary cooperation of the nuclear related organizations.

6.3. Social impacts

The effects of the accident were very large both socially and economically. Residents near the facility suffered not only from inconveniences due to the evacuation and to the indoors shelter recommendation, but also from mental and physical effects caused by rumors. There were many adverse effects such as returned goods, rapid fall in price, and boycotts of the agricultural and marine products in the whole region of Ibaraki Prefecture, and cancellation of the reservations in hotels and tourist facilities due to rumors based on misunderstanding. To help industries suffering from such adverse effects, the Ibaraki Prefecture interests for the farmhouses and fishery companies who bore losses stemming from the accident. The Ibaraki Prefecture also financed small and medium-sized enterprises with low interest loans amounting up to 4.3 billion Japanese yen (JPY) in total.

The principles governing compensation for nuclear damage in Japan are set out in the Law on Compensation for Nuclear Damage, its implementation ordinance and the Law on the Indemnity Agreement for Compensation of Nuclear Damage. The Compensation Law provides for the strict, exclusive and unlimited liability of the operator of a nuclear installation even in respect of nuclear damage caused by the manufacturer of nuclear fuel material. The JCO accident caused the first application of the Compensation Law was applied. The Compensation Law formulates an outline of the institutional framework for nuclear third party liability together with the operators' insurance scheme, but it does not specify details of the actual compensation procedure. Therefore, it was anticipated that a considerable period would be required to establish compensation to victims. The compensation procedure with these accident, however, led to an unexpectedly successful result. By the end of September 2000, over 98 % of 7025 claims were settled for a total amount of 12.73 billion JPY. This success was the result of the local authorities, Ibaraki Prefecture and Tokaimura's immediately taking the leadership in implementing a temporary regime of compensation procedures, such as offering mediation between JCO and victims for an early settlement.

6.4. Chronology of events and actions taken

The following table provides a chronology of major events and actions taken from the time of first occurrence of criticality on 30 September 1999 to December 2005. The events and actions listed include mitigation actions, administrative implementation of protective measures, and technical actions for definitions and termination of the accident.

It should be noted that the emergency actions performed in response to the JCO accident were made in accordance with the Disaster Countermeasures Basic Act in which radiological emergency had been dealt with as a natural calamity. The responsibilities of the regulatory authority, the local governments and the licensee concerned as well as their relations were not appropriately provided to handle a nuclear or radiological emergency effectively. The JCO accident elicited such problems in the former legislative framework. Therefore the Special Law for Nuclear Emergency Preparedness was enacted to improve and strengthen the preparedness for and response to a nuclear and radiological emergency. (Chapter 10)

Table 6.1. Chronology of Events and Actions Taken

Time and date	Event and action taken	Notes
September 30, 1999 10:35	The criticality excursion started Three workers were exposed seriously to radiation. Employees were evacuated.	Three workers who experienced a strange shock (one saw a "bluish white flash") immediately left the site. Two workers developed acute symptoms. All radiation monitors sounded alarms, and employees were evacuated to an area in the JCO site. A considerable time passed before it was recognized that a criticality accident had occurred at the CTB and even longer that it continued.
September 30, 1999 10:43	The fire department in Tokaimura received a rescue call from JCO.	A local ambulance crew, being unaware that a radiation accident occurred, arrived 3 minutes after the call. It took about one hour before an appropriate hospital could be determined.
September 30, 1999 11:19	STA received the initial alert (via fax).	Because of limited information, all authorities initially prepared for an atmospheric release of radioactive substances. (The amount of actual release, in the end, was trivial.)
September 30, 1999 11:22	Ibaraki Pref. received the initial alert (via telephone).	
September 30, 1999 about 11:30	Ibaraki Pref. asked the Environment Pollution Research Center to monitor environmental radiation.	Ambient gamma dose rate levels were measured at fixed radiation monitoring stations, and by mobile measurement devices. Radioactive materials were detected at monitoring stations in other municipalities downwind from JCO.
September 30, 1999 11:33	Tokaimura received the initial alert (via telephone).	It was more than 40 minutes after the accident when JCO sent the initial alert to the government, Ibaraki Prefecture and Tokaimura.
September 30, 1999 ~ 11:34	JCO dispatched the initial alert (via fax).	
September 30, 1999 12:10	Ibaraki Police Department blocked the roads around the JCO site.	
September 30, 1999 12:15	Tokaimura set up a EHQ for the accident.	

September 30, 1999 12:30	Tokaimura call for people to stay indoors.	After setting up the EHQ, the Tokaimura advised residents to stay indoors via emergency radio. In this way, many residents first learned about the accident.
September 30, 1999 12:30	Press release "A possibility of a criticality accident at JCO."	
September 30, 1999 12:35-13:10	Nuclear energy organizations set up individual EHQ for the accident.	
September 30, 1999 12:35-13:30	The Director General of the NSB and the Director General of AEB of the STA instruct the Presidents of JAERI and JNC, subsidiary organizations of STA, on the support to deal with the situation by phone.	
September 30, 1999 12:40	The Prime Minister received the initial report.	
September 30, 1999 12:46	Mass media TV stations broadcasted reports on the accident.	
September 30, 1999 13:30	An alert was received by neighbouring municipalities.	Due to the lack of an emergency notification system, considerable time was wasted before the neighbouring municipalities learned about the accident.
September 30, 1999 14:00	The NSC concluded that it was a criticality accident.	
September 30, 1999 14:08-14:40	JCO asked the public office of Tokaimura to evacuate residents.	JCO board was kept busy by a flooding of questions, that resulted in a significant delay in understanding the accident, and of necessary cooperation with the government and on-site HQs.
September 30, 1999 14:16-15:25	Three workers airlifted by helicopter to a hospital in Chiba Pref.	The three workers exposed to radiation were first treated at the National Mito Hospital, and then transferred to the NIRS for intensive treatment.
September 30, 1999 15:00	Tokaimura Mayor decided to evacuate residents in the vicinity of JCO.	The Mayor decided to evacuate neighboring residents within a radius of approximately 350 m from the CTB in the JCO site.
September 30, 1999 15:00	The government EHQ composed of plural ministries and departments was organized.	
September 30, 1999 15:30	Curfew for school children was called off, so they could return home.	
September 30, 1999 15:30	The NSC summoned the ETAB.	Exact information had not been given in the early stage. As many data showed that the criticality accident had occurred and still continued, the on-site HQ prepared to stop the criticality reaction.
September 30, 1999 15:45	Neighbourhood residents started to evacuate.	

September 30, 1999 16:00	Ibaraki Pref. set up a EHQ.	
September 30, 1999 16:10	Ibaraki Pref. asked JNC to measure neutrons.	According to the advice of JAERI scientists, Ibaraki Pref. asked JNC to make neutron measurements in the vicinity of JCO.
September 30, 1999 16:16	Chief cabinet secretary's press conference: "Effect of accident doesn't seem to be increasing."	
September 30, 1999 16:30	Local EHQ of STA was set inside JAERI.	Cooperation between the government and experts of atomic energy institutions hadn't worked effectively due to a lack of information concerning the accident.
September 30, 1999 About 16:30	A continued nuclear chain reaction was confirmed.	JNC staff detected high levels of neutrons inside the JCO site, which confirmed that a chain reaction was sustained.
September 30, 1999 16:50	The first meeting of STA on the accident was held.	
September 30, 1999 17:14	Radiation monitoring for evacuated residents was started.	Radioactive contamination on the evacuated residents was measured by specialists of JNC and JAERI.
September 30, 1999 18:30	NSC dispatched two members to the site.	
September 30, 1999 about 18:30	The possibility of terminating the criticality event was examined with computer calculations.	JCO staff joined the on-site EHQ. This was how the EHQ members could figure out the details of the accident. An action program was discussed to stop the criticality reaction.
September 30, 1999 20:00	Chief cabinet secretary press conference: "Suggestion of a possible further criticality."	
September 30, 1999 20:00	By the arrival of the STA parliamentary vice minister, the STA local EHQ had been joined by representatives from other ministries.	
September 30, 1999 about 20:10	Residents evacuation finished.	
September 30, 1999 21:00	The first meeting of the government EHQ (Chairman: the Prime Minister) was held.	
September 30, 1999 21:36	Mass media TV stations broadcasted news of a sheltering initiative for residents within a 10 km range.	
September 30, 1999 22:00	Discussion how to stop the criticality reaction.	An action plan was proposed. The first action was to drain the cooling water surrounding the precipitation vessel. The second action was to inject a boron solution into the vessel.
September 30, 1999 22:28	East Japan Railway Co. stopped train services between Mito and Katsuta	

	stations.	
September 30, 1999 22:30	Governor of Ibaraki Pref. gave press conference : "Requested a temporary sheltering for 310 thousand residents within a 10 km radius."	
September 30, 1999 23:00	Radiation measurements in the vicinity of the accident place.	
September 30, 1999 23:30	Ibaraki Pref. calls for farmers to suspend harvesting crops.	
October 1, 1999 about 01:00	Road blocks were set up on the Joban Expressway.	
October 1, 1999 01:40	On-site HQ discussed expansion of the evacuation area to a 500 m radius.	
October 1, 1999 02:35-06:10	Water drainage works implemented to stop criticality reaction.	According to the action plan, 10 teams of JCO employees had worked over a total of 4 hours under strict radiation exposure control
October 1, 1999 05:00	Tokaimura closed elementary and middle schools.	
October 1, 1999 06:14	Termination of the criticality event	With the success of water draining, the neutron radiation levels dropped dramatically. This took place at 6:14 a.m. on October 1.
October 1, 1999 07:45	The Joban Expressway was opened.	
October 1, 1999 08:30	Termination of the criticality event was confirmed	To completely terminate the criticality event, a boron solution was injected into the precipitation vessel.
October 1, 1999 09:20	Termination of the criticality event was announced.	The government HQ and the chairperson of the NSC declared that the criticality event was terminated.
October 1, 1999 16:30	The sheltering within the 10 km radius was lifted.	Since no radioactive contamination was discovered, the 10 km radius sheltering was lifted.
October 1, 1999	Ibaraki Pref. set up medical relief posts, where the amounts of radioactive contamination were measured on 76,256 residents.	
October 2, 1999	It became clear that illegal actions of JCO caused the accident.	Illegal actions of JCO such as unauthorized work manuals and the use of buckets for mixing uranium solutions, etc. were uncovered successively.
	Schools reopened.	
	Health checks were given to 1844 residents.	Radioactive contamination in Tokaimura and in the neighboring municipalities was tested in more than 75,000 residents, rice, well-water, vegetables, futon mattresses etc. Medical interviews were conducted, and urine and blood samples were taken from

		residents and workers and analyzed.
October 2, 1999 15:30-23:00	Sandbags were stacked up as radiation shields.	
October 2, 1999 18:30	Government press conference: "No problem in lifting evacuation."	
	Evacuation request lifted for residents living in vicinity of the JCO.	The sandbag shields were stacked up to reduce the ambient radiation level and made it reasonable for the evacuated residents within a 350 m to return home.
October 4, 1999	The public office of Tokaimura was pressed to handle the accident aftermath.	Resident evacuation was lifted, and in order to cope with the aftermath, Tokaimura, together with neighboring municipalities and Ibaraki prefecture asked the central government and other related organizations to deal with bad rumors about the safety of agricultural products and about other serious post-accident effects.
October 5, 1999	The Governor and the Mayor inspected the JCO site.	
October 6, 1999	The Prime Minister inspected the JCO site.	
October 6, 1999	The Prefectural Police of Ibaraki Pref. started a compulsory investigation.	
October 7, 1999	NSC organized the Accident Investigation Committee.	The NSC organized an Accident Investigation Committee to examine the cause of the accident, and to prevent such an accident in the future.
October 9, 1999	Safety campaigns to support Ibaraki's agricultural products were implemented.	
October 9, 1999	Authorities of Ibaraki Pref. and Tokaimura investigated JCO.	
October 15, 1999	IAEA investigation of the JCO accident commenced.	
October 18, 1999	The inside of the building was investigated by JCO employees.	
October 27, 1999	The parent company of JCO announced its intention to compensate detriment.	
Since October, 1999	JAERI supports the accident investigations.	
November 7, 1999	NSC organized the Health Management Inspection Committee.	The Health Management Inspection Committee organized by the NSC gave basic information concerning health care for people exposed by radiations.

November 5, 1999	An emergency proposal and an interim report by the Accident Investigation Committee were submitted.	
December 5, 1999	Preparation of criticality accident consultation desk.	
December 9, 1999	Nuclear industries organized Nuclear Safety Network (NS Net)	
December 10, 1999	A task force office for compensation measures was set up in Ibaraki Pref.	
December 17, 1999	Enactment of a special law for nuclear disasters	126 billion Japanese Yen was allocated as the Governmental Special Budget for enforcing the countermeasure of nuclear disaster.
December 21, 1999	The first death due to a nuclear accident in Japan	
December 24, 1999	Submission of an investigation report by the Accident Investigation Committee (AIC).	The AIC pointed out that serious violations of the regulations was the cause of the accident, and proposed measures to prevent another accident.
January 20, 2000	Tokai NOAH Agreement[1] was set.	Nuclear plants in Tokaimura, Oaraimachi, Asahimura, Nakamachi and Hitachinakashi concluded a safety cooperation agreement among nuclear operators named the Tokai NOAH Agreement.
April 24, 2000	STA rated the accident at Level 4 on the INES-scale.	
April 27, 2000	The second patient died of multiple organ failure.	
September, 2000	The atomic energy safety accord with nuclear organizations was expanded to many municipalities.	
September 20, 2000	Implementation of nuclear emergency drills for residents' participation.	
October 11, 2000	Six executive persons in JCO were arrested.	
October 13, 2000	Assessment report on radiation exposure from the accident.	The STA submitted an exposure summary report to the NSC.
March 27, 2001	The Tokaimura Atomic Energy Disaster Prevention Week was established.	Tokaimura set aside the last week of September as the Atomic Energy Safety Week. Every year, many kinds of nuclear emergency drills and forums have been established.
March, 2001	Publication of a supplementary textbook on atomic energy	

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[1] Agreement on cooperation of information exchange and mutual assistance concerning nuclear accident/incident among nuclear organizations agreed after the JCO accident.

March 22, 2002	Establishment of an Off-Site Center	An off-site center and an emergency support and training center were established in preparedness for response to a nuclear or radiological emergency, where the government, Ibaraki Pref., Tokaimura etc. are able to collaborate.
September 28-29, 2002	A forum on atomic energy disaster prevention was held.	
March 3, 2003	Mito District Court sentenced JCO.	Mito local court ruled that JCO and managerial personnel should be charged for performing illegal operations and for neglecting their duties on the safety and education of their employees.
February 20, 2005	Publication of a comprehensive report by the Atomic Energy Society of Japan	The AESJ report gave a comprehensive document with the cause of the criticality accident analyzed scientifically.
June 6, 2005	Removal of the facilities involved in the accident.	
December, 2005	99.9 % of requests for compensation were settled.	Bad rumors due to the accident gave significant damage to agricultural and industrial products in Tokaimura and Ibaraki Prefecture. As of the end of 2005, the affected 99.9 % party was compensated by JCO and parent company.

<<Figure 6.1 will be inserted.>>

Caption

Figure 6.1. Local map indicating the area enclosed by the bold line, for which evacuation was implemented. The circle shows a 500 m radius from the CTB, and circled numbers indicate positions of radiation monitoring.

7. DOSE EVALUATION

7.1. Introduction

Two different sources caused exposure of workers on the site and of neighboring residents. One was radioactive material produced in the precipitation tank and then released into the environment. Radioactive gases and iodine were monitored in the surrounding area, and atmospheric dispersion was calculated by a computer simulation code package SPEEDI. It was concluded that the dose contribution due to the released radioactive materials was at most 0.1 mSv even in the vicinity of the facility. The other exposure source was neutrons and γ rays generated in the precipitation tank. The radiation affected the residents and the on-site workers including the three on the spot. Considering the above-mentioned low exposure due the escaped radioactive materials in this accident, dose assessment was focused on external exposure due to the neutrons and γ rays.

Dose assessment covered the three workers at the accident spot, employees inside the premises of JCO and related companies, emergency response personnel, and the neighboring residents. Dose assessments were performed using records of dosimeters, radiation monitoring data in and around the site, analysis of biological specimens, and computer simulation technique. Dose assessment of the three workers who worked in the CTB was performed from their biological specimens. In addition, skin dose distribution, depth dose distribution inside the trunk, and neutron-to-γ-ray dose ratios were analyzed using computer simulation method. The doses of all other JCO employees and the emergency workers were estimated by personal dosimeters, by whole-body counter measurements or by behavior surveys. The dose assessment of the neighboring residents had to be carried out by behavior surveys, since they did not wear any dosimeters. Except for the three workers, doses were evaluated in terms of effective dose equivalent according to the Japanese laws and regulations.

7.2. Dose Assessment for the Three Main Victims

The three workers at the accident spot were heavily exposed to neutrons and γ rays produced by the first power burst in the precipitation tank. After the exposure, the workers were transferred to the National Mito Hospital to receive first aid treatment, and then about 5 hours after the accident transported to NIRS, which was designated as the tertiary national radiation emergency hospital.

A dose estimation team was established at NIRS, and they made efforts to measure a lot of specimens: patients' blood, vomitus, clothes and so on. Average whole-body doses were estimated from prodromal symptoms, lymphocyte counting, chromosome analysis, and measurement of the specific activity of ^{24}Na in blood samples [8, 9]. An analysis using computer simulation techniques was applied later to determine dose distributions in the body [10].

(1) Estimation of whole-body doses from biological specimens and induced activity in the body [8, 9]

Dose estimation from prodromal symptoms: Acute radiation syndrome has four stages that are characterized by the symptoms that appear after radiation exposure.

The stage when nausea, vomiting, and fever (prodromes) appear immediately after exposure or within several hours of the exposure; it is called the prodromal period. The IAEA Safety Reports Series No. 2 [11] shows the relationship between the prodromes of acute radiation syndrome and γ-ray doses, which was determined by studying victims exposed to γ rays in the past. Equivalent doses to γ rays, GyEq, were estimated for the three workers by observing their prodromal symptoms.

Dose estimation from lymphocyte counting: Lymphocytes are one of the most sensitive to radiation and show sharp drops in numbers, which are proportional to the exposure. The Appendix of ANNEX G "Early Effects in Man of High Doses of Radiation" of a 1988 UNSCEAR Report [12] describes a method for estimating doses using the reduction curves of lymphocytes, neutrophils, and platelets after the exposure to γ rays of 0 to 10 GyEq range. Whole-body doses of three workers were estimated from the numbers of lymphocytes as a function of elapsed day from the exposure.

Dose estimation by chromosome analysis: Chromosome aberrations in the peripheral lymphocytes are an indicator in biological dose estimation. This conventional method, however, could not be applied to the case of heavy exposure, since it was impossible to make a chromosome preparation containing a sufficient number of metaphase cells necessary for dose estimation. To overcome these difficulties, a new method applicable to high-dose radiation exposure developed at NIRS [8, 9] was used to dose estimation of the three heavily exposed workers.

Dose assessment based on ^{24}Na measurements: The human body contains ^{23}Na that will produce ^{24}Na when it absorbs neutrons. Sodium-24 decays by emitting two γ rays having energies of 1.369 MeV and 2.754 MeV and can be used to estimate doses in a criticality accident. This method for estimating neutron doses was applied to the three workers using the measured radioactivity of ^{24}Na in their blood. The method is fundamentally the same as that described in a report published by the Oak Ridge National Laboratory [13]. The latest data were employed for various parameters that were needed for the estimation, such as neutron energy spectrum, percentage of neutrons captured by the human body, and the conversion coefficient of absorbed dose per unit fluence for each organ. Since the method can only be applied to dose estimation for neutrons, γ-ray dose was evaluated from the neutron/γ-ray dose ratios determined from previous accident data and computer simulation, described below.

Table 7.1 summarizes the methods and the estimated doses. The finally estimated doses shown at the bottom of the table were derived based on all the results of these dose reconstruction analyses.

(2) Analysis of dose distribution by computer simulation [10]

The two workers who were pouring the uranium solution into the tank were in positions extremely close to the tank at the moment of exposure and were heterogeneously exposed to neutrons and γ rays by nuclear fission. Heterogeneous exposure influenced the clinical course observed in the skin and organs of these workers. Dose estimation using biological specimens at NIRS revealed neither heterogeneity of dose nor the neutron-to-γ-ray dose ratios. By request from the medical team that treated the workers, the dose distributions of the heavily exposed workers were analyzed by computer simulation at JAERI.

The three-dimensional Monte Carlo codes, MCNP-4B and MCNPX, were adapted to the analysis. Figure 7.1 shows procedures for establishing simulation geometry for the dose calculation of the workers. Computational human models with movable arms and legs were used to describe the posture of the workers at the moment of exposure. The posture of the two workers was reconstructed by (1) inquiring of the workers themselves (Figure 7.1(a)); (2) conducting an experiment using a mock-up life-sized facility (Figure 7.1(b)); and (3) comparing observed skin lesions and induced activity in bone samples taken from the workers [15] with calculated dose distributions. Then, the generation and transport of neutrons and γ rays from the critical system and their interactions in the human body were simulated by the Monte Carlo method (Figure 7.1(c)).

Figure 7.2 shows dose distributions in the skin of Worker A. Extremely high dose areas were found in the frontal right side of the trunk and the right arm, which parts were close to the side and to the top of the tank including the uranium solution, respectively. The highest dose, 67 Gy (29 Gy for neutrons and 38 Gy for γ rays), was found at the upper-right abdomen. This dose is five times higher than the averaged whole body dose of neutrons and three times higher than that of γ rays. The absorbed doses dramatically decreased as distance from the highest-dose part increased, and were obviously reduced in the skin of the back, which was protected by the torso from direct exposure to the solution. The reduction of absorbed dose was significant for neutrons, so that the dose in the skin of the back was mainly imparted by γ rays. The analyzed dose distributions in Figure 7.2 corresponded to the extent and the severity of the skin injuries observed in Worker A.

Figure 7.3 illustrates absorbed dose distributions of neutrons and γ rays in horizontal planes at various heights of the trunk of Worker A. The absorbed doses of neutrons and γ rays depend largely on the depth from the body surface facing the tank as well as the height of the trunk. The highest dose was found at around $z = 35$ cm, which corresponds to the height of the uranium solution in the tank, as found in the skin dose distributions (Figure 7.2). The absorbed doses dramatically decreased in vertical directions along the z-axis from that portion. It was also found that the absorbed doses decrease from the frontal right, which was facing the tank, with increasing the depth in the trunk.

Gastrointestinal bleeding due to deteriorated intestinal mucosa was considered to be one of the major causes of death of Worker A. From the computer simulation, the absorbed doses around the small intestine of Worker A were calculated to be 5 – 12 Gy and 15 – 22 Gy for neutrons and γ rays, respectively. According to past clinical and laboratory data, absorbed doses over 8 Gy in whole body by γ rays cause heavy diarrhea indicating gastrointestinal symptoms within 1 hour after exposure and death in 1 – 2 weeks [11]. However, Worker A, who received 18 Gy in the whole body and about 30 Gy around the gastrointestinal tract, did not have massive diarrhea until 4 weeks after exposure. The obvious difference between the clinical course of Worker A and the course predicted by previous data might imply new findings on heavy exposure to neutrons and γ rays, and/or on the effect of clinical interventions that were performed on Worker A, such as selective digestive decontamination, bone marrow transplant, and cytokine therapy.

Table 7.1. Final estimated doses (biologically equivalent dose of γ exposure, GyEq)

Method	Worker		
	A	B	C
Initially estimated doses1)	18	10	2.5
Report of the Criticality Accident Investigation Committee2)	16~20 or over 20	6~10	1~4.5
1. Prodromes	over 8	4~6 or over 6	Less than 4
2. Blood components (mainly lymphocyte counts)	16~23	6~8	1~5
3. Chromosome analysis	16~ over 30	6.9~10	2.8~3.2
4. Specific activity of ^{24}Na in the blood (neutron and γ ray: Gy) Total dose (assuming RBE=1.7)	(5.4, 9.9) 19	(2.9, 4.1) 9.0	(0.81, 1.5) 2.9
5. Whole-body counter (neutron and γ ray: Gy)	-	-	(0.62, 1.1)
Finally estimated doses3)	16~25	6~9	2~3

- 1) The “Initially estimated doses” which were urgently evaluated within 7 days after the admission of the three workers to NIRS in order to predict the development of their symptoms and determine their medical treatment strategies. The values were primarily determined by measuring the activity concentration of ^{24}Na in the blood and by using the Sarov’s conversion coefficient [14].
- 2) The values in the final report of the Criticality Accident Investigation Committee [2], which was established within the government to identify the causes of the accident, based on the dose estimation presented by NIRS in the Committee in December 1999.
- 3) Estimated doses derived based on all the results of these dose reconstruction analyses [8].

7.3. Dose Assessment for JCO Employees and Persons Involved in Emergency Response

In total 169 employees of JCO and its related companies were working on the site, excluding the three heavily exposed workers. Among them, 18 persons were engaged in drainage work of cooling water of the precipitation tank, and 6 persons were involved in the work of pouring boric acid into the tank. Personnel from the national and local governments and related nuclear organizations (JAERI and JNC) were engaged in disaster prevention-related work, such as radiation monitoring, construction of a radiation shield, and consulting about countermeasures. They were in total 234 people, including three members of the emergency service staff involved in rescue work for the three heavily exposed workers. Some media organizations dispatched 26 employees to the area in question. Dose evaluation to these people was performed based on whole body measurement of ^{24}Na activity and area monitoring [16].

(1) Dose estimation for employees of JCO and related companies

Several different methods were applied to the dose estimation for the JCO workers, because not all the workers involved were wearing dosimeters. Some workers wore a film dosimeter for γ rays and some wore an electronic dosimeter for both neutrons and γ rays when they were engaged in the work for terminating the criticality event. For some workers, ^{24}Na activities produced in their bodies through neutron capture reaction were determined using a whole-body counting system, and their doses were calculated based on these results.

The remaining people did not have any record available for dose estimation. By taking into account available data for dose assessment, the following principle was applied for dose estimation for the workers. If some dosimetric records by dosimeters were available, these records were employed as a top priority. If any dosimetric records were not available but ^{24}Na activities in the body were measured, their doses were determined based on the measured ^{24}Na activity. For the rest of the employees, the same method as that applied to the residents, which is discussed in Section 7.4, was adopted: dose calculation using the distance-to-dose rate formula considering their behaviors and shielding effect of the facilities.

For dose assessment based on ^{24}Na in the human body, the contents of ^{24}Na were measured by the whole body counter of the Tokai Works of JNC. The neutron-energy spectrum around the facility was calculated using the radiation transport codes. The relation between the activity of ^{24}Na in the human body and the neutron dose was evaluated from the calculated neutron energy spectrum and the theoretical neutron capture probability by the human body. The calculated conversion coefficients, which relate the specific activity of ^{24}Na to the effective dose equivalent, were used to the individually measured ^{24}Na data. Reliability of the dose assessment based on ^{24}Na activity was confirmed from the correlation between the doses measured with the dosimeters and those evaluated from the ^{24}Na activity for the JCO employees who were engaged in operations to terminate the criticality.

Figure 7.4 shows the individual dose distribution for the employees of JCO and the related companies. No one received doses exceeding 50 mSv and the maximum dose was assessed to be 48 mSv.

(2) Dose estimation for emergency response personnel

Employees of the government-related nuclear organizations (JAERI and JNC) engaged in the emergency response activities wore individual dosimeters, and their doses were estimated using the dosimeter records. Dose assessment for three fire fighters involved in the rescue task of the three heavily exposed workers was carried out from the measured ^{24}Na activity by the whole-body counting system. The other personnel from national and local governments and the press employees had no dosimetric records, and the method based on the behavior survey was adopted to them. Figure 7.5 gives the dose distribution for the persons involved in emergency response. Almost all of them received doses less than 5 mSv and the maximum dose was assessed to be 9.4 mSv.

7.4. Dose Assessment for Neighbouring Residents

The criticality accident affected the residents around the JCO. It was required for the authorities to take responsible action concerning dose estimation and health consultation. The Health Management Inspection Committee of the NSC recommended that the area for the dose estimation should be limited to the evacuated zone of 350 m around the JCO facility. The concerned people were the residents in the evacuated zone and employees whose companies were located in this area. Persons who entered the evacuated zone from the outside during the criticality period were also included. Sodium-24 activity in the body was measured only for seven of them by the whole-body counter. Therefore, dose estimation of the residents was carried out based on (1) personal behavior survey, (2) spatial distributions of the dose rates of neutrons and γ rays evaluated from radiation monitoring data, and (3) calculation of shielding effects of buildings. The personal behavior survey was performed jointly by the STA, NIRS, Ibaraki Prefecture, Tokaimura, and Nakamachi. The data of the dose rate distribution in the environment and the shielding effect of buildings were analyzed by JAERI and were then presented for the estimation.

(1) Interview of residents for behavior

On 19 and 20 November, 1999, the staff of NIRS and health nurses from Ibaraki Prefecture interviewed the residents in the evacuated zone around JCO to obtain the following parameters every 30 minutes starting from 10:35 on 30 September to 06:15 on 1 October: the distance from the precipitation tank, the type of the house, positions in the house, and wall materials and their thickness, if they stayed inside the house. When the person was found to be moving during the accident, including the evacuation, the basic information concerning time, route and means of transportation was obtained during the interview.

The interviewers also provided the residents general information about radiation and its risks so as to reduce their fear concerning radiation exposure.

(2) Estimation of dose distribution in the environment [2, 17]

Model of dose rate evolution: As shown in Figure 7.6, a model of the dose rate evolution was established from the records of γ-ray area monitors of the JCO facilities and neutron monitors in the JAERI Naka site. The progress of the critical situation was divided into two periods, BURST and PLATEAU. The BURST is the first 25 min, in which the dose rate changed remarkably in a short time range. The PLATEAU is the period of about 19 hours after the BURST, in which (I) the dose rate decreased gradually by an exponential function, (II) remained constant, and (III) decreased by draining the cooling water around the precipitation tank. The model of Figure 7.6 was supported by measurement of neutrons with a Uranium Neutron Coincidence Collar (UNCL) installed in MNF (Figure 5.6) [18].

Relation between ambient dose equivalent rates of neutrons/γ rays and distance: Neutron and γ-ray dose equivalent rates in and around the JCO site were measured by several teams from JCO, JNC and JAERI. Figure 7.7 shows the ambient dose equivalent rates, $\dot{H}^*(10)$, for neutrons and γ rays surveyed at around 20:45 on 30 September, 1999 by the JAERI team with Anderson-Braun Rem Counters and ionization chamber type instruments. Using these data, fitting formulas [19] representing a relation between $\dot{H}^*(10)$ and distance, r, from the precipitation tank were determined by the least-squares method for neutrons and γ rays. The formulas are depicted in the figure, where f (t) is a factor expressing the relative dose rate for the regions (I)-(III) in Figure 7.6. The standard deviations in the least-squares fitting were estimated to be ±42 % for neutrons and ±35 % for γ rays. Accumulated doses in the PLATEAU were calculated for each time and distance using these equations.

Evaluation of the dose ratio of BURST to PLATEAU: There were no monitoring data around the JCO site during the BURST period. The doses in BURST were therefore estimated using the dose ratio of BURST to PLATEAU. The two neutron monitors of the JAERI Naka site (Figure 5.6) located about 1.7 km and 2 km away from the JCO site captured neutrons coming from JCO and recorded them every second in the computer memory of the monitors. The record of the neutron monitor was processed statistically to determine the dose ratio between BURST and PLATEAU, and their ratio was evaluated to be (11±2): (89±2).

Conversion from ambient dose equivalent to effective dose equivalent: The neutron and γ-ray survey instruments were calibrated in terms of the ambient dose equivalent, which represents the dose in the radiation field rather than the human dose. The measured dose rates were converted to the effective dose equivalent from energy spectra of neutrons and γ rays and their angles incident on a human body. The energy spectra were calculated using a one-dimensional discrete ordinates code ANISN-JR, where the Anterior-Posterior (AP) irradiation geometry was chosen because it gives the maximum dose.

Table 7.2 shows the accumulated effective dose equivalent for selected time and distance. Dose contributions of γ rays are given in parentheses and they account for about 16 % of the total doses. The doses in the table give hypothetical maximum doses in the case where a person continued standing in the open air facing the CTB.

(3) Calculation for shielding effect of buildings [20]

Since some of the residents were inside their houses, the shielding effects of the houses were estimated by computer calculation. The neutron and γ-ray leakage spectra from the precipitation tank were calculated with ANISN. Using the calculated source spectra, radiation transport was carried out with a geometry consisting of the CTB, soil and atmospheric air using a two-dimensional discrete ordinate code, DOT-3.5, to obtain the incident energy spectra of neutrons and γ rays to the houses in the evacuated area. The transmission of neutrons and γ rays for the building materials were calculated with ANISN by taking into account their composition and thickness, which were defined based on consultations with an architect.

(4) Personal doses of the residents [20]

The doses due to neutrons and γ rays were reconstructed based on Table 7.2 and the shielding results for every 30 minutes in which the distance from the precipitation tank, the shielding effect and occupancy factor were identified. The dose during each 30-minute segment was then summed up until the evacuation or the end of the criticality to obtain the total individual dose.

Figure 7.8 shows summary of dose estimation for the residents. The individual effective dose equivalents for 207 persons were less than 5 mSv, and the highest dose was found to be 21 mSv. The individual doses were reported to the residents during the second visit by the staff of NIRS and Ibaraki Prefecture to each house and company at the end of January, 2000.

Table 7.2 Evaluated effective dose equivalent

Time Distance	Accumulated effective dose equivalent H_E (mSv)*				
	30 September 11:00	16:00	21:00	1 October 2:00	6:15
80 m	11** (1.7)	44 (7.1)	66 (11)	83 (14)	92 (15)
100 m	6.1 (1.0)	25 (4.2)	38 (6.2)	48 (7.9)	53 (8.8)
150 m	2.1 (0.35)	8.6 (1.5)	13 (2.2)	16 (2.8)	18 (3.1)
200 m	0.91 (0.16)	3.7 (0.65)	5.6 (0.97)	7.1 (1.2)	7.9 (1.4)
300 m	0.24 (0.044)	1.0 (0.18)	1.5 (0.27)	1.9 (0.34)	2.1 (0.38)
350 m	0.14 (0.026)	0.58 (0.11)	0.86 (0.16)	1.1 (0.20)	1.2 (0.22)
500 m	0.033 (6.2×10^{-3})	0.14 (2.6×10^{-2})	0.20 (3.8×10^{-2})	0.26 (4.9×10^{-2})	0.29 (5.4×10^{-2})
1000 m	7.5×10^{-4} (1.5×10^{-4})	3.1×10^{-3} (6.2×10^{-4})	4.6×10^{-3} (9.3×10^{-4})	5.8×10^{-3} (1.2×10^{-3})	6.5×10^{-3} (1.3×10^{-3})

* The accumulated H_E in the case where a person stayed in the open air at the distance from 10:35 on 30 September until the specified time.

** The upper value in each cell is the sum of H_E of neutrons and γ rays, and the lower value is the contribution from γ rays.

7.5. Radiological Impacts from Released Radionuclides

Radiological impacts due to radionuclides released from the CTB into the environment were evaluated from data of monitoring stations, activities in environmental samples, and calculations using an atmospherics dispersion model. It was found from these analyses that the radionuclides did not have any significant impact on the health of local residents nor the environment.

(1) Evaluation of radioactivity released into the environment

Radioactive iodine and noble gas, produced in the uranium solution, were released through vents of the precipitation tank and the CTB into the environment. Radiochemical analysis of the uranium solution was performed to estimate released percentage of radionuclides from the solution [21]. The analysis for ^{131}I, ^{137}Cs (decay product of ^{137}Xe), and ^{140}Ba (decay product of ^{140}Xe) revealed that the released percentages of ^{131}I and ^{137}Xe were evaluated to be about 4 % and 23 %, respectively, while that of ^{140}Xe was negligible.

After the termination of criticality, additional filters for gaseous effluents were placed at the vent of the CTB to collect radioiodines [22]. Monitoring of radioiodines at the vent showed that the filters effectively reduced the release of radioiodines. It was estimated from the effluent monitoring data that the radioactivity of radioiodines (^{131}I, ^{132}I ^{133}I, ^{134}I and ^{135}I) released into the environment was 13 GBq, which corresponded to about 0.02 % of the total activity of radioiodines produced in the uranium solution.

(2) Environment Monitoring

Monitoring of γ-ray dose rates in surrounding monitoring stations: There were 21 monitoring stations prepared by Ibaraki Prefecture in the Tokai-Oarai district and several monitoring posts by JAPCO, JAERI and JNC (Figure 7.9). Gamma-ray dose rates from radioactive plume released from JCO were continuously monitored during the accident. In addition, integrated absorbed doses in free air by γ rays were measured using thermo luminescent dosimeters (TLD). The maximum γ-ray dose rates were measured at 3.1 μGy h^{-1} at a routine monitoring post near the site, but in a short period. The integral γ-ray dose during the criticality period was estimated to be a few micrograys.

Radioactivity in environmental samples: Radioactivity of environmental samples was measured by two independent groups. One was Ibaraki Prefecture and related nuclear organizations (JAERI, JNC, JAPCO and STA) [2]. The other was a collaborating scientific investigation group, consisting of members of universities as well as national and prefectural institutes [23]. The purpose of the latter group was to use the measured data for verifying the radiation environment simulated by radiation transport analysis as well as for estimating the radiological impact of released radionuclides.

Ibaraki Prefecture and related nuclear organizations measured radioactivity of various samples including dust and iodine in air, soil, agricultural products, farm products, marine products, rain, service water, well water, lake and seawater. Several fission products and induced radionuclides were detected in the air samples and soil. No radionuclides that resulted from the accident were found from the water samples, farm or marine products. The fission products and activation products were detected in the environmental samples, but those levels were extremely low and well below the intervention level prescribed for foodstuffs.

(3) Dose Estimation by Calculation

The radiation doses due to the radionuclides released into the atmosphere from JCO were estimated by using an emergency response system SPEEDI [24]. Calculation conditions were determined based on the radiation monitoring data and observational meteorological data. Both external exposure and internal exposure were considered. The calculation indicated that the maximum effective dose equivalent due to noble gas and iodine was about 0.1 mSv.

7.6. Summary of Dose Assessment and Health Effect

Dose assessments were performed for all persons, a total of 666, with a potential for a significant dose due to the JCO criticality accident. The effective dose equivalents of most of the neighboring residents were less than 5 mSv, and the highest dose was found to be 21 mSv. In the employees of JCO and the related companies, no one received doses exceeding 50 mSv, and the maximum dose was assessed to be 48 mSv except for the three severely overexposed workers. Most of the emergency response personnel received doses less than 5 mSv, and the maximum dose was assessed to be 9.4 mSv.

The results of dose assessment were reported to the Health Management Inspection Committee of NSC for planning health care. The Committee examined the results of dose assessment and concluded [25] that

- Deterministic effects are not expected except for the three overexposed workers, and
- The probability of stochastic effects is very small and will be undetectable.

Ibaraki Prefecture implemented a long-term health care program based on a health care policy suggested by the Health Management Inspection Committee, and has been conducting annual medical examination and consultation for the residents. JCO also has been continuing a health care program for the employees.

<<Figure 7.1 – 7.9 will be inserted>>

8. MEDICAL RESPONSE AND PUBLIC HEALTH

8.1. The Role of the Medical Network Council for Radiation Emergency

In May 1997, the Basic Plan for Preventing Disasters by the Central Committee for Preventing Disasters was revised; nuclear accident countermeasures were added. Based upon the directive "The National Institute of Radiological Sciences (NIRS) established a cooperative network to facilitate cooperation with external specialist treatment facilities in the area of radiation emergency medicine, and through this network will improve everyday and emergency treatment systems by means of the exchange and release of information, joint research, and the exchange of personnel", the NIRS established the Medical Network Council for Radiation Emergency (Figure 8.1) in July 1998, as an advisory and supporting framework complementary to the NIRS's function. The first session was held in January 1999. The 2nd meeting was held in July 1999 and deliberated upon a system of emergency medicine. The Network Council consisted of 18 national experts in various fields, such as hematology, radiology, general surgery, burn surgery, critical care medicine, dermatology, and health physics. A Network Council meeting was held on July 21, 1999, almost 2 months prior to the JCO accident to discuss specific details, such as the official means to facilitate the use of outside experts when asked to work for NIRS in the case of a radiation emergency.

On day 1 (October 1, the day of the accident is assigned to day 0), upon request by the chairman of the Council, the first official expanded Network Council meeting was held at NIRS. A detailed description of the accident, initial evaluation, clinical course, and various dose estimations of the three victims were presented. The basic strategy of medical management of these Workers was discussed. A number of the Council members joined the clinical conference of NIRS on the morning of day 2 (October 2). It had become clear by then that at least Worker A needed an intensive care, particularly very close observation of his bone marrow, gastrointestinal system, skin, lung, renal and vascular volume status. Human leukocyte antigen (HLA) of Worker A's sister was identical to that of Worker A. Because the hematology group at the University of Tokyo Hospital had experiences of a fair number of peripheral blood stem cell transplantations (PBSCT) and had a critical-care unit, it was agreed that Worker A should be transferred to the University of Tokyo Hospital. Worker A was transferred in the late afternoon of day 2 (October 2).

On day 4 (October 4), a meeting was held to discuss the treatment of the marrow injury of Worker B. Since the estimated dose was not higher than 10 GyEq, the discussion focused on the possibility of self-recovery of bone marrow and the compatibility of the transplanted hematopoietic stem cells. The members of the meeting concluded that his bone marrow might recover, and even if the transplanted cells were consequently rejected, the transplantation would be significant since the transplanted cells might play a bridging role to prevent infection and bleeding, during his marrow suppression. Since cord blood cells with a relatively large cell number that was matched to Worker B's HLA, were found, he was transferred to the Institute of Medical Sciences of the University of Tokyo. This institute has a lot of experiences of stem cell transplantation from cord blood. The treatment was a cooperative effort between doctors from The Institute of Medical Science, Kyorin University, and Nippon Medical School. Thus, the transfer of Worker B to the Medical Research Institute, the University of Tokyo on day 5 (October 5) was also arranged by the Network. The 3rd Worker (Worker C) could recover his own bone marrow, and was not likely to show serious dermal injuries or failure of the digestive tract. Therefore, it was decided to treat him in a sterile room at the NIRS using cytokine therapy and other therapeutic methods.

The Network Council of NIRS played a very important role. Six Network Council meetings were held at each important turning point in the clinical courses of victims thereafter. Each time the clinical course of a victim was reported individually, exchanged ideas, discussed common problems, and finally decided the basic strategy of treatment.

8.2. Medical Responses to the Victims Exposed to High Dose Radiation

8.2.1. Occurrence of the Accident

When the UNH solution that was being poured into the precipitation tank reached criticality, Worker C, who was outside the precipitation tank room, saw a flash of blue light and heard a cracking sound. At the same time, the alarms went on indicating high γ dose rate. Worker C asked the two Workers A and B to evacuate the room. Workers A and B rushed to a decontamination room which was used for changing clothes. Worker A went to the toilet of the decontamination room, vomited, and lost consciousness. Worker B felt restless numbness. An employee of the SMM hurried to the decontamination room and asked the three workers (A, B, and C) to evacuate. Worker C did not evacuate but asked the employee to call an ambulance. An ambulance was called at 10:43 (Figure 8.2). At 10:46 an ambulance arrived at the facility. The ambulance crew entered the gate of the company and came to the aid of the three workers. A JCO member, who was surveying radiation at the site, detected a high radiation level and ordered the ambulance crew to go to a safer place. The ambulance crew transferred Worker A on a stretcher to the JCO office and then to the gate of the company even though he was suspected of being contaminated. At 11:27, the ambulance team carried the three victims into the ambulance and asked the Tokaimura fire department to identify a hospital to take these workers. The fire department called the NIRS, informed that there were two people who felt ill at the Tokaimura facility (the number of victims was first stated as being two, not three and the name of the facility was not identified) and asked where they send these workers. The NIRS asked the fire department to check the workers' vital signs such as pulse, blood pressure and respiration, as the first priority and then to take them to the National Mito Hospital. This hospital was a second level of hospital for radiation emergency at Ibaraki prefecture. The institute also indicated that it would prepare to accept those workers should it be necessary to do so. The fire department informed the institute as follows:

1) the accident site was the CTB located on Sumitomo Metal Mining Company's premises at Tokaimura (the name of JCO was not mentioned),
2) the fire department had received the first call at 10:43 from the facility, and
3) the facility used uranium and one person had a symptom like seizure but had soon regained consciousness.

However, the JCO had not yet informed the fire department of what was happening and the NIRS did not know the type of exposure. Around then, the first notice was sent from JCO to the Science and Technology Agency by facsimile that two people had been exposed to high radiation levels and that it was possibly a criticality accident. However, since no information was provided to the NIRS, the institute started to prepare the facility for receiving victims with contamination.

About 11:33, the National Mito Hospital received the 1st notice of the exposure accident from the Tokaimura fire department, informing that

1) There had been a radiation exposure accident at the JCO,
2) The fire department wanted the National Mito Hospital to accept three workers,
3) Two workers had vomited, and
4) One of the two workers had lost consciousness once but was conscious again.

The National Mito Hospital told the fire department that the workers were likely to have received high doses since they showed symptoms such as vomiting and unconsciousness and it would be better to transfer the workers directly to the NIRS. The NIRS asked the department to bring the workers to the National Mito Hospital for first aid treatment. The National Mito Hospital thus understood that the NIRS had requested the acceptance of the workers, that the workers were not contaminated internally and decided to accept the workers. At 11:49, the ambulance left the facility for the National Mito Hospital and arrived at the hospital at 12:07 (Figure 8.2). Since no radiation safety experts accompanied the workers, the National Mito Hospital did not understand:

1) what was conducted at JCO and what kind of accident had occurred,
2) why radiation was detected from the body surfaces of the workers even though clinical symptoms showed external exposure,
3) what were the appropriate protection measures to be taken to workers suspected of internal contamination with unknown radionuclides of over 30 μSv/h,
4) whether the workers could be received in ordinary wards and what were the adequate protection measures to be taken while transferring the workers in the hospital and
5) what treatment should be done for internal contamination.

The hospital staff felt that the situation increasingly worsened without any solutions being found. The National Mito Hospital decided to transfer the workers to the NIRS since γ-rays were detected from the body surfaces of the workers and the workers showed severe diarrhea, vomiting and a reduction in lymphocyte numbers.

8.2.2. Transfer to NIRS

Around 13:00, the NIRS asked the Mito Atomic Energy Office of STA through phone about the accident. The office informed NIRS that the area monitor was sounded at the JCO facility about 10:35 and that two people were exposed. At its peak, a maximum dose of 0.84 mSv/h was detected at the border of the site. The Tokaimura fire department informed the NIRS by phone that the fire department would transfer the three workers from the National Mito Hospital to the NIRS. The NIRS prepared to accept the workers. From then on, the questions from press and other mass media increased. The Ibaraki Prefecture police and Hitachinaka police also made inquiries.

At 13:43, two ambulances left the National Mito Hospital for the Mito Heliport. Assuming high dose exposure, the NIRS communicated with the Japanese Red Cross Society about hematopoietic stem cell transplantation and prepared for HLA typing. About 14:00, the NIRS fully prepared all the necessary equipment for protecting the ambulance crew of the Inage branch of the fire department of Chiba-city to prevent the fire department and the medical staff from being contaminated by α emitters, they wore full-face masks, disposable operation scrubs, aprons, caps and personal dosimeters, since the NIRS was informed that workers might be contaminated with uranium. Three NIRS experts on radiation protection with survey meters and protective gears left the NIRS for the heliport of the Chiba-city Fire Department by ambulances. The ambulances arrived at the heliport about 14:30 and waited for the workers. The helicopter that left Mito at 14:16 arrived at the Chiba heliport at 14:45. An immediate radiation survey was conducted on the three workers including two who showed prodromal symptoms of acute radiation syndrome. Although α-rays were not detected, a GM survey meter detected γ radiation on the workers and in the vomit. Even if there had been some level of contamination by uranium hexafluoride, it was not likely to cause significant radiation exposure of the medical crew. The two ambulances left the heliport at 14:58 and arrived at the NIRS at 15:25 (Figure 8.2).

8.2.3. Receiving workers and radiation survey at NIRS

Since the NIRS considered the possibility of contamination with radionuclides, physicians and nurses wore full-face masks. The contamination of the body surfaces of the three workers was checked in the corridor of the unit of radiation emergency medicine using an α-ray survey meter and a GM survey meter. Worker A showed approximately 13 kcpm (kilo counts per minute) at the head and 26 kcpm at the chest. Worker B showed approximately 15 kcpm at the chest. Worker C showed approximately 6 kcpm at the head and 4 kcpm at the chest. A background level was approximately 100 cpm. On the other hand, an α-ray survey of the body surfaces showed just background levels and the contamination of the blankets that covered the workers was also low. Since radiation exposure from these workers or cross contamination of the medical crew was unlikely to occur, the NIRS decided to transfer the workers to its hospital ward; it was the highest priority to save the lives of the workers by maintaining the electrolyte balance and preventing dehydration, which was likely to be caused by vomiting and sweating. The measurements by a whole-body counter and a thyroid monitor at the unit of radiation emergency were suspended and the workers were transferred to the hospital ward. The radiation surveys of the ambulance crew and of the vehicles detected no contamination with radionuclides.

Even at around 16:00, the NIRS still did not have information of the accident. Since the mobile phone of an exposed worker had a high level of radiation, it was analyzed by γ-ray spectrometry with a germanium detector. The phone showed peaks of ^{24}Na, ^{56}Mn and ^{198}Au. At 16:40, an analysis of Worker A's vomit was conducted, and peaks of ^{24}Na and ^{42}K were detected at 18:25. These results revealed that the workers had been exposed to neutrons.

Table 8.1. Sequence of events related to medical responses before NIRS's treatment on 30 September 1999 (Figure 8.2)

10:35	Criticality accident occurred at the JCO
10:43	Ambulance was called.
10:46	Ambulance arrived in the entrance hall of the JCO.
11:27	Three workers were carried into the ambulance.

11:49 The ambulance left for the National Mito Hospital.
12:07 The workers arrived at the National Mito Hospital.
13:43 The workers left the National Mito Hospital.
14:16 The helicopter left Mito Heliport.
14:45 The helicopter arrived at the Chiba Heliport.
14:58 The workers left the heliport.
15:25 The workers arrived at the NIRS.

8.2.4. Initial medical treatment at NIRS

The three workers arrived at NIRS at 15:25, about five hours after the accident. Workers A and B entered the unit of radiation emergency on stretchers and Worker C on foot. The medical team tried to stabilized the workers, checked their vital signs, secured blood vessels and administered intravenous drip injections to prevent dehydration. At the same time, radiation dosimetry experts started to estimate the physical and biological doses of the workers exposed. The workers exhibited intensive sweating. Worker A was hypotensive on admission; fluids and methyl-prednisolone (mPSL) was administered to prevent drops in blood pressure. Workers A and B were awake but lethargic, looked reddish in color and somewhat edematous in the face, continued to vomit, and had a temperature of 37 to 38 °C. The notable initial laboratory findings included leukocytosis (25,900 counts per mm^3 in Worker A and 13,400 counts per /mm^3 in Worker B) with lymphocytopenia (1.6 % or 414 counts per mm^3 in Worker A and 2 % or 264 counts per mm^3 in Worker B) (Figure 8.3, 8.4, 8.5, 8.6). The total white blood cell and lymphocyte counts of Worker C (Figure 8.6) were 13,700 counts per mm^3 and 794 counts per mm^3 or 5.8 % when he was admitted to the hospital. These data showed the prominent leukocytosis and lymphocytopenia typical of heavily irradiated victims. When these workers were transferred to NIRS, they developed a painful bilateral enlargement of the parotid glands. An examination of serum amylase in the three workers showed that its levels had increased in a time-dependent manner. Isoenzyme analyses of serum amylase revealed a predominant S-fraction, indicating damage to the salivary glands.

Table 8.2. Serum amylase levels upon admission.

Workers	Day 0 (16:00)	Day 0 (19:40)	Day 1 (7:00)
A (IU/ml)	176	781	2,143
B	421	1,593	2,454
C	104	187	1,094

Reference levels 76 – 231 (IU / ml) from J. Radiat. Res., 42: SUPPL., S157–S166 (2001) [26]

Serum uric acid also increased in Workers A and B. Findings of arterial blood gas analysis showed hypoxaemia, with partial pressure of oxygen in arterial blood (PaO2) values of approximately 60 mm Hg at room air in all workers. In Worker C, PaO2 gradually improved to 79.8 mmHg by day 5. A respiratory function test on Worker C initially revealed a slightly decreased diffusion capacity of the lung for carbon monoxide (DLCO) value of 13.36 ml min^{-1} $mmHg^{-1}$.This value had returned to normal when the test was repeated three months later. Respiratory function was not assessed on Workers A and B because of the impracticality of doing so under reverse isolation. Details of laboratory findings are shown in J. RADIAT. RES., 42: SUPPL., S157–S166 (2001) [26] and in The British Journal of Radiology, 76 (2003), 246–253 [27].

Although the precise doses were unknown and could not be determined soon, the monitoring of the body surfaces, nasal swabs, and clothing suggested that there was almost no external contamination with radionuclides. There might be the possibility of internal contamination but the degree was likely to be negligible. Because NIRS was not informed of the exact nature of the accident but suspected possible internal contamination/inhalation with uranium, intravenous administration of sodium bicarbonate was begun in both Workers A and B to facilitate urinary excretion of uranium. However, this was terminated late in the evening of the day of the accident (September 30) when ^{24}Na, ^{42}K and other sources were detected in vomits and blood by γ-ray spectrometry [28, 29]. This indicated the nature of exposure to external neutron radiation. During the evening of September 30, Worker A continued to have diarrhea, his urine output became marginal, and his blood oxygen saturation deteriorated. To treat acute radiation syndrome, administration of broad-spectrum antibiotics, antifungal drugs, granulocyte colony stimulating factor (G-CSF), and selective digestive-tract decontaminants was initiated in Workers A and B on the evening of September 30.

Based on several methods of dose estimation (i.e., the onset time of prodromal signs, the rate of decrease of the peripheral lymphocyte count, chromosomal aberration analysis [30, 31], and measurement of ^{24}Na in blood [29]), the estimated doses of radiation (predominantly neutron) were 16 to 25 Gy equivalent (GyEq) for Worker A, 6 to 9 GyEq for Worker B, and 2 to 3 GyEq for Worker C (see also Section 7.2 in Chapter 7).

Further detailed medical treatment given to the three workers at NIRS and other medical facilities, and lessons learned from a medical viewpoint are provided in Appendix IV.

8.3. Medical Responses to the Local Residents

8.3.1. Introduction

This accident affected not only JCO employees, but also residents of the surrounding area. Low level of radiation leaked outside the nuclear facility and resulted in members of the public being exposed to low levels of radiation. According to the NSC Health Management Inspection Committee Report [25], the effects of this radiation were as follows.

1) The radiation level was not high enough to cause any noticeable radiation effect on health.
2) The possibility of any radiation effects on health was extremely low, and the detection of any effects was not possible. Despite this, residents were concerned, since they had been “unnecessarily” exposed to radiation.

   As shown in Table 8.3, the Ibaraki Prefecture set up five first-aid and care centers during 22 days (October 1-22), and conducted radiation survey for 14,236 persons. Tokaimura, Nakamachi, Hitachinaka City, Hitachi City, Hitachiota City, Kanasagoumachi, Urizuramachi performed aldo radiation survey for 62,026 persons. No radiation over than a background level was detected. The number of measuring devices was 37 sets. A total of 788 persons was involved: 55 medical doctors, 220 public health nurses, 39 nurses, 144 radiological technologists, and 330 others.

Table 8.3. Numbers of people who received radiation survey at first-aid care centers and others.

Facilities	Date	Number of people	Radiation detection
Ibaraki Prefecture			
Mito Red Cross Hospital	October 1-3, 1999	5,701	0
Hitachi Health Center	October 1-22, 1999	1,310	0
Mito Health Center	October 2-22, 1999	5,186	0
Omiya Health Center	October 2-22, 1999	1,159	0
Hitachinaka Health Center	October 5-22, 1999	880	0
Tokaimura			
Funaishikawa Community Center	September 30, 1999	571	0
Tokai Village Central public hall	October 1-11, 1999	13,975	0
Tokai village office	October 2-22, 1999	426	0
Nakamachi			
Yokobori Public Hall	October 1, 1999	2,652	0
Katobe Public Center	October 1, 1999	1,126	0
2nd Municipal Junior High School	October 2, 1999	4,306	0
Motokomezaki elementary school	October 2, 1999	1,345	0
Central public hall	October 3-4, 1999	4,505	0
Nakamachi Office	October 5-31, 1999	1,179	0
Hitachinaka City			
Health Care Center	October 1-3, 1999	15,880	0
Sawa Public Hall	October 2-4, 1999	4,403	0
Matsudo gymnasium	October 4, 1999	924	0
Hitachi City			
Kuji Public Hall	October 4-11, 1999	1,824	0
Hitachiota City			
Health Service Center	October 1-3, 1999	4,225	0
Kanasagoumachi			
Health Service Center	October 6-8, 1999	2,221	0
Urizuramachi			
Health Care Center	October 2-3, 1999	2,464	0
Sum			
Ibaraki Prefecture		14,236	0
Municipalities		62,026	0
Total		76,262	0

8.3.2. Role of Local Governments

8.3.2.1. From the accident to establishment of first-aid and care center

The Ibaraki Prefecture government had received the 1st report (possibility of a criticality accident) of the accident from JCO at 11:33 a.m. However, it was not reported that γ-rays and also neutrons were emitted. The Tokaimura local government established headquarters for the nuclear emergency at 12:15, and at 12:17 asked the Ibaraki Prefecture what measurements should be done to support information to the public. At 12:30 Ibaraki Prefecture gave the press release that the possibility of a criticality accident was high. The local government of Tokaimura informed the residents that they should stay at home using emergency disaster radio. The Ibaraki Prefecture informed the Hitachinaka health center and the Mito health center about the accident and asked to standby and to prepare for distribution of stable iodine at 14:00. Hitachi-city also established headquarters for nuclear emergency. Moreover, the local government requested the residents within 350 m of the facility (about 150 persons) to evacuate to the nearby community center by its own judgment at 15:00 in the afternoon, since no further information of the accident was provided. After that, the Naka-machi local government established the headquarters for nuclear emergency at 16:30.

Nine hours and a half have passed before set-up of a first-aid and care station was decided; it was almost at 20:00. In the Hitachinaka health center, a team for radiation survey consisting of the JAERI staff and the health center personnel, a first-aid diagnostic/decontamination team consisting of the personnel of the Ibaraki Prefectural Central Hospital, and a relief team from the Japanese Red Cross Society, Ibaragi branch were organized. The Ibaraki Prefecture set up the health consultation office in the Health Service Disease Control Division. Headquarters for nuclear emergency of the Ibaraki Prefecture requested residents within 10 km radius of JCO to stay indoors at 22:30. At 22:30, the director of the department of health and social services of the Ibaraki Prefecture decided to move the first-aid and care station in the Hitachinaka health center to the nursing school in the Mito Red Cross hospital, since the Hitachinaka health center was located within 10 km of the JCO. The Ibaraki Prefecture asked the NHK, a national broadcast, to announce about movement of a first-aid and care station at 0:30 on October 1.

8.3.2.2. Set-up of a first-aid and care station

The first-aid and care station was set-up and opened at the nursing school in the Mito Red Cross hospital at 9:00 a.m. on October 1; 22 hours or more had already passed since the accident occurred. In this station, radiation survey for body-surface contamination, medical examination, and health consultation were performed. Since many people came to the station, more radiation measuring devices were needed and radiation technologists were invited from the Mito Red Cross hospital and the Ibaraki prefectural central hospital. The Prefecture decided the set-up of another first-aid and care station in the Hitachi health center. Radiation survey of body surfaces was started in the first-aid and care station of the Hitachi health center at 10:00. The Prefecture decided to set up two more first-aid and care stations in the Mito health center and the Omiya health center at 15:00. The Prefecture lifted the indoors sheltering recommendation to 10 km residents at 16:30.

8.3.2.3. Closing the first-aid and care station

The decontamination vehicles of the Self-Defense Army were arranged at the Mito and Omiya health centers at 8:30 on October 2, and two first-aid care centers were opened there at 9:00. The Ibaraki Prefecture accepted staffs from Nagasaki Prefecture, Hiroshima Prefecture, a Japanese medical relief mechanism (MeRU), and others. Thus, a full-scale activity was started in the first-aid and care stations. The first-aid and care station of the Mito Red Cross hospital was closed on October 3. On October 7, the last station was closed.

8.3.3. Public response from the point of health effects

8.3.3.1. Medical Advisor to the Mayor of Tokaimura

On October 8, an expert of the National Institute of Radiological Sciences (NIRS) was sent as a medical advisor to the mayor of Tokaimura. At that time, the radiation doses received by nearby residents were not yet known. The major concerns of the Tokaimura Mayor were the health effects on the residents as a result of the criticality accident and the calming of residents' mental uneasiness. The medical advisor proposed the followings to the mayor.

1) Lectures on “Radiation Effects” should be given by experts from the NIRS.
2) A “Health Consulting Office” should be established to relief the health related concerns of residents. This office opened 17 days between October 19 and December 21 at the Tokaimura civic center.

8.3.3.2. Medical check-up for residents

The Ibaraki Prefecture conducted the medical check-up for the residents around the JCO on October 2-4 1999. Results of this medical examination, including lymphocyte number counting, conducted by Ibaraki Prefecture on 1,800 people residing within a 500 meter distance of the accident site were reported on October 12. None of those medically examined showed clinical evidence of radiation injury. Around this time, the health check results were formally reported to the mayor of Tokaimura, and the medical advisor explained the data from a medical viewpoint.

The radiation doses of the JCO employees and staff of the Tokaimura fire department were estimated by means of ^{24}Na radioactivity in the body. Results showed that the accident had little effect on health. However this information, despite of health consultations with doctors, could not relieve the concerns of the residents for a long time.

8.3.3.3. Explanation of health effects to residents

The mayor of Tokaimura requested the NIRS to send lecturers for better understanding of radiation effects on the public on October 8. Upon this request, the NIRS sent two experts to the Tokaimura. The lectures were given on October 18, 1999 at the Tokaimura Culture Center. An expert of radiation physics explained qualities of radiation, units used to express radiation dose and radioactivity, and radiation half-life. The other expert of radiation emergency medicine explained acute radiation injury, methods for estimating radiation dose for human, and the effects of radiation exposure. This was followed by a question and answer session.

Lectures for residents were also given on November 13, 1999 in Naka-machi and on November 14, 1999 in Tokaimura. Types of radiation and their qualities, and the effects on human health of radiation were explained by experts from the NIRS. The results of radiation assessment and the actions planned to take thereafter were also explained. For those who could not attend, lectures were recorded on a video tape. In addition, the outline was published in local notices.

8.3.3.4. Health consultations at Tokaimura

(1) Health consultation office

Tokaimura set up the health consultation office. The NIRS supported the health consultations conducted by Tokaimura. The health consultation office dealt with large numbers of residents at the early stages, and the attending doctors were very busy. However, after the initial rush, the number of residents asking for consultation was less than expected. Since most of the consultations were about uneasiness and distrust; these residents were unable to express uneasiness in the presence of large audiences. Rather than medical issues, psychological problems were frequently dealt with.

(2) Telephone consultations

The results of the evaluation of radiation doses received by local residents were released to the press by the Science and Technology Agency on November 4. In order to set up a telephone consultation office at the Tokaimura civic center, the Science and Technology Agency requested the NIRS to send a medical doctor and a researcher with knowledge of the effects of radiation on the human body as consultants. However, it was very difficult to find researchers with knowledge of the effects of radiation on the human body who were also able to play a consultative role. Initially, large numbers of residents visited the office for consultation. Many journalists also came to the consultation office and took photographs. However, the response to mass media had not been appropriately planned by local governments. Thus, several problems showed up during the initial stages.

In December, the dose-estimation of residents was performed based upon the results of the survey of residents' behaviour during the accident period. The results were explained to residents individually by NIRS researchers and public health nurses on January 29 and January 30, 2000. The number of residents requiring consultations was smaller than expected.

(3) Medical check-ups for the residents by Ibaraki Prefecture

The Ibaraki Prefecture conducted medical check-ups for the residents on May 13, May 14, and May 21, 2000. Prior to this, health consultations were held on April 25, April 26, and April 27, 2000. Thereafter, the Ibaraki Prefecture has been continuing the medical check-ups for the public people until now (2006).

8.3.3.5. Hitachinaka City

The city of Hitachinaka is located in the north east part of central Ibaraki Prefecture. This city is faced to Tokaimura in the south. On October 1, Hitachinaka city asked NIRS to estimate the radiation doses received by residents. NIRS sent six staff members on October 1, eight on October 2, and eight on October 3, and conducted screening of radioactivity by survey meters. The Hitachinaka city also asked to check the radioactivity of marine products. On October 1 and October 4 samples were analyzed, and a report titled “Concentrations of radioactive cesium 137 in seaweed and shellfish from areas of Isozaki and Hiraiso in Hitachinaka City” was submitted to the city on November 12.

8.3.4. Does estimation of residents

The dose estimation of residents around the JCO facility was performed both physically and biologically. Details are given in Chapter 7 and Appendix III.

8.3.5. Response at the NIRS

8.3.5.1. Telephone consultations

Immediately after the accident, the NIRS received many phone calls asking questions. A response manual and list of predicted questions were distributed to involved staffs of NIRS. The content of the consultation is as follows:

- Effect of radiation exposure on those who passed through the area around the accident site and surrounding area
- Whether or not table salt is safe to eat since neutron induces radioactivity
- It was rainy in the evening of September 30. Whether or not wet laundry is contaminated with radionuclides
- Whether areas outside of the indicated 10 km radius sheltering zone are safe
- Whether the waters surrounding Chiba and Shonan could be considered safe for weekly body surfers.
- About stable iodine
- Requests for radiation dose assessment

8.3.5.2. Questions from local governments

- What should be done in case of an accident (a prefecture with nuclear power facility)?
- What response should be made to questions concerning stable iodine?
- The scale of equipment and facilities used for decontamination, and the management plans.

8.3.5.3. Requests for measurement of radioactivity from Residents

NIRS received requests for measurement of radioactivity from 42 people: 11 mass media, 7 transportation workers, 13 construction workers in Tokaimura, 9 people who passed through areas surrounding the accident site, and 2 others. All of them were considered to be not significantly exposed. In order to make them feel easy, however, radiation surveys were performed for them. Using survey meters for alpha, beta, and gamma rays, measurements were taken of the individual's body surface and of clothing. Before performing the test, these individuals were interviewed concerning where they were at or after the accident. Of the 42 subjects, nobody showed higher readings than the background level. In addition, 13 persons among them were checked for internal radioactivity; nobody showed higher levels than the background.

<<Figure 8.1 – 8.6 will be inserted>>

9. ANALYSIS OF CAUSES AND BACKGROUND OF THE ACCIDENT

9.1. Direct causes

The direct cause of the accident was putting 16.6 kg U in UNH with an enrichment of 18.8 wt.%, which is much more than the criticality safety mass limit of 2.4 kg U, into a precipitation tank not having geometry to prevent criticality. This operation was carried out intending to homogenize seven batches of UNH (amounting to about 16.8 kg U) to prepare 14.5 kg U (about 40 L) as a single production lot to be delivered to the client (JNC). It was the last part in the UNH production process according to the specification instructing to refine U_3O_8 powder and re-dissolve it to produce 370 gU/l of UNH. Utilizing the precipitation tank instead of the pure UNH storage tank, which had been used in the preceding campaigns for UNH production, was decided by a work team called the special crew.

9.2. Processes

(1) Homogenization procedure change into utilizing the precipitation tank in September 1999

As described in the written procedure, homogenization should have been carried out by utilizing a pure UNH storage tank with temporary upper and lower piping attached. Without either experience or reading the written procedure for UNH homogenization, they did not recognize the lower piping to be attached. And they regarded the procedure inefficient because of existence of dead space and too low position for transferring UNH to product vessels. They found a more efficient way to utilize the precipitation tank.

The reason why they looked for a more efficient way was that the workers wished to complete the campaign as soon as possible, because the campaign for JOYO fuel was felt additional and work load of other routine missions of the special crew was high. The situation of no experience of UNH production within the special crew had emerged in 1998 July, when an experienced worker had to move out from the special crew due to health problem because of introducing night shift work for liquid waste treatment. This resulted from JCO`s organization restructuring in 1998 July called “2P concentration”.

The written procedure had not been read by the workers because they had been busy with other missions and because the procedure had not been described in an easily understandable way.

The procedure of utilizing the pure UNH storage tank was regarded as temporary by the foreman of the special crew, partly because there was no specific instruction paper for the homogenization process, and partly because written procedures had not been respected as to be strictly followed in JCO. Procedures utilizing stainless steel buckets in dissolution and re-dissolution processes would have enhanced the feeling of “temporary” on the production system in the CTB.

From the viewpoint of quality control, he assumed no problem as long as the tank was cleaned carefully. From the view point of criticality safety, he had not expected any problem as long as uranium was in solution condition without precipitation.

His understanding on criticality control was that there was no mass limit for uranium solution, which had been formed in the 13-year experience with another plant (first facility) of JCO for low enriched uranium re-conversion for commercial LWRs. In the plant, concentration control requiring less than 100 gU/l had been applied to uranium solution process for criticality safety control. However, the meaning of the concentration requirement had not been informed to the workers. Therefore, the workers assumed the concentration requirement was for quality control. And they assumed that any amount of uranium solution would be subcritical. They had not had any effective education in JCO on criticality safety control to correct the wrong mental model and had not been informed on the criticality control measures in the CTB. Therefore, the special crew members had not known that criticality had been prevented in the homogenization process with utilizing the pure UNH storage tank due to the small diameter of the tank.

The planning group chief engineer, who was not a supervisor of the special crew but responsible for quality control, gave permission to the foreman for utilizing the precipitation tank. From the viewpoint of quality control, he expected no problem because he was told that the precipitation tank had been cleaned carefully. Based on his testimony, he had not expected any problem, as long as the uranium was in solution condition without precipitation, with the presumption that any uranium solution was concentration-controlled for criticality safety in JCO. The chief engineer had not had appropriate education on the criticality safety control to correct the foreman's inadequate safety view.

The supervisor of the special crew was not consulted on the procedure change.

Appropriately designed warning signs would have been effective in preventing the workers from putting the large amount of UNH into the precipitation tank. However, there was no indication around the precipitation tank about the mass limit.

Witnessing the UNH homogenization process by the client (JNC) could have prevented the final operation change consisting of utilization of the precipitation tank. However, such witnessing had been omitted in the contract since 1993.

(2) Homogenization procedure change into utilizing the pure UNH storage tank in 1995

The change from cross-blending method into utilizing the pure UNH storage tank was proposed by a chief engineer of the special crew mainly for decreasing workload of the process, and was approved by the technical division which was responsible for safety design. Although the pure UNH storage tank is designed with favorite geometry, the procedure change is very important, because it introduced a process in which seven times of the mass limit for criticality control were allowed to exist in a unit vessel. It violated the regulatory requirement. Most of the workers were not informed that criticality was prevented with the geometry control (favorable geometry with small diameter).

(3) Introduction of UNH homogenization process with the cross-blending procedure in 1986

In the negotiation process between JCO and PNC for the first campaign of UNH production in 1986, the size of one lot was determined to be about 40 liters (about 14.5 kg u). The lot is defined as a product unit within which chemical and physical property is uniform. The 10 x 10 cross-blending method using twenty product vessels was proposed by JCO and approved by PNC in order to obtain the homogenized UNH. The UNH cross-blending was a simple application of the same method as adopted in the UO_2 powder production for JOYO fuel since the early part of 1970s. The product examination for quality assurance and transportation was to be carried out for each lot, and then the size of a lot could not be the same size of batch to keep acceptable productivity. The UNH homogenization process had not been considered in the design and construction stages of the CTB modification, and had not been reviewed in the licensing process. Thus introduction of the UNH homogenization process was a violation of the regulations. Furthermore, although the method satisfied the unit mass limit and geometry limit for criticality safety control, it virtually violated the regulation that mass within a batch should not be more than 2.4 kg U, because the whole process of the 10 x 10 cross blending could be regarded as "one batch".

In the campaign in 1986, the first production of UNH was carried out. But the cross blending actually implemented was 7 x 10 cross-blending utilizing 10 product vessels instead of 10 x 10.

(4) Production of UNH with high concentration required

In a JCO and PNC meeting in April 1984, when the licensing process for the modification of the manufacturing business was at the final stage, PNC informed JCO that the UNH production was expected in 1985 and that concentration should be around 400 gU/l. In the specification of the first UNH campaign in 1986, the concentration was specified as 350 ± 30 gU/l. Such a high concentration was required because the mixing ratio in the Pu-U co-conversion process in PNC was to be 1:1. In the case of an enrichment around 20 wt.%, the minimum critical mass corresponds to a concentration around this value. However, such risk characteristics were never noticed by JCO, PNC and regulatory authorities. In the licensing process, the UNH concentration was never specified and discussed.

(5) UNH production suggested

At the design stage of the modification of the CTB, UNH production had not been conceived by JCO people as highly probable, and thus the process for UNH production was not considered seriously at the design and construction. This was due to a lack of timely and appropriate information from PNC to JCO on the planned annual need for each product form (UO_2 and UNH). In the license application document for the manufacturing modification, the UNH was simply described, but was not mentioned in the first licensing review by the STA. In the auditing review by the NSC, it was mentioned but the production process and specifications (e.g. concentration) were never discussed.

9.3. Organizational Factors

9.3.1 Organizational factors within JCO

(1) Inappropriate restructuring of the JCO organization

The restructuring of the JCO organization called “2P concentration” had been carried out one year before the accident (August, 1998). It drastically increased the number of missions and the work load of the working group (special crew), and brought about a big change in working conditions such as the introduction of night shift work. This change in the working condition forced an experienced worker, who had experience with production of UO_2 and UNH for JOYO fuel rods since the early years of 1980s, to move out from the special crew due to a health problem. This resulted in the situation where the special crew members had no experience in producing UNH. They also had a desire to finish the CTB work as soon as possible. These conditions played a very important role in the emerging and execution of the idea to utilize the precipitation tank for UNH homogenization instead of the pure UNH storage tank. The restructuring “2P concentration” was one of JCO’s means for survival in the very severe economical situation which originated from electricity deregulation as follows:

1) Deregulation of the Japanese electricity market,
2) Cost reduction for electricity generation,
3) Cost reduction for fuel production,
4) Intense competition for fuel production,
5) Intense competition for re-conversion of uranium,
6) Cost reduction in JCO, and then
7) Restructuring of JCO organization.

(2) Incorrect system understanding by the workers

The workers put seven batches of UNH into the precipitation tank based on the incorrect system understanding that “uranium could not be critical as long as it is in solution” and that “one batch mass limit for the precipitation tank is required for criticality control for precipitation, but no limit is needed for solution”. Such an incorrect system understanding had been formulated in the experience of working in the 1st and 2nd processing facilities, where uranium concentration control was adopted for criticality safety control for the solvent extraction process while mass limit control was adopted for the precipitation process. Workers had not been informed that the requirement of uranium concentration limit is for criticality safety control. Thus, they misunderstood that the concentration requirement was for quality control. Furthermore, the special crew members were not informed on how a criticality accident is prevented in the CTB facility. Information on the safety boundaries and their meanings had not been communicated to the workers.

(3) Ambiguous system of instruction and responsibility

The workers utilized the precipitation tank for UNH homogenization instead of the pure UNH storage tank without permission by the formal immediate supervisor, the work site director. It was a deviation from the JCO organization rule. Such a decision, neglecting the formal line, reflects the situation that a proposal which already had been implemented was more appreciated in “kaizen” (improvement) campaign than a proposal only at the idea stage, that the planning group leader for QA related troubles had been consulted, and that the task in the CTB had been virtually commissioned to the special crew.

(4) Problems in safety management within JCO

There are four types of criticality safety limits: one-batch control from dissolution through the precipitation process, unit mass control, safe subcritical mass, and favorable geometry. One-batch control within equipment from dissolution through the precipitation process is a regulatory requirement to limit the total mass of 18.8 wt.% enriched uranium, which is not to exceed 2.4 kg U. Unit mass control is also a regulatory requirement to limit the mass of 18.8 wt.% enriched uranium, not to exceed 2.4 kg U within any equipment in the production process.

The safety limit of subcritical mass is a functional requirement to prevent exceeding the subcriticality limit for mass. The subcriticality limit for mass is influenced by shape, neutron reflection, chemical concentration of fissile uranium (^{235}U), and enrichment. The regulatory required mass limit of 2.4 kg U takes into account a safety factor of 2.3 on the minimum subcriticality mass, which is determined by assuming spherical shape, full neutron reflection, chemical concentration of 60 g U/l, and 20 wt.% enrichment. Finally, favorable geometry is a functional requirement for geometry, not to exceed the diameter of a tank or depth of a tray. This limit is also a regulatory requirement, except for the precipitation tank. As long as a favorable geometry is adopted, a system can be kept subcriticality with any amount of uranium.

Most technical management people, including members of the JCO safety committee, were aware of the violation of the regulatory critical safety limit during the actual production campaign. However, they had not regarded the violation as actually dangerous because it didn't matter as long as the functional safety limit was kept. They accepted the violation. Most of the workers were not aware of any criticality safety limits except a limited rule that "for critical safety control, uranium mass should not exceed the one batch limit in the precipitation tank when precipitating", which had been communicated and learned based on experience. Such ignorance resulted from the following situation: For workers to be aware of the regulatory critical safety limits communication was needed on criticality safety control through education, job manuals, job instructions and warning etc. But there had not been any communication. Furthermore, there were no means for workers to learn about the functional limits.

9.3.2. Organizational factors between JCO and the client (PNC/JNC)

(1) Omission of witnessing the UHN homogenization by the client (JNC/PNC)

In the contract specification between PNC and JCO for the 4th JOYO campaign (1986-1988), the UNH homogenization had been identified as a process to be witnessed by the client (PNC). PNC had actually done this, at least once. However, this specification was deleted from the contracts since the 6th-2 campaign (1992-1993). This deletion was agreed to in December 1992 in order to respond to the tight schedule for UNH production, which had emerged with the abrupt change of the plan from UO_2 production into UNH production. JNC/PNC lost the opportunity to detect the deviations and changes of the method for UNH homogenization process from the originally agreed cross-blending with product vessels into one with the pure UNH storage tank, and into the final one with the precipitation tank.

(2) UNH production was not seriously considered in the design

In the communication between PNC and JCO in relation to modification of CTB (1983-1984), basic specifications such as uranium concentration in the UNH and long term plans with annual production rate and frequency of UNH production were not informed timely from PNC to JCO. Then, on the JCO side, UNH production was not recognized as highly probable but rather as having low probability. Therefore, UNH production was not seriously taken account of in the design. Then the facility was not convenient for UNH production with high concentration. This inconvenience resulted in the ad hoc re-design of the production system such as utilization of stainless steel buckets for re-dissolution.

(3) UNH homogenization was not considered in the design

Treating the amount of UNH of one batch (2.4 kg U) as one lot could not have been acceptable from the viewpoint of productivity because of too much manpower resource required for the quality assurance that was required in the specification. Thus homogenization to enlarge the lot size was indispensable.

In the case of intermediate-enriched UO_2 powder production for the "JOYO" reactor, a two step homogenization procedure had been carried out since the $U(23)O_2$ production campaign in the period of 1972-1974. The first step was carried out by mixing the amount of 5 batches in a mixing can with rotation. The second step was carried out by 10 x 10 cross-blending, utilizing 11 mixing cans.

In the case of the $U(19)O_2$ production campaigns after the modification of the CTB, the two step homogenization resulting into one lot of 120 kg U had been carried out from 1985 through 1998.

Considering such situations, the need for an improved homogenization method in the case of UNH production could have had been anticipated by both the client (PNC) and JCO.

9.4. Regulatory Aspects

9.4.1. Problems at the stage of design and construction

(1) The UNH production process was almost not reviewed at all in the licensing process

In the first step review by STA on application for modification of the CTB, the potential for UNH production was not recognized by the STA officer, although one product form of UNH was simply described in the application document. The cause of this miss was due to the fact that the review had not been based on formal application documents, but rather on meeting handouts provided by the applicant (JCO). In the second step review by the NSC, the existence of the product form UNH had been observed, but even a basic specification such as uranium concentration was not investigated.

(2) The UNH homogenization process was not reviewed

At the time of the licensing review by STA and NSC, the need for a homogenization process for UNH was not recognized by JCO and PNC. Such a process had not been described in any material. However, STA and NSC could have had imposed some questions on the necessity for UNH homogenization if they had recognized the homogenization process with cross-blending in the case of UO_2 production. This had been carried out since the early 1970s. The regulation authorities had not recognized the existence of the two step cross-blending homogenization method.

9.4.2. Problems at the operation stage

(1) Licensing conditions had not been implemented in the operational safety program or its subordinate criticality control criteria of JCO for a long time

The regulation body had not recognized the inconsistency but approved the operational safety program.

Licensing conditions for criticality safety control, which had been imposed by STA and NSC during the review process, had not been implemented in the operational safety program or its subordinate criticality control criteria of JCO for a long time. Two kinds of mass limit for criticality control had been imposed: (a) total mass from dissolution (or hydrolysis) process through precipitation process should be no more than the maximum mass limit per batch (2.4 kg U), and (b) no more than 2.4 kg U should exist in any vessel or facility even if it had been designed with favorable geometry for criticality safety control. However, the condition (b) had never been described either in the operational safety program or in it's subordinate criticality control criteria. And the condition (a) had also never been described until it appeared in the criticality control criteria in 1995. The criticality control criteria had not been updated until 1988.

(2) The requirement of the technical standards effective in 1987 was not implemented

The Technical Standards on Design and Construction Method of Manufacturing Business of Nuclear Fuel Material which was effective in 1987 required for manufacturing facilities processing uranium with enrichment more than 5 wt.%, that "appropriate measures including criticality alarm should be implemented with assumption of the occurrence of a criticality accident". Although the existing gamma radiation area monitors were regarded as virtually criticality alarm, no measure was investigated for terminating the criticality accident or mitigating the consequence. The reason is not yet clear.

(3) Inspection and patrols did not work effectively

In order to monitor JCO's compliance with the operational safety program, STA's inspection had been carried out seven times on April 9, 1985 through November 26, 1992. Patrols by an officer of the STA Tokai office had been carried out every month since April, 1998. However, no violation had been detected even at the 1st, and 2nd facilities. The method for inspection and patrol had not been appropriate in effectiveness.

10. AMENDMENT OF LEGISLATIVE AND REGULATORY FRAMEWORK AFTER THE ACCIDENT

This chapter provides how the legislative and regulatory framework were amended in Japan after the accident. The source of information provided in this chapter is the National Report of Japan from the Second Review Meeting of the Convention on Nuclear Safety. [32]

10.1. Summary

The national regulatory bodies, local governments, industries and academies viewed the accident as an alarm bell with regard to the safety of nuclear installations in Japan, and took a number of remedial actions.

The NSC established the JCO Criticality Accident Investigation Committee, which investigated the cause of the accident and issued an urgent proposition and the final report. The White Paper on Nuclear Safety issued by the NSC in 2000, referring to the final report of the committee, pointed out violations of authorized rules by the operating company as the direct cause of the accident, and the defective safety culture behind it. It also served to point out insufficiencies in the regulatory process in that unbalanced emphasis was put on design validity of systems and facilities rather than on details of operating procedure, and that the Periodical Inspection by the regulatory body had not worked effectively to monitor the operating company’s compliance with the Operational Safety Programs.

Considering the urgent proposition of the committee, the government amended the Reactor Regulation Law to establish the Nuclear Safety Inspection System which mandates resident Nuclear Safety Inspectors to confirm compliance of the operating company with the Operational Safety Programs. An amendment to safety education procedures was also included in the Operational Safety Programs. The Allegation System by employees and the Periodical Inspection System on Fuel Fabrication Facilities were established. Moreover, the Special Law for Nuclear Emergency Preparedness was enacted in December 1999 to strengthen national nuclear emergency preparedness.

Nuclear industries established the Nuclear Safety Network to enhance and maintain sound safety culture through dialogue among industries and with local residents.

10.2. Discussions in the Health Management Inspection Committee established in NSC

A special committee to discuss health-related matters after the JCO criticality accident was established in NSC, November 1999. Ten experts of medical doctors specialized in radiology as well as health-physicists and environmental biologists joined in discussions.

The committeee's first job was to estimate the radiation doses obtained by the persons who were involved in the accident, i.e. the three workers on the spot, the operators who stopped the criticality event, other JCO employees, the emergency workers, and a total of 439 neighboring residents, as indicated in Chapter 7. The committee announced that the estimated individual doses to the residents were less than 21 mSv, therefore observable health effects due to radiation were none. Nevertheless, the committee decided to provide annual health examinations to those inhabitants whose irradiation doses due to the accident were estimated to be above 1 mSv and to those who lived within a 350 m radius, if they wanted to be checked. The committee announced that there should be no health effect at the level of 1 – 100 mSv. However, it was found later that this statement was misunderstood by some people to mean that the government officially had admitted that a radiation dose above 1 mSv is harmful, though this is not true in reality. It is important to understand the difference between a manifestation on scientific matters and that of a social or political statement.

10.3. Amendment of the Reactor Regulation Law

By the amendment of the Reactor Regulation Law in December 1999, the Nuclear Safety Inspection System was introduced and the Operational Safety Programs were strengthened. In the Nuclear Safety

Inspection System, a resident Nuclear Safety Inspector is posted to each nuclear related facility to confirm compliance of the operating company with the Operational Safety Programs. The Inspector conducts three-week Nuclear Safety Inspections four times a year, nonscheduled investigations as well as patrols in the facility and he observes the regular inspections.

The Nuclear and Industrial Safety Agency (NISA) took initiative to revise the Operational Safety Programs and refined the contents, referring to the related provisions in the IAEA-NUSS and the U.S. standards technical specifications. After being reviewed by the technical advisers, the Operational Safety Programs for each commercial power reactor was revised in January 2001. The new Operational Safety Programs were strengthened to include programs on fostering of safety culture, safety-related education of personnel and quality assurance of facilities and activities.

Moreover, the Allegation System was established, encouraging personnel to allege violation of safety regulation at nuclear installation without unfavorable treatment, and the Periodical Inspection System on Fuel Fabrication Facilities was established.

10.4. Enactment of the Special Law for Nuclear Emergency Preparedness

The JCO Criticality Accident was a very serious accident in that local residents were instructed for sheltering or evacuation for the first time in Japan. Lessons learned from the accident clarified the special characteristics of a nuclear emergency, which would demand quick initial response actions, coordinated cooperation between the national government and local governments, strengthening of the national preparedness for response to a nuclear or radiological emergency and the clarification of nuclear facility operator's responsibilities. The Special Law for Nuclear Emergency Preparedness was enacted in December 1999 and enforced in June 2000, addressing the special characteristics of nuclear emergency mentioned above. The Special Law for Nuclear Emergency Preparedness was enacted within the legal framework already established by the Basic Law on Emergency Preparedness, which had defined roles of the national government, local governments, etc. in emergencies such as earthquakes, typhoons, and conflagrations.

The Part 10 “Nuclear Emergency Preparedness” in the Basic Plan for Emergency Preparedness, based on the Basic Law on Emergency Preparedness, was extensively revised in accordance with the Special Law for Nuclear Emergency Preparedness, clarifying roles and responsibilities of the national government, local governments, and license holders etc.

The Special Law for Nuclear Emergency Preparedness defines specific initial events in nuclear facilities. At the occurrence of such an event, the facility operator shall immediately notify the competent minister and the heads of related local governments. When the competent minister recognizes that the specific initial event exceeds the predetermined level and has developed into an emergency, the minister immediately reports it to the Prime Minister. The Prime Minister declares “Nuclear Emergency”, and establishes the "Nuclear Emergency Response Headquarters" in Tokyo, which he will head, and the "Local Nuclear Emergency Response Headquarters".

The competent minister designates a facility in the vicinity of a nuclear facility as an Off-Site Center to be used in an emergency. In case of an emergency, the national government, the local governments and the operator establish, at the Off-Site Center, the "Joint Council for Nuclear Emergency Response", in order to share information and to coordinate their activities. The Off-Site Centers have equipment facilitating communication with the Prime Minister’s Official Residence, the Cabinet Office, the Emergency Response Centers of the NISA or the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and related local governments. The Off-Site Centers also have other equipment, necessary to display on-line the environmental radiation levels and information on the accident at the nuclear facility.

The NSC, taking into consideration the Special Law for Nuclear Emergency Preparedness and the lessons learned from the JCO Criticality Accident, revised in May 2000 the "Guidelines on Emergency Preparedness" on technical and special matters of nuclear emergency measures, to include research reactors and nuclear fuel cycle facilities in addition to commercial power reactors, and to include accidental release of nuclear fuel material, etc. in addition to release of noble gases and iodine. Also, the NSC revised in May 2001 the “Guidelines on Environmental Monitoring in Emergency” and the “Guidelines on Environmental Monitoring”.

10.5. Strengthening the Nuclear Safety Commission

The JCO Criticality Accident led to a strengthening of the functions of the NSC by increasing the number of supporting staff by five times. The newly established Subsequent Regulation Review aims to audit the adequacy of regulatory activities of NISA at each stage after issuing a license, in addition to the audit of NISA's safety examination during licensing of a nuclear installation.

From June 2001, the chairman and other commissioners of the NSC, in response to the accident, started to visit nuclear facilities across the nation to hold discussion meetings with field managers and shift supervisors on how to enhance safety culture at the facility.

Also, the NSC decided on the "Important Issues concerning Operation of Uranium Fuel Fabrication Facility (September 25, 2000)", the "Examination Guide for Safety of Specific Uranium Fuel Fabrication Facility (September 25, 2000)" and the "Examination Guide on Technical Capacity of Nuclear Facility Operator (May 27, 2004)".

10.6. Response of the Nuclear Industry to the Accident

The Japan Atomic Industrial Forum Inc., consisting of about 800 business operators including reactor operators, manufacturers, etc., who were directly or indirectly engaged in the nuclear business, published a statement entitled "Toward Reform of Japan's Nuclear Industry" in October 8, 1999, in response to the JCO Criticality Accident.

Moreover, nuclear business operators (36 operators such as reactor operators, fuel fabricators, plant manufacturers, and research organizations) covering the whole country founded the "Nuclear Safety Network (NS network)" in December 1999, for sharing and improving "nuclear safety culture", and started the following activities:

a) cultivation of "nuclear safety culture" among members through seminars and educational sessions, a web site, and publication of periodicals,
b) peer review among members for identification of issues and dissemination of good practices, and
c) exchange and circulation of information on nuclear safety.

The activities of the NS network were transferred to the Japan Nuclear Technology Institute, which was established in May 2005 to strengthen technical infrastructure of the nuclear industry and to promote safety-related activities at nuclear facilities.

In Tokai district, Ibaraki Prefecture, where 21 nuclear business operators are located, the "Nuclear Business Operators Safety Cooperation Agreement" was signed in January 2000, to support cooperative activities in nuclear emergency as well as to improve safety of installations and employee's abilities.

11. LESSONS LEARNED

The JCO accident is one of the most thought-provoking experiences in a nuclear energy related facility, not only in Japan but also in the world. It caused fatalities among employees as well as emergency evacuation of neighboring residents. It poses a lot of issues which should be discussed not only among nuclear fuel processing industries but also among other nuclear industries and among those who handle radioactive materials.

This chapter extracts lessons learned from the JCO accident based on the information provided in previous chapters. The informationis basically assembled by NSC and AESJ in their reports. Most of the lessons are categorized into two generic issues: management system together with emergency preparedness and response. These issues are meaningful for all the sectors dealing with nuclear facilities or radioactive materials and for the government authorities concerned.

11.1. Management System

The Management System or the system required to assure not only the quality of the product but also to assure the safety as a part of "satisfaction of interested parties", had not taken root in JCO. The licensed design of the nuclear fuel process had been continuously revised in an unauthorized manner, and finally made vulnerable to the occurrence of a criticality event. Not only the three workers, who triggered the accident, but also the manager who allowed the last modification of the process lacked practical understanding of criticality safety. Four major lessons are learned:

- Competency of Human Resources
- Organization Drift and Safety Culture
- Authorization Scheme
- Cooperation of the Client

11.1.1. Competency of Human Resources

Staff in charge of activities which can potentially affect nuclear safety should be well trained so that the staff members can get familiar with the operation processes and relevant operation limits and conditions. Moreover, operational staff should be able to recognize and respond to foreseeable abnormalities, malfunctions, or consequences caused by their own handling errors of the facilities or equipments. Managerial competency to establish and implement safety-related authorization schemes (e.g. that for changing operation processes) and to ensure compliance in the organization is also indispensable.

As mentioned in Chapter 9, the JCO staff did not sufficiently have fundamental knowledge on nuclear safety and their safety culture was not properly promoted or supported. Operation limits and conditions regarding criticality safety control defined through the licensing process were modified without any safety consideration. The workers had not been properly trained for and informed about such limits and conditions and their rationale, and therefore could not recognize a possibility of criticality due to lack of relevant knowledge. The authorization scheme to change operation processes had not been properly established and implemented so as to proactively screen deviation from the limits or conditions (see Section 11.1.3.). Accordingly, they could modify the operation process beyond the limits and conditions, and directly triggered the accident. After the occurrence of the criticality, the lack of competency of the JCO staff to recognize, respond to and be accountable for the abnormality caused delays in decision-makings for mitigation.

Therefore, training programs and its certain implementation are essential for achieving competency goals such as: making trainees familiar with the operation processes, making the trainees competent to recognize, respond to and be accountable for deviation from normal processes, as well as making them competent to properly establish and comply with authorization schemes which assure safety. The following three items are recommended to be included as compulsory subjects in the training programs based on the experience of the JCO accident:

1) Technical training on operation processes and nuclear safety controls in the facilities,
2) Training on internal and external communication, especially for recognition of and response to

abnormal states of the operation processes, and

3) Training on management strategies to establish and implement appropriate safety-related procedures (e.g. for changing operation processes and emergency response), and to enhance compliance in the organization.

As for the first item, technical basics of nuclear safety such as criticality safety control is an essential subject for operational staff handling fissile material and for their managers making decisions on the operation processes.

It is also crucial in training strategies to accurately identify who actually requires training to acquire an understanding of the technical bases of the safety limits and conditions of the operation processes. It should be noted that there might be persons who are practically experienced but lack such understanding of the technical bases and thus may be over-confident, assuming that their experience gives them adequate understanding.

11.1.2. Organization Drift and Safety Culture

An appropriate safety culture, which includes organization norms, managerial belief system, attitudes, and behaviours, worker training and which maintains primacy of safety in the face of tension with production, priorities, and worker environment, should be fostered throughout the organization on a repeated basis. In the JCO, discontinuation of workers' experience, and knowledge essential to nuclear safety, which was resulted by intermittent and long-term contracts, prevented sound safety culture from being enhanced. Under such a condition, much attention is needed to develop safety culture. Lack of an appropriate safety culture increases the chance of an incident because operators can consciously override almost any engineered safety feature of a system.

The JCO "organization drift", affecting design and operation processes, involved "creeping" changes and small increments but aggregated over time to create an undesired result. There was no system to detect or prevent the deviations. Several precursors had been overlooked.

All changes having taken place in an organization should be reviewed. The collection of changes should be periodically checked to determine if an unintended organization drift is occurring. Deviation from approved procedures can increase the risk of an accident. Every process for making changes should be documented and authorized, otherwise the habit of "working around" compliance can be encouraged. Compliance with a procedure needs to be reinforced by the procedure development. Nothing in the procedure development and compliance process should result in negating the primacy of appropriate safety culture principles. If a deviation from the planned program or process is revealed, the opportunity should be taken to examine whether correct controls are being exercised (e.g. whether the safety specialists had been consulted.)

11.1.3. Authorization Scheme

In JCO, a staff member who had no responsibility for the use of the precipitation tank allowed the workers to utilize the tank for homogenization process.

Authorization scheme in the company (e.g. authorization of change of operation processes) had not been properly established. That had allowed deviations from the licensed processes, leading to the accident. Lines of supervision and authority should be clear, especially where a change of organization has taken place. Clarity of those who can authorize changes should be well known by workers and those persons should have competencies in line with their responsibilities. Managers should be clear on their responsibility and knowledge limits within the management system. Training should be given not only to workers but also to managers to support their understanding of their duties so that the well established authorization scheme is surely implemented (see Section 11.1.1.).

11.1.4. Cooperation of the Client

11.1.4.1. Communication on product specification

The client should clearly and timely communicate requirements of the product specification to the subcontractor in order that the design of the related facilities and the production process may be based on sufficient safety consideration. In case the requirements are exceptional (e.g. an order related to a special experiment), the client should have closer communication.

In relation to modification of the CTB in 1984, JCO was not timely informed by PNC about basic specifications such as uranium enrichment of the UNH and about long term plans on annual production rate and frequency. Accordingly, the UNH production and homogenization processes were not sufficiently taken into account of in the design of modifications of the CTB. The difficulty in dealing with the UNH solution resulted in ad hoc re-designs of the production process such as introduction of the homogenization process with cross-blending and utilization of stainless steel vessels for re-dissolution.

11.1.4.2 Design of the entire procurement system based on total risk evaluation

Procurement should be planned taking broader safety implications into consideration, i.e., not only the safety during the production process but also the safety during transport should be evaluated.

There was actually another available option for producing UNH with IEU for the JOYO reactor: JCO could have produced purified U_3O_8 and PNC/JNC could have dissolved it into UNH. This option with low-moderated uranium (dry U_3O_8) would have reduced the criticality hazard of the transport on public roads. Furthermore, it might have been more efficient from the viewpoint of productivity because the JCO product examination for quality assurance could have been much easier for U_3O_8 than for UNH.

11.1.5. Comparison between the lessons and the IAEA safety principles and requirements

Regarding issues of the management system, the IAEA issued a Safety Fundamentals publication, “Fundamental Safety Principles”, SF-1 [33], which establishes the fundamental safety objective, safety principles and concepts including significance of the sound management system, and a Safety Requirements publication, “The Management System for Facilities and Activities”, GS-R-3 [34], which defines the requirements for establishing, implementing, assessing and continually improving a management system. In this subsection, lessons learned from the JCO accident in relation to the management system are linked with relevant safety fundamentals and safety requirements provided in the above-mentioned publications. and the lessons learned are intended to serve as a set of practical guides which will help users of the two publications to understand the actual meaning of each stipulation better.

11.1.5.1.Competency of Human Resources

As mentioned in subsection 11.1.1, the immediate cause of the JCO accident was the lack of competency of the workers. The importance of identifying and maintaining necessary competency of each staff member is a lesson learned. The essence of the point is well covered in both SF-1 and GS-R-3.

On the competency of human resources, SF-1 stipulates in its Principle 1, “Responsibility for Safety”, that:

- “The licensee is responsible for:
  - Establishing and maintaining the necessary competences;
  - Providing adequate training and information.” (Para. 3.6.)

And GS-R-3 requires in the section of “Human Resources” in Chapter 4, “Resource Management”, that:

- “Senior management shall determine the competence requirements for individuals at all levels and shall provide training or take other actions to achieve the required level of competence. An evaluation of the effectiveness of the actions taken shall be conducted. Suitable proficiency shall be achieved and maintained. (Para. 4.3.)
- “Senior management shall ensure that individuals are competent to perform their assigned work and that they understand the consequences for safety of their activities. Individuals shall have received appropriate education and training, and shall have acquired suitable skills, knowledge and experience to ensure their competence. Training shall ensure that individuals are aware of the relevance and importance of their activities and of how their activities contribute to safety in the achievement of the organization’s objectives.” (Para. 4.4.)

Determination of competence requirements such as a worker’s understanding of criticality safety controls and ensurance that every staff member achieves competence requirements are definitely responsibilities of the senior management or the organization itself and should therefore be strictly implemented organization-wide. The staff’s competence should be managed as an organization resource requiring maintenance.

11.1.5.2.Organization Drift and Safety Culture

In JCO, safety implications relating to UNH production had been overlooked and higher priority had been placed on short-term productivity. Not only the licensed procedure, but also internal rules had been changed without proper authorization to pursue higher productivity and lower workload. Importance of fostering an appropriate safety culture in the organization is a lesson learned from the JCO accident as stated in subsection 11.1.2.

On the issue of organization drift and safety culture, SF-1 stipulates in its Principle 3, "Leadership and Management for Safety", that:

- "Leadership in safety matters has to be demonstrated at the highest levels in an organization. Safety has to be achieved and maintained by means of an effective management system. This system has to integrate all elements of management so that requirements for safety are established and applied coherently with other requirements, including those for human performance, quality and security, and so that safety is not compromised by other requirements or demands. The management system also has to ensure the promotion of a safety culture, the regular assessment of safety performance and the application of lessons learned from experience." (Para. 3.12.)

And GS-R-3 requires in the section of "Safety Culture" in Chapter 2, "Management System", that:

- "The management system shall be used to promote and support a strong safety culture by:
  - Ensuring a common understanding of the key aspects of safety culture within the organization;
  - Providing the means by which the organization supports individuals and teams in carrying out their tasks safely and successfully, taking into account the interaction between individuals, technology and the organization;
  - Reinforcing a learning and questioning attitude at all levels of the organization;
  - Providing the means by which the organization continually seeks to develop and improve its safety culture." (Para. 2.5.)

The safety culture should be fostered with strong leadership and all-out commitment of management. Sound safety culture can effectively avoid organizational drift.

11.1.5.3. Authorization Scheme

Relating to the authorization scheme, SF-1 stipulates in its Principle 1, "Responsibility for Safety", that:

- "The licensee is responsible for establishing procedures and arrangements to maintain safety under all conditions." (Para. 3.6.)

And GS-R-3 requires in the section of "Developing Process" in Chapter 5, "Process Implementation", that:

- "The development of each process shall ensure that the following are achieved:
  - Process requirements, such as applicable regulatory, statutory, legal, safety, health, environmental, security, quality and economic requirements, are specified and addressed.
  - Hazards and risks are identified, together with any necessary mitigatory actions.
  - Interactions with interfacing processes are identified.
  - Process inputs are identified.
  - The process flow is described.
  - Process outputs (products) are identified.
  - Process measurement criteria are established." (Para. 5.4.)

As analyzed in Chapter 9 and 11.1.3, JCO had not established an authorization scheme such that violations of safety limits could be effectively screened. An authorization scheme should be recognized as one of the procedures to maintain safety which SF-1 requires to be established. The authorization for a certain process should be recognized as a phase of the process development where the achievement of safety requirements is ensured, as required by GS-R-3.

11.1.5.4. Cooperation of the Client

As for the issue of cooperation of the client, SF-1 stipulates in its Principle 1, "Responsibility for Safety", that:

- "The licensee retains the prime responsibility for safety throughout the lifetime of facilities and activities, and this responsibility cannot be delegated. Other groups, such as designers, manufacturers and constructors, employers, contractors, and consignors and carriers, also have legal, professional or functional responsibilities with regard to safety." (Para. 3.5.)

And GS-R-3 requires in the section of "Developing Process" in Chapter 5, "Process Implementation", that:

- "Suppliers of products shall be selected on the basis of specified criteria and their performance shall be evaluated. (Para. 5.23.)
- "Purchasing requirements shall be developed and specified in procurement documents. Evidence that products meet these requirements shall be available to the organization before the product is used. (Para. 5.24.)
- "Requirements for the reporting and resolution of non-conformances shall be specified in procurement documents." (Para. 5.25.)

According to the consideration in 11.1.4, the client could have communicated with JCO sufficiently to reduce the probability of the accident significantly. SF-1 and GS-R-3 imply that the client could have been more carefully concerned with the manufacturing process in JCO. With the responsibility for safety throughout the lifetime of the fuel materials, the client could have reacted when evaluating JCO's manufacturing performance and when developing procurement documents.

11.2. Emergency Preparedness and Response

Several weaknesses were disclosed concerning Japanese emergency preparedness and response system by the JCO criticality accident. A general lesson learned not only from the JCO accident but also from the accidents of TMI and Chernobyl is that there was an implicit assumption both by the operators and by the regulatory authorities that such severe accidents could not happen and thus enough attention had not been paid to preparedness for the accidents. For all activities using nuclear or radiological materials, preparedness for all postulated emergencies (including those of low probability) and events that may be perceived as serious by the public or media should be maintained. Careful attention should be given to human factor aspects for the preparedness (e.g., procedures, training, see Section 11.1.1.).

Major specific lessons are derived from the following areas:

- Communication
- Procedure, Authority and Responsibility
- Exercise
- Decision-making
- Radiation monitoring and Dose Assessment
- Medical Response

11.2.1. Communication

There was confusion in communication in the early stage of the accident; such confusion is more or less inevitable in such a serious accident. Communication systems in emergencies must be well planned and practiced so that confusion can be minimized. There are a lot of points to be organized and known by each person or party concerned: who should communicate to whom about what and for which actions, who has authority and responsibilities for decisions about the site or off-site actions, information to the public, how to access experts in an emergency.

Establishing information flow from the site of the incident to the decision-makers and experts should be given high priority by the management of the facility, by local governments and by regulatory authorities. Factual information without editing or any interpretation should be quickly transferred to appropriate authorities even with ambiguity—that is, even before complete diagnosis of the event, information should be available and reported to the decision-makers and experts.

All communication should be recorded in written form to share the information accurately with interested parties including the mass media.

11.2.2. Procedure, Authority and Responsibility

Management a priori should identify emergency operating procedures and specialists to carry out the actions during an event. Lines of authority need to be derived appropriately by the licensing authorities and be well known in case of an incident, among various entities involved in the management of the site. Incident response duty rosters at the facility should be staffed by knowledgeable and trained incident managers. These managers are responsible for initial decisions on magnitude of the incident and who needs to be notified.

Facility staff should assess the off site consequences and recommend to relevant authorities about actions needed to protect the public.

In the JCO accident, the mayor of Tokaimura decided to evacuate residents without instruction and advice that should have been given by the national government. The Deputy Chair of NSC, which is an advisory committee for the prime minister rather than an administrative authority, conducted the operation to terminate the criticality event. A national authority should have flexibility to support local or other national authorities by making an independent assessment of the potential off site consequences. A national authority should also supply experts and coordinate resources needed to support the local authorities in coping with the event.

11.2.3. Exercise

Exercises are needed to reinforce emergency procedures and emergency response authorities. Exercises must be conducted repeatedly enough to maintain skills of emergency responders and decision makers with participation of all interested parties such as industry, autonomies and residents.

The occurrence of the JCO accident suggests that accidents can come up even at peripheral facilities by simple works in small organizations. These should be taken into account in the exercises, it is very important to study lessons learned from previous accidents. Therefore even small organizations can benefit from frequent exercises. Through the exercise, it should be confirmed whether warning notices or labels are placed visibly on key pieces of the facility to identify where safety limits and conditions are applied. Where applicable, such notices should indicate consequences of deviation from safety limits or conditions.

11.2.4. Decision-making

In order to take appropriate emergency response actions, timely and proper decision-making is required even though it is very difficult under conditions when accurate and enough information is not available. The experience of the JCO accident suggests that the hierarchy of decision-making in emergency should include the temporal transfer to local authorities.

Through exercises and training, emergency decision makers should gain confidence to take responsibility for making emergency decisions, and also have background to understand how to make dicisions.

11.2.5. Radiation monitoring and Dose Assessment

The interaction between radiation monitoring and emergency response is important to take action for protecting the operators, general public and environment. A failure of this will lead to failure in protection measures even for saving lives. In order to take effective initial countermeasures in the early state of accidents, it is important to establish a wide area network for radiation monitoring by the cooperation of related organizations to detect unusual situation and to share the information.

Dosimetry instrumentation must be provided and results of dose assessment for operators should be followed up and systematically checked even during normal operations. These include calibration of dosimetry instrument and check of wear of dosimeters at all times while working with radiation sources. This should also take place in facilities where low exposure is expected. By these activities one can avoid negligence in dosimetry follow up.

The Agency published examples of accident dosimetry in its previous technical guidance [35] and the lessons learned from the past criticality accident [14]. The guidance and lessons were utilized for dose assessment in the JCO criticality accident, and therefore the Agency believes that it is important to go over them again. Individual dose estimation should be carried out using all available information. If some records by dosimeters are available, these records should be employed as a top priority. If dosimetric records are not available but biological specimens including activation products in the body of exposed persons are available, these should be utilized for dose estimation. The method is useful not only for heavily exposed persons but also for the public. If neither dosimetric records nor biological specimens are available, individual doses will be estimated from radiation levels monitored by fixed instruments and from calculations. Measurements of neutron-induced nuclides are available in the case of neutron irradiation. The information would be useful when no other information related to the dosimetric records is available. However, it should be noted that the reliability of the estimated dose significantly depends on the reliability of the estimated neutron energy spectrum.

11.2.6. Medical Response

Accurate information for the accident is extremely important for allowing appropriate measures to be taken. First, the word "criticality" that Worker C had mentioned immediately after the accident was not communicated to the ambulance crew and thus did not reach the NIRS. This is probably because nobody thought that Worker C understand what criticality was. If the JCO staff in charge of radiation safety at the site had been informed that there was a possibility of a criticality accident, a member of staff would have accompanied the workers to the hospital and correctly explained the accident to the medical staff. Also the NIRS would not have needed to prepare unnecessary masks/protection gears and the other institutes would not have been so confused. Furthermore, the ambulance crew entered a room with high level of radiation even though the γ-ray alarm was sounded immediately after the accident and the ambient dose rates at the site exceeded a certain value. Fortunately, the ambulance crew was not exposed to high radiation doses affecting their healths. Radiation cannot be detected without special devices. This accident showed the extreme importance of correct and quick information.

Therefore, the site manager should be responsible to make up the record of radioactive contamination of the patients who were injured during the criticality and to send those contamination records to the rescuing team and to the hospital outside of the nuclear facility site. A good practice would be to have someone who knows the circumstances of the accident to escort the patient to the medical facility to explain the circumstances to the medical treatment personnel. Such a person should also be expected to stay and become the contact point between the site and the hospital, not only for communication but also for mutual confirmation of the circumstances of the accident.

Further, activities of the first-aid and care station for residents neighboring the JCO taught us that exact information could not be easily obtained and that the knowledge about radiation was needed for the public health nurses who came into contact with residents. The information about an accident was to be distributed from the general headquarters for nuclear emergency which was constituted by local and central governments. However, the accident information needed for a first-aid and care station was not transmitted because radiation in a criticality accident was a complex mixture of γ-rays and neutron.

As for the procedures for acceptance of contaminated or/and irradiated patients into a certain medical facility, such facilities should be nominated and clearly listed in the emergency preparedness of the nuclear facility and agreement with nominated medical facilities should be obtained.

Detailed lessons learned from medical treatment given to the three workers at NIRS and other medical facilities are provided in Appendix IV.

11.2.7 Compliance with the international requirements [36]

The Agency prepared and issued a set of standards regarding the basic requirements for preparedness for and response to any nuclear or radiological emergency situation [36]. Although this document was published in 2002 after the JCO nuclear criticality accident but it was built on concepts and experiences that existed (and were available in different publications) even before the accident happened. Therefore it is interesting and important to view the events in light of the main paragraphs of Ref. [34], to identify lessons and draw conclusion about the compliance with the concept of these requirements.

In its Section 3 Ref. [36] discusses the GENERAL REQUIREMENTS, which basically covers the requirement of clear and agreed definition of the *basic responsibilities* and the need for a thorough *threat assessment* prior to any activity with a potential of leading to nuclear or radiological emergency.

The deficiencies regarding the definition of the *basic responsibilities* were discussed in 11.2.2, with the consequence of creating confusion in the decision making and to unacceptable delays during the implementation of the response.

One of the most striking lessons of the JCO accident was the apparent lack of proper *threat assessment* prior to the planning, licensing and operating the facility. Criticality is a major hazard in such a facility, therefore providing measurement of neutrons around the workplaces (continuous dose rate monitoring) where fissile material is processed is a basic requirement. As it was formulated in Chapter 6.1 "…

the possibility of a radiation accident due to criticality in a fuel material processing plant like the JCO accident was not specifically taken into account in the national or local emergency plans". The lack of a properly established and constantly operating Early Warning System is a clear violation of another requirement of Ref. [36] (Section 5: REQUIREMENTS FOR INFRASTRUCTURE). As a consequence of not having neutron detectors at the site neutron monitoring started with 6h delay!

Section 4 (FUNCTIONAL REQUIREMENTS) of Ref. [36] discusses the following issues:

- *Establishing emergency management and operations;*
- *Identifying, notifying and activating;*
- *Taking mitigatory actions;*
- *Taking urgent protective actions;*
- *Providing information and issuing instructions and warnings to the public;*
- *Protecting emergency workers;*
- *Assessing the initial phase;*
- *Managing the medical response;*
- *Keeping the public informed;*
- *Taking agricultural countermeasures, countermeasures against ingestion and longer term protective actions;*
- *Mitigating the non-radiological consequences of the emergency and the response;*
- *Conducting recovery operations.*

The relatively long time needed for setting up the emergency response management system shows the importance of the first requirement above (*Establishing emergency management and operations*). Time and effort could have been saved if a well designed, coherent and exercised plan had been available. From the diffuse and distributed network of decision makers, decision aiding organizations and first responders it is very hard to draw a clear-cut scheme of the Incident Command Structure that would be in charge of a coordinated response to all aspects of the emergency. With the development of the response both the management and the field operations became more and more adequate and finally the situation was handled properly.

The requirement for having an established and tested set of procedures for *identifying, notifying and activating* proved to be essential in many instances of the JCO emergency. This is, again, more pronounced in the first few hours of the response. For example: the staff in the JAERI Naka site was not clearly informed of the possibility of a criticality and could not recognize the relevance of the recorded neutron data at the moment of the accident. Another example of delayed notification is the late transmission of the alert status to the municipalities surrounding Tokaimura.

Taking mitigatory actions was a crucial part of the successful response. A properly designed and carefully implemented sequence of actions (draining water from the cooling water jacket) led to regaining the control over the source.

Taking urgent protective actions was actually initiated by *providing information and issuing instructions and warnings to the public* when Ibaraki Prefecture officially announced a recommendation for residents living within a radius of 10 km from the JCO site to stay indoors late in the evening (22.35pm). This recommendation had been authorized in accordance with the Disaster Countermeasures Basic Act which is a general law for preparedness for natural disaster and agreed by the ETAB. However, it seems that there had not been any common agreeable technical evaluation among nuclear specialists, on which the evacuation could be based. The importance of proper, pre-designed and tested communication procedures towards the affected population is underlined by the method and content of disseminating information and instruction to the people living nearby the JCO site.

The careful planning of the steps of the cooling water jacket drainage proved that the requirement for *protecting emergency workers* was taken seriously during the emergency response operation. In the report reference is made to the maximum planned exposure (100 mSv) that was not allowed to be exceeded by the law and ordinances prevailing at that time of the accident, and that the aim when planning the operation was to keep the exposure below one half of that. This means a dose guidance level of 50 mSv was used for the non-lifesaving operations, which is fully compliant with the IAEA recommendations [35].

The lessons learned regarding the *medical response* to the emergency are described in details in

11.2.6. As the fate of the three overexposed persons are the most serious consequence of the JCO accident the requirement for adequate preparedness for and implementation of the medical response are explicitly highlighted.

Chapter 6.3 gives details of some of *the non-radiological consequences of the emergency and the response* and on the efforts of mitigating them. There were many adverse effects such as returned goods, rapid fall in price, and boycotts of the agricultural and marine products in the whole region of Ibaraki Prefecture, and cancellation of the reservations in hotels and tourist facilities due to rumors based on misunderstanding. To help industries suffering from such adverse effects, the Ibaraki Prefecture interests for the farmhouses and fishery companies who bore losses stemming from the accident. The Ibaraki Prefecture also financed small and medium-sized enterprises with low interest loans amounting up to 4.3 billion Japanese yen (JPY) in total.

Defining the proper criteria for a certain intervention or action is a crucial element of any emergency response system. It may be equally important to clarify, and well in advance rather than during the emergency, the criteria of lifting the recommended protective measures (with special regards to sheltering and evacuation). The Governor of Ibaraki Prefecture requested the government to give advice on early lifting of the recommendation to residents within a 10 km radius of the facility to stay indoors around (this was after the water had been drained from the cooling jacket of the precipitation tank). Unfortunately there were no specific criteria for lifting protective measures such as sheltering and evacuation in the Guideline on Nuclear Emergency Preparedness issued by NSC. The lack of clear criteria for lifting countermeasure is a serious deficiency of the country’s nuclear/radiological emergency preparedness.

11.3. Regulatory System

Consistency between regulatory activities for the design phase and the operation phase should be ensured. Operational conditions should be clearly and carefully defined through regulatory review or assessment of the facility design, and the licensee’s compliance with the conditions imposed at the granting of design authorization should be effectively monitored and encouraged through the operation period.

4 points are drawn as major lessons in this context:

- Design review taking operation conditions into consideration;
- Retroactive review based on newly established safety requirement; and
- Regulatory control in the operation phase.

11.3.1. Design Review Taking Operation Conditions into Consideration

During the design review for licensing, all operation modes and conditions for the facility should be considered in detail to support definition of appropriate safety characteristics of the facility design. This is particularly true for those facilities with unique or special design features from a safety point of view. The regulators should have capabilities to identify safety implications of both explicit and implicit indications.

As analyzed in Chapter 9, the JCO’s application documents for the license stipulated that the aqueous solution of UNH was one of the envisioned forms of product besides UO_2 powder for shipment from the CTB. The STA staff, however, overlooked this stipulation and thus failed to look into its safety implications in the design review for licensing. The NSC’s audit demanded briefing on the planned process for UNH production, which was not described in the application document at all, even in the amended version through the NSC’s audit. The NSC’s audit, however, did not request further detailed explanation on the process specifications such as the concentration and the amount of the solution to be produced, and thus failed to identify the risk significance of the process.

Findings in the design phase or during the licensing process, including in licensing conditions, should be surely incorporated into operation programs. Consistency of safety considerations between phases including siting, design, construction, commissioning, operation and decommissioning should be checked carefully.

Licensing conditions on criticality safety control which had been imposed on JCO through the licensing process by STA and NSC were not incorporated into the JCO operation safety program nor into its subordinate criticality safety control criteria for a long time. The regulatory body did not recognize the inconsistency but approved the operation safety program.

11.3.2. Retroactive Design Review based on Newly Established Safety Requirements

Retroactive application of new design requirements to existing facilities should be considered in accordance with their safety significance based on careful review of the facility design.

The Technical Standards on Design and Construction Method of Manufacturing Business of Nuclear Fuel Material which was adopted in 1987, after the commissioning of the CTB, required manufacturing facilities processing uranium with more than 5 wt.% of enrichment to take appropriate measures. These included installation of a criticality alarm under the postulate of a criticality accident. Although the existing gamma-ray radiation area monitors were virtually regarded as criticality alarms in the CTB, no measure was requested either for terminating a postulated criticality event or for mitigating its consequences.

11.3.3. Regulatory Control in the Operation Phase

Regulatory control in the operation phase such as inspection and patrol should be carefully and strategically designed for all facilities to ensure and encourage licensees' active compliance.

In order to monitor JCO's compliance with the operation safety program, STA's inspection had been carried out seven times between April 9, 1985 and November 26, 1992. Patrols by an officer of the STA Tokai office had been carried out once every month since April, 1998. However, no violation had been detected or prevented because the CTB was a peripheral facility and its operation was iregular.

11.4. Other Issues

11.4.1. Preparedness for Social Impact

The public tends to be affected by radiation-phobia and is sensitive against radiation threats even if there is no evidence of a risk. In the case of the JCO accident, such tendencies were even stronger due to the Japanese people's unforgettable memories of the atomic bombs in Hiroshima and Nagasaki in 1945 as well as of nuclear bomb tests near the Bikini atoll in 1954 when Japanese victims died or suffered from radiation hazard while fishing. After the JCO accident, neighboring farmers had suffered a lot from economic damages. Their agricultural products were refused because their customers unreasonably felt a radiation threat even though the doses were extremely small and no radioactive materials were released.

Proper risk education is necessary for the public to better understand radiation. The quantitative magnitude of radiation effect varies so broadly that it is difficult for the public to obtain a clear view of the radiation effect. It is therefore recommended to promote continuous communication between the public and radiation specialists such that the potential health effects of radiation are clearly explained.

It is also recommended to establish a system to estimate or judge the risks and health effects of radiation and make the findings public promptly during and after an accident. In order to avoid public confusion, it is effective to maintain availability of multidisciplinary experts who have enough knowledge and experience on radiation and who can communicate with the public during and after the accident as a part of emergency preparedness.

11.4.2. Future Issues to be Discussed

(1) Medical responses to local residents of low dose exposure

As described in Chapter 7, the residents surrounding area of JCO received doses at which the possibility of radiation effects on health is extremely low and the detection of any effects is impossible. It was decided to serve medical checkup once a year for the residents who hope it, and it has been continued up to present. Although the medical checkup might not be effective and reasonable from a view point of detection of health effect due to low dose exposure, it seems to be a better effect for mental treatment. It is desired to have a guideline concerning medical and mental care for residents who are exposed to low dose radiation by nuclear accidents.

(2) Cooperation of the communication

In the JCO accident, the communications broadcasted the special news through various medias. A picture of the roof of just under-repaired next building of the CTB gave a misunderstanding that a serious accident took placed and massive radioactive material was released. The correction had asked tedious works. Inaccurate news by media cause a confusion in residents and society, and give significant loss.

Accurate information of media is important in nuclear accidents to prevent unnecessary confusion in the public and society. It is especially true when decision-makers have to inform residents and others of their decision using media. Cooperation with media should be considered in preparedness for emergency of nuclear accidents.

12. CONCLUSION

Almost ten years have passed since the completion of the legislative measures for prevention of recurrence of this kind of accidents and since the strengthening of emergency preparedness and response (Chapter 10). However, the JCO accident is still drawing global attention. The occurrence of the accident is truly regrettable but provides a lot of records and lessons which can serve as a very meaningful and practical references for those who are concerned with nuclear facilities or radioactive materials. The accident has shown us that deterioration of the safety culture and of the management system can cause fatal consequences. It has also demonstrated what is actually required for effective emergency response, including medical response.

From the above-mentioned standpoint, this report overviews the social and economical environments surrounding JCO, the technical details of the JCO facilities and activities, the detailed sequence of the criticality event and the measures taken for mitigation, evaluation of criticality characteristics, dose evaluation, emergency response actions including medical response performed, analysis of causes of the accident, and legislative and regulatory reforms carried out after the accident. The information is based on an AESJ report and other existing open official reports. Taking such information into consideration, the report extracts lessons learned which are worth sharing worldwide.

The extracted lessons are categorized into three generic issues: management system; emergency preparedness and response; and the regulatory system. Comparisons between each major lesson and existing IAEA safety fundamentals and requirements are drawn. The comparisons are intended to serve as practical guides for effectively using the IAEA documents. The lessons are meaningful for all the sectors dealing with nuclear facilities or radioactive materials and governmental authorities concerned.

As for the management system, the importance of maintaining competency of human resources, preventing organization drift and deterioration of safety culture, establishing well planned authorization scheme, and being cautious about external influences to safety activities such as economical or political factors is extracted as lessons.

As for emergency preparedness and response, establishing a robust and reliable system for communication in an emergency, clarifying procedures and responsibilities for authorizing decisions, conducting effective exercises, maintaining competency of decision-makers, conducting reliable radiation monitoring and dose assessment, providing medical facilities adequate information, and establishing a robust medical network for each nuclear facility were extracted as essential points for establishing practical emergency preparedness.

Relating to regulatory systems, the importance of ensuring consistency between regulatory activities during the design phase and during the operation phase was emphasized. Clearly and carefully defining operation conditions, prior to the licensing of a design and effectively monitoring and encouraging the licensee's compliance with the conditions, were recognized as crucial points.

Besides the above-mentioned three major lessons, importance of preparing for social impact, paying sufficient attention to facilities for special purposes, careful consideration for change of facility design and maintaining safety equipments in facilities using fissile materials were derived as lessons to be shared broadly.

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Appendix I. The history of contracts JCO had been awarded

1. SMM produced in the “laboratory”, in 1972 through 1974, the total amount of 1546 kg U as $U(23)O_2$ from $U(23)F_6$ for JOYO MK-1 core fuel and delivered it to PNC.
2. SMM and JCO produced in the “conversion test building (CTB)”, in 1979 through 1983, the total amount of 1846 kg U as $U(12)O_2$ from $U(12)F_6$ for JOYO MK-2 J1 core fuel and delivered it to PNC.
3. JCO produced in the modified CTB, in 1985 through 1998, 1775.2 kg U as UO_2 and 817.0 kg U as UNH from $IEUU_3O_8$ and delivered it to PNC. The detail is as follows:
4. In the JOYO 3rd campaign (1985-1986), JCO produced and delivered to PNC, seven lots of 421 kg U as $U(19.75)O_2$.
5. In the JOYO 4th campaign (1986-1988), JCO produced and delivered to PNC, two lots of 190 kg U as $U(18.5)O_2$ and 20 lots of 296 kg U as U(18.5)NH.
6. In the JOYO 5th campaign (1988-1989), JCO produced and delivered to PNC, five lots of 430 kg U as $U(18.5)O_2$.
7. In the JOYO 6th –first campaign (1990-1991), JCO produced and delivered to PNC, four lots of 305 kg U as $U(19.16)O_2$.
8. In the JOYO 6th –second campaign (1992-1993), JCO produced and delivered to PNC, fourteen lots of 203 kg U as U(19.05)NH.
9. In the JOYO 7th –first campaign (1994-1995), JCO purified and produced 83 kg U as $U(19.05)_3O_8$.
10. In the JOYO 7th –second campaign (1995-1996), JCO produced and delivered to PNC, three lots of 201 kg U as $U(18.8)O_2$.
11. In the JOYO 7th –third campaign (1995-1996), JCO produced and delivered to PNC, three kinds of UNH, as nine lots of 130.5 kg U as U(18.8)NH, five lots of 72.5 kg U as U(19.05)NH, and one lot of 14.5 kg U as U(19.02)NH.
12. In the JOYO 8th –first campaign (1996), JCO produced and delivered to PNC, seven lots of 100 kg U as U(18.8)NH.
13. In the JOYO 8th –second campaign (1996-1997), JCO produced and delivered to PNC, one lot of 108 kg U as $U(18.8)O_2$.
14. In the JOYO 8th –third campaign (1998), JCO produced and delivered to PNC, one lot of 120 kg U as $U(18.5)O_2$.
15. In the last campaign (1999), JCO planned to produce and deliver to JNC (former PNC) , four lots of 57 kg U as U(18.8)NH.

Appendix II. Nuclear Characteristics of the JCO Criticality Accident

1. *Nature of the solution led to supercritical state*

The accident occurred during the ninth campaign of JCO for production of JOYO fuel material. The contract covered production of 57 kg U solution of 18.8 wt.%-enriched UNH. The work started on September 10. The raw material U_3O_8, supplied by JNC, was purified and re-converted into the form of U_3O_8 by September 28, 1999.

The next step was producing an aquatic solution of UNH (UNH ($UO_2(NO_3)_2{*}\cdot 6H_2O$) by dissolving the purified U_3O_8 powder. A shape-controlled dissolution tower[5] should have been used for this step according to the approved procedure, but JCO had been using a portable container made of stainless steel, which they called a "bucket" or a "mixing can", for this step since 1993 (see Chapter 9).

The dissolution work, started at 13:00 on the day before the accident (September 29, 1999), followed a bylaw in JCO. For each batch, purified U_3O_8 powder equivalent to the mass limit for one batch was brought from a storage room to a table in the calcination and reduction room using a 10-L "bucket". The mass limit for one batch was 2.4 kg U but the actual batch size dealt with in this process varied up to 2.6 kg U or more. The powder was mixed with warm water and slurried in the "bucket", and then dissolved in 15-N HNO_3 slowly. The amount of HNO_3 (1.7 l) was determined not to be much more than stoichiometric since the free HNO_3 concentration in the product solution was specified to be less than 0.5 N. The mixture in the "bucket" was then heated on a small cooking heater and stirred until complete dissolution. The NOx gas arising in this process was vented through a hand-built stack connected to the facility ventilation line. After complete dissolution, water was added to make a 6.5 L solution with a nominal concentration of 370 gU/l. The dissolution work took 20 to 30 minutes per batch reportedly. The solution was then filtrated and held in another "bucket" for natural cooling before delivery to the precipitation tank. Four batches had been dissolved and put into the precipitation tank by the end of September 29.

The workers intended to use the precipitation tank for homogenization of solution over a single shipment lot (about 16 kg U, or about 6.7 batches). It was the first time that the precipitation tank was utilized for this purpose. Previously, the homogenization had been performed through manual cross-blending, and then using a shape-controlled buffer column. All of these methods were introduced without regulatory approval.

The precipitation tank had an internal capacity of 96 L. Both its diameter (450 mm) height (600 mm) were much greater than the limits for 20 wt.% enriched uranium provided in TID-7016[6]: 170 mm and 69 mm, respectively (all other components of the facility conformed to these limits). The tank had a hand hole on its top that had been used regularly for washing out the sediments on the tank inner surfaces, and supposedly for transfer of solution to and from the tank[7].

The solution was poured into the tank through a funnel inserted into the hand hole. The funnel was held by one of the workers who stood aside the tank. The electric heater and the stirrer in the tank were unused for the work, but the cooling water was circulating through the water jacket at an unknown flow rate.

The alarm connected to the gamma-ray area monitor in the CTB went off at 10:35, soon after the workers started pouring the second half of the seventh batch. The gamma ray monitor recorded indication of an abrupt increase from the normal background level. It is thus considered unlikely that the solution became critical before the second half of the seventh batch started adding.

2. *Final quantity and composition of solution*

In the post-accident analyses, the change in the uranium inventory in the precipitation tank

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[5] The tower was designed for dissolution of raw-material uranium, but licensed also for dissolution of purified uranium, and later substituted by "buckets" for both aims without regulatory approval.

[6] J.T. Thomas (ed.), Nuclear Safety Guide, TID-7016 Rev. 1, NUREG/CR-0095 (1961).

[7] This is known to be the case for the antecedent facility in the CTB.

was evaluated based on the hand-written records on the work sheet. The final inventory, at the moment when the pouring was interrupted, was evaluated to be 16.59 kg U by subtracting the quantity of the remaining solution in the 5-L beaker, left by the workers without spilling, from the total amount of the seven batches. The water inventory in the tank was estimated with the specified concentration of the solution (370 gU/l) rather than the actual quantity of the solution, since the accuracy of the work record of the volume of the solution, which was measured by ruler readings of solution level in the bucket, was questionable. The solution left in the precipitation tank after the accident was not used in the analysis, since the solution was diluted in the boron injection operation to keep the subcritical state after the criticality termination, and an unknown amount was drained out of the system during the same operation. The free HNO_3 concentration was evaluated to be 0.5 N from the work records. The solution composition used in the post-accident analyses are summarized in Table 5.5.3.

3. *Reactivity analysis*

The reactivity during the JCO workers' feeding the solution into the precipitation tank was calculated with a detail model of the precipitation tank, using a combination of a Monte Carlo code MCNP 4B and the Japanese Evaluated Nuclear Data Library JENDL-3.1. It was confirmed that the calculation bias for the neutron multiplication factor was negligible according to a benchmark evaluation based on critical experiments in TRACY and STACY (Static Experiment Critical Facility) using 10 wt.%. and 93 wt.% enriched UNH solution. Sensitivity calculations show that the combined reactivity effect of the surrounding structural material, floor and sidewalls of the building, and of the two workers near the tank was negligibly small.

Figure A.II.1 shows results of the reactivity calculations. The Figure shows that the solution was subcritical at the end of the sixth batch, and that it became critical with the first feed of the seventh batch (i.e., six batches + 3 L). The calculations show that the maximum excess reactivity in the accident was about 2.7 $. However, there are considerable uncertainties in the fuel specifications and in the solution height in the tank. It is therefore difficult to determine the actual excess reactivity only by the reactivity calculations.

Consequently, considering the uncertainty of parameters relating to the criticality and calculation methods, the maximum excess reactivity was estimated to be between 1.5 $ to 3 $.

4. *Kinetic analysis*

1) Evaluation of Kinetics Parameters

Kinetics parameters such as temperature and void coefficients of reactivity, a prompt neutron lifetime and an effective delayed neutron fraction were calculated with two neutron calculation codes, SRAC and TWODANT with JENDL 3.2 library. In the TWODANT deterministic calculation, a model of the precipitation tank as a cylinder with the known diameter and the estimated solution volume was used. Results of the calculations are shown in Table 5.5.4.

The reactivity insertion rate is estimated to be about 0.2 dollar/s, which corresponds to the pouring rate of the solution to the precipitation tank using a portable container.

2) Power Profile for the Initial Power Burst

The power profile in the initial power burst (during the first 25 minutes of the accident) was calculated by a one-point reactor kinetics code, AGNES2. This code has been developed to evaluate criticality accidents in a fissile solution system, and can also deal with radiolytic gas void reactivity effects as well as temperature effects. This code was validated by transient experiments of TRACY using 10 wt.% enriched UNH solution. This code could simulate the total fission number and the maximum power of the first power pulse within 20 wt. % for the ramp feed mode experiments of TRACY. These experiments are considered to have provided almost the same conditions of reactivity insertion as in the JCO accident. The power profile in the JCO accident therefore could be calculated by input of estimated parameters of inserted reactivity to AGNES2.

Figure A.II.2 shows an estimation of the released energy during the first power pulse for each assumption of the maximum excess reactivity. As shown in the figure, the energy was almost independent of the inserted reactivity, about 5×10^{16} fissions, because the reactivity insertion rate was relatively small. The result was compared with an evaluation based on the records of a gamma-ray area monitor located in the First Fabrication Building of JCO. As shown in Figure A.II.3, the power profile evaluated with the gamma-ray monitor records was considered to be between the calculated power profile by AGNES2 for the inserted reactivity 1.5 dollars and that of 3.0 dollars.

3) Power Profile for the Plateau Part

The long-time power profile strongly depends on the heat removal by the cooling jacket surrounding the precipitation tank. A thermal simulation experiment has been performed with a mockup apparatus at JAERI to investigate the thermal characteristics of the precipitation tank in order to estimate the inserted reactivity and the flow rate of the cooling water in the cooling jacket. In the experiment, water was used instead of UNH solution, and the electric heater was used as a heat source to simulate the power profile in the plateau part (after 25 minutes from the occurrence of criticality to the termination of the criticality). The fact that the power in the plateau part was almost constant means that the state of the solution was almost critical. Thus, the inserted reactivity (i.e., the maximum excess reactivity) at that time was just compensated by the feedback reactivity of temperature. Then the solution temperature corresponding to the inserted reactivity at the critical state can be calculated using the temperature coefficient of reactivity. Using this relation between inserted reactivity and solution temperature, the power of the heater for the thermal simulation was determined to reproduce the power profile in the plateau part.

The simulation experiment shows that the flow rate of the cooling water should be in the range of 0.6 to 0.2 l/min. to reproduce the accident situation for the initial reactivity of 1.5 to 2.7 $, although the accident investigation by JAERI estimated that the cooling water flow rate was about 2 l/min. In addition, when the water evaporation effect was considered, the inserted reactivity of 2.5 to 2.7 $ can reproduce the slight power decrease in the plateau part as shown in Figure A.II.4.

4) Power Profile for Whole Period

The power profile for the whole period of the accident was calculated with the quasi-steady state method using the heat removal data obtained by the thermal simulation experiment described above. In this calculation, the inserted reactivity and the cooling water flow rate were varied as the calculation parameters, and the parameters which reproduce the energy released in the initial power burst and that in the whole period (total energy) were surveyed.

Figure A.II.5 shows the results of parameter survey calculation. For the total energy, if the cooling flow rate is in the range of 0.6 to 0.2 l/min., the inserted reactivity can be 1 $ to 3 $. On the other hand, for the initial power burst, the inserted reactivity can be less than 1.8$. The intersection of two lines in the figure will give the optimum parameters. Using these optimum parameters (0.375 L/min. and 1.52 $), the power profile for the whole period of the accident was calculated as shown in Figure A.II.6. The calculation result well fits to the observed profile, although the slight decrease in the plateau part can not be reproduced.

5) Evaluated Inserted Reactivity

The thermal simulation experiment indicates that the inserted reactivity is 2.5 $ to 2.7 $. On the other hand, the quasi-steady state method shows that the optimum inserted reactivity is 1.52 $. If the reactivity larger than 1.52 $ was inserted, the energy in the initial power burst would be largely different from the observed one. However the reactivity of 1.52 $ could not reproduce the slight decrease of power in the plateau part due to the underestimation of the effect of water evaporation in the analyses.

The actual value of the inserted reactivity has not been evaluated yet so far. To clarify this problem, further investigation, such as accurate evaluation of water evaporation effect is necessary.

Table 5.5.2. Amount of Uranium Inserted in Each Batch

No.	Uranium weight (kg)	Sum of uranium weight (kg)	Solution volume (L)	Sum of Solution volume (L)
1	2.405	2.405	6.500	6.500
2	2.431	4.836	6.570	13.07
3	2.244	7.080	6.065	19.14
4	2.630	9.710	7.108	26.24
5	2.268	11.978	6.130	32.37
6	2.409	14.387	6.511	38.88
7	2.201	16.588	5.949	44.83

*) Remain of 182.7 g U is subtracted from the uranium weight of 7th batch

Table 5.5.3. Fuel Specifications

<table>
<tr><td>U concentration</td><td colspan="2">Acidity</td><td colspan="2">U weight</td><td colspan="2">Solution volume</td><td>Temperature</td></tr>
<tr><td>370 g U/L</td><td colspan="2">0.5 N</td><td colspan="2">16.59 kg</td><td colspan="2">44.83 L</td><td>25 °C</td></tr>
<tr><td rowspan="2">Isotopic composition</td><td colspan="3">U-234</td><td colspan="2">U-235</td><td colspan="2">U-238</td></tr>
<tr><td colspan="3">0.15 wt .%</td><td colspan="2">18.8 wt.%</td><td colspan="2">81.05 wt.%</td></tr>
</table>

Table 5.5.4. Kinetic Parameters

Effective delayed neutron fraction	Prompt neutron lifetime	Temperature coefficient of reactivity	Void coefficient of reactivity
0.00788	3.0×10^{-5} s	-0.022 % Δk/k/°C	-0.31 % Δk/k/ %Void

Appendix III. The dose estimation of residents around the JCO facility by chromosome analysis

(1) Identifying the 43 people that needed chromosomal analyses

The Ibaraki Prefecture central hospital counted the number of lymphocytes of 1,844 people living near the JCO on October 2, 3, and 4. The numbers of lymphocyte were lower values (910 cells /µl or less) in 8 persons. Thus, 8 people were subjected to chromosome analysis that was supported, in part, by the Ministry of Education, Culture, and Sports. On October 12, this hospital contacted the NIRS and asked if it was possible to perform chromosome analyses for these eight patients. On October 14, a formal letter arrived from the Ibaraki Prefecture requesting the chromosome analyses of the eight persons. Blood was collected on October 18 from the eight people, who showed abnormally lower numbers of lymphocytes, at the old Tokaimura City Hall by the medical staff of the Ibaraki Prefecture central hospital. Since one of these people was a small child, chromosome analysis was not performed for him. Blood specimens were taken from the other 7 people. There were people among these seven who were old and/or had been receiving treatment for blood disorders and chronic diseases before the exposure. To obtain their informed consent, NIRS explained about chromosome analysis, and asked about their medical history and where they were at the time of the accident. It took more than two hours to take the blood specimens and to ask information from the seven residents. The blood specimens and the smear specimens were brought to the NIRS.

Whole-body counters also detected ^{24}Na in JCO staff members and its neighbors. On October 20, it was discussed on chromosome analyses of the residents who lived near the JCO and chromosome analysis for further dose assessment was performed on these persons who were identified as being low-dose exposed. The second and third blood sampling was conducted at National Mito Hospital on October 21 and 22. Thirty-six people including 7 persons working near the JCO plant, 26 JCO employees and 3 fire fighters, came to the hospital. To obtain the informed consent of the persons, NIRS explained that 1) it is possible to estimate the doses by chromosome analyses, 2) we are always being exposed to natural radiation even when there is no accident, 3) the residents in areas of natural high back-ground radiation in China are always being exposed to dose higher than that during this accident but do not show increases in the incidence of cancer and leukemia and 4) since abnormal chromosomes are also induced by factors other than radiation, such as mutagens in the environment, it is difficult to estimate lower dose of radiation by chromosome analysis. Moreover, result of investigations at NIRS and in China were introduced to these people. The blood specimens were brought to the NIRS in sterile tubes that contained preservative agents.

(2) Analysis of the chromosomes

Five research institutes participated in this investigation: the Radiation Biology Center of Kyoto University, the Radiation Effects Research Foundation (RERF), the Research Institute for Radiation Biology and Medicine of Hiroshima University, the Nagasaki University School of Pharmaceutical Sciences and the NIRS. The first meeting was held on November 5 at the NIRS and the precise methods for chromosome analysis and procedures for describing the analytical results were discussed. It was decided that the NIRS should prepare five slides from each of the 43 persons and send a set of specimens to each of the aforementioned five institutes (each institute was to receive a total of 43 slides). Each institute was to analyze at least 200 cells for each patient and record all cells that were suspected of abnormality in microscopic photographs. Any points and comments obtained during the analyses and the results of the analyses were sent to the others via e-mail. The same program (Microsoft Excel) was used to show the analytical results so as to make it easy to compare and summarize the results. On March 6 and 7, 2000, the second group meeting was held at the Radiation Biology Center of Kyoto University. The microscopic photographs of all abnormal chromosomes and those that were suspected of aberration brought from the five institutes were examined and final conclusions were reached. Thus, the analytical data was highly precise and highly reliable.

The National Radiological Protection Board (NRPB) in UK, L'Institut de protection et de sûreté nucléaire (IPSN) in France and the Laboratory of Industrial Hygiene in China, which had experiences in estimating radiation doses by chromosome analyses, offered their cooperation in performing chromosome analyses. Their cooperation was also essential.

(3) Estimation of exposed doses

After subtracting the spontaneously occurring abnormal chromosomes, no increase was detected in the frequency of abnormal chromosomes induced by radiation in the 7 persons who had significantly low lymphocyte numbers in the first medical examination. However, 18 persons out of the remaining 36 showed an increase in the frequency of abnormal chromosomes. The median dose values that were estimated from the chromosome analyses were 5 mSv or less for 13 persons, 6 – 10 mSv for 3 persons and 11 - 16 mSv for 2 persons.

(4) Lessons learned for future direction

In early May, the seven people with reduced numbers of lymphocytes were explained of the estimated doses by physicians and the others by mail. Their radiation doses were not as high as reducing the numbers of lymphocytes. It has been reported that a significantly higher frequency of chromosomal aberrations can be detected at a dose of 20 mGy of low LET radiation such as X- or γ-rays. It is a matter of concern that the number of such skilled analysts remains few among the younger technicians. One of the solutions to this problem may be to train technicians in private chromosome test centers to learn this special technique.

Appendix IV. Medical Treatment Given to the Main Victims of the JCO Accident after Initial Treatment in NIRS and Lessons Learned in Medical Aspects

1. Worker A

Initial symptoms and treatment

Worker A developed nausea, vomiting and a transient loss of consciousness for 20-30 seconds, and diarrhea within 1 h. On admission to NIRS, he was febrile without any evidence of infection, slightly drowsy and his systolic blood pressure was 70 mmHg. He also had diffuse erythema on his body surface, facial edema, injection of the conjunctiva bulbi and painful bilateral parotid swelling. He complained of diffuse tenderness of the abdominal wall by palpation and difficulty in voiding. These findings indicated that he was exposed to high dose of radiation, comparable with the victims of prior accidents with fatal outcome.

Bone marrow was aspirated from the sternum and iliac crest on day 1 and showed marked hypo-cellularity in both the erythroid and myeloid lineages. The myelogram of the smear from the sternum was as follows: myeloblast 1 %; promyelocyte 1 %; myelocyte 3.6 %; metamyelocyte 4 %; band 32.4 %; segmented 54.4 %; eosinophil 1.4 %; monocyte 0.8 %; lymphocyte 1 %; and plasma cell 0.2 %. Some cells had intranuclear vacuolations, which was also reported in previous accidents. Granulocyte colony-stimulating factor (G-CSF) was administered intravenously on the evening of day 1. Shortly after G-CSF was administered intravenously, the patient complained of mild dyspnea and systemic rash. The symptoms resolved after inhaled oxygen concentration was increased to 50 %. The patient's facial edema slightly improved on day 2. However, he complained of painful forearm swelling on the right on day 2, which subsequently became severer. Although the patient continued to have watery diarrhea and complained of diffuse abdominal tenderness, he was apparently well on days 1 and 2, suggesting that he was at the latent phase of acute radiation syndrome.

White blood cells (WBC) of Worker A increased on day 2, then rapidly decreased and almost reaches zero by day 7. Lymphocytes kept decreasing and disappeared on day 3. The number of platelets also decreased steeply, necessitating platelet transfusion starting from day 5. The hemoglobin concentration was rather elevated initially, possibly reflecting concentration of blood, but then decreased rather steeply by day 7. From the preliminary dose estimation based on his symptoms and signs, the recovery of the bone marrow was judged to be quite unlikely. Therefore on day 2 it was decided to treat the patient with hematopoietic stem cell transplantation and to transfer him to the University of Tokyo Hospital.

Treatment at the University of Tokyo Hospital

The patient was transferred to the University of Tokyo Hospital on day 2. Upon his admission to the University of Tokyo Hospital, his vital signs were relatively stable, except for a body temperature of 37.3 °C. His face, upper torso, and upper extremities were reddish and swollen. He complained of a diffuse abdominal pain and of tenderness and pain in the right arm. Otherwise, physical and neurological examinations were essentially normal. He was placed under sterile conditions in the intensive care unit (ICU). On day 7 and 8, the peripheral blood stem cells (PBSCT) were transplanted from a family member with the identical HLA. On day 17, a marrow biopsy showed that the transplanted cells had been engrafted. However, he needed transfusions of over 4,000 ml per day. Hypoxemia that was attributable to pulmonary edema advanced, and on day 10, endotracheal intubation and artificial ventilation were introduced.

For the first 3 weeks, the major problems were bone marrow suppression and respiratory complications. These conditions were managed by PBSCT, vigorous infection control, and appropriate respiratory care. After 3 weeks, progressive, generalized skin loss and gastrointestinal injuries manifested themselves, and caused massive body fluid and blood loss. Infection prophylaxis was carried out (i.e., sterile environment; administration of antibiotics, antifungal, and antiviral agents; and selective digestive tract decontamination). Tacrolimus and methotrexate were used for graft versus host disease (GVHD) prophylaxis. Additionally, hematopoietic growth factors such as G-CSF, erythropoietin (EPO), and thrombopoietin (TPO) and blood components were administered as needed. Respiratory failure caused by pulmonary edema progressed. Pentoxifylline and vitamin E were administered intravenously throughout the course to prevent radiation lung injury. The skin of highly irradiated areas, such as the right forearm and anterior chest, was swollen and stated to form blisters within 2 weeks.

The skin damage was serious throughout the body. From day 2l to cardiac arrest on day 58, massive effusion and also bleeding from the skin and GI were the main problems. Appearance of sequential skin changes (beginning with erythema, desquamation, blister formation, and excoriation) was apparently dose dependent. The major portion of the body except for the back revealed complete loss of the dermal component. The amount of body fluid lost from the skin ranged from 2000 to 4500 mL/day. Repeated upper and 1ower gastrointestinal tract endoscopies demonstrated a mucosal-integrity loss similar to the skin loss. Accordingly, meticulous fluid management was necessary. Despite the repeated use of cultured allogenic skin grafts and pharmacological intervention, the effusion from the skin and gastrointestinal bleeding continued to increase.

On day 58, an unexpected cardiopulmonary arrest caused by hypoxia occurred from which the patient was resuscitated. Following cardiac arrest, his course became quite turbulent, complicated with renal shutdown, liver failure, pulmonary failure, hemophagocytic syndrome, and finally hemodynamic instability. The patient died of multiple organ failure on day 83.

Autopsy

The major autopsy findings include marked atrophy and degeneration of striated muscles of the extremities and torso, marked hypoplasia of the bone marrow with predominant immature cells, loss of intestinal, esophageal, and tracheal epithelium, and lung edema.

2. Worker B

Initial symptoms and treatment

Worker B also experienced nausea and vomiting within1 h of exposure, but had no early diarrhea. Although his blood pressure was normal on the day of the accident, his blood pressure was rather low for the next several days (lowest recorded 80/44 mmHg). The patient was slightly drowsy, febrile, had erythema on his body surface and salivary gland swelling, and complained of mild epigastralgia on admission. These findings indicated that he would also undergo a severe form of ARS, although to a lesser magnitude than Worker A.

Bone marrow aspirates from the sternum and iliac crest on day 1 were markedly hypocellular with some intranuclear vacuolations. The myelogram of the smear from the sternum was as follows: promyelocyte 0.4 %; myelocyte 2.2 %; metamyelocyte 2.0 %; band 32.4 %; segmented 58 %; eosinophil 1.2 %; lymphocyte 2.2 %; and phagocyte 1.6 %. G-CSF was started on day 1. This worker also exhibited systemic rash after the infusion. The number of leucocytes slightly increased on day 2, almost plateaued on day 3 and then rapidly decreased and almost reached zero by day 7. Lymphocytes also rapidly decreased and disappeared on day 7. His platelet number and hemoglobin concentration decreased rather gradually. As he might exhibit severe skin injury and gastrointestinal injury soon, the medical staffs reached a conclusion that it should be more beneficial than detrimental to support his leukopenic period with hematopoietic stem cell transplantation.

Treatment at the Institute of Medical Science, University of Tokyo

He was transferred to the Institute of Medical Science, University of Tokyo on day 5 to receive umbilical cord blood transplantation. The graft initially took, and then was gradually replaced by his own hematopoietic cells. The patient also had edema in the right forearm in the first several days, and later evolved severe skin lesions involving the large part of his body surface, in particular the face and extremities. Although the skin injury was extensively treated with grafts, he later evolved gastrointestinal bleeding and infectious complications. As described above, the dose estimation suggested that the patient was likely to suffer severe bone marrow failure. The patient received cord-blood stem cell transplantation. On day 7, the number of peripheral lymphocytes reached zero, and cord-blood stem cells were transplanted into the patient on day 10. Cytokines were also applied, such as G-CSF, GM-CSF (granulocyte and macrophage colony stimulating factor), TPO, and EPO. The transplanted stem cells were engrafted, but the residual marrow of the patient was still functioning. Cyclosporin-A and methy1predniso1one were used for GVHD prophylaxis. His own bone marrow eventually recovered about 2 months later. During this period, there existed stable mixed chimerism between donor cells and recipient ce1ls. Despite recovery of his bone marrow function, T-cell subset abnormality was observed; there were increased numbers of naive T cells and helper T-cell subtype 1, but the mitogenic responses of T cells and the allogeneic mixed leukocyte reaction were severely suppressed. Moreover, endogenous immunoglobulin production remained low until 120 days after the accident. Thus, he was immunologically deficient and needed a sterile environment. On day 153, the patient suffered a complication of pneumonia by methicillin-resistant Staphylococcus aureus (MRSA), causing respiratory insufficiency and leading to acute respiratory distress syndrome (ARDS). Secondary to radiation-induced oropharyngeal mucosal damage, he developed obstructive sleep apnea syndrome. His infectious complications included cytomegalo virus (CMV) infection.

Bleeding from the GI tract also started on day 145 and did not stop until his death. On day 194, the patient was transferred to the Hospital of the University of Tokyo. He eventuallydeveloped refractory respiratory failure and died of multi organ failure on day 211.

Treatment of skin injury

The emergency medical staff of the Kyorin University, as well as the staff of the Institute of Medical Sciences, organized to support the radiation burn treatment and intensive care throughout the period of the treatments. Radiation burns such as redness and blistering were observed on the hands, face, and legs from the fourth week, slowly worsened during the subsequent two months, and caused the exfoliation of 67 % of the skin by day 70, which corresponded to a Class II burn. Therefore, skin graft was performed on the lesions that were considered unlikely to cure by themselves: the forearms and the lower legs. On day 80, allograft was performed on the forearm lesions of a Class IId burn (15 %). On day 88, moreover, his own autograft, which had been cultured and provided by the Tokai University Hospital, was taken on the lower leg sections of a Class IId burn (20 %). Both the allografts and autografts engrafted successfully (over 90 %), and notably improved his general statsus. On day 120, autograft was transplanted on the face, which almost entirely covered the wound in one month. Thus, a series of skin grafts was undertaken to cover the face, hands, and feet with allografts and autografts, with evidence of engraftment until his death. However, the most notable finding in his skin was progressive fibrosis, beginning about 3 months after exposure; strong fibrosis and sclerosis appeared throughout the body during the subsequent sub-acute period.

Autopsy

The autopsy findings showed marked generation of collagen fibers of the dermis, marked atrophy of striated muscles of extremities and torso, hypocellular bone marrow, segmental distribution of multiple erosions of the gastrointestinal tract, and various presentations of organized pneumonia with bleeding and neutrophil infiltration.

3. Worker C

Initial symptoms and signs

When the criticality accident occurred, Worker C was sitting in the corridor with a thin wall screening the precipitation tank. After Workers A and B were evacuated, Worker C remained at the site for approximately five minutes trying to make emergency calls and looked into the precipitation room several times. Since he was walking around, he was likely to have been relatively uniformly exposed.

When he arrived at the NIRS, Worker C felt no prodromal symptoms except a little nausea when he was on a helicopter. Dose estimation at NIRS based on initial symptoms and signs of Worker C suggested that his bone marrow might be able to recover. Therefore, he remained at the hospital of the NIRS and was treated without hematopoietic stem cell transplantation. The bone marrow aspirates from the sternum and iliac crest on day 1 showed decreased erythroid series and well preserved myeloid series. The myelogram of the smear from the sternum was as follows: myeloblast 0.4 %; promyelocyte 2.8 %; myelocyte 5.2 %; metamyelocyte 4.6 %; band 17.3 %;segmented 32.6 %; eosinophil 3.4 %; monocyte 1.8 %; lymphocyte 17.2 %; plasma cell 1 %; phagocyte 0.4 %; basophilic normoblast 1 %; polychromatic normoblast 5 %; and orthochromatic normoblast 6.8 %. Some morphologically abnormal megakaryocytes were also seen. The patient's leucocyte count returned to normal on day 1, then increased in response to G-CSF, which was started on the evening of day 2.

Treatment at NIRS

Numbers of neutrophils then started to decrease and reached a nadir on day 20. The patient was kept under reverse isolation during his neutropenia. Following the recovery of the neutrophil count, G-CSF was reduced and eventually discontinued on day 28. The decrease in platelet numbers was slower than that of the other two patients, but necessitated platelet transfusion on days 17, 20 and 23. The number of lymphocytes was lowest on day 2 and also made a slow recovery. The concentration of hemoglobin slowly decreased without any evidence of bleeding. He did not show any complications such as serious infection. During admission he showed spotty epilation as well as marked diminution in the growth of beard. In addition, he had a localized painless defect of the oral mucosa without awareness, which was pointed out on day 19. These symptoms were presumed to have been caused by irradiation and improved gradually. He steadily recovered and left the hospital on day 82. The cooperation of an ophthalmologist, dermatologist, and circulatory system and diabetes specialists from the Chiba University, and a dentist from the Tokyo Dental University. The patient receives periodical counseling by a psychiatrist from the Chiba University.

4. Lessons learned

Criticality accidents are rare. There have been more than 60 criticality accidents from 1945 through 2000; 18 fatalities were involved. Because of this rarity, there are few reports describing details in pathology of the severe ARS, particularly that caused by neutrons. The clinical manifestation of various symptoms and signs observed in these 3 workers in the Tokaimura were quite different from prior experiences. Depending on the absorbed dose, symptoms appear within minutes/hours to weeks, following a predictable clinical course. The latent phase is a short period characterized by improvement of symptoms, as the person appears to have recovered. This effect is transient. The latent phase was thought to lack in the high dose exposure such as over than 8 GyEq. However, the latent phase was observed on day 2 in Worker A. The other thing to be particularly noted in this case was the onset of gastrointestinal injury. An exposure to over 10 GyEq should have caused the injuries of the GI tract to appear four to five days after exposure. Upon exposure to around 20 GyEq, massive diarrhea did not occur until day 26; this is well beyond the cellular turnover of the intestinal epithelium. The endoscopic biopsies of the upper (four times) and lower (six times) digestive tract showed findings similar to a regeneration of the mucous of the upper digestive tract. Thus, experience of this accident showed important findings in ARS.

Until the Tokaimura accident, there has been no consensus regarding the treatment strategy of bone marrow injury caused by radiation. Unlike therapeutic whole body radiation, radiation in the accidental exposure is heterogeneously delivered, indicating the presence of functional residual hematopoiesis; autologous hematopoietic recovery is possible. Experiences of prior radiation accidents suggest that the role of hematopoietic stem cell transplantation (HSCT), especially bone marrow transplantation, is limited. In the Tokaimura accident, one of victims exposed to approximately 10 GyEq of neutrons and γ-rays received an HLA-DRB1, mismatched, unrelated umbilical cord blood transplant. Donor/recipient mixed chimerism was attained and this victim had autologous hematopoietic recovery, indicating that this HSCT might play a role as “a bridge” to autologous recovery. However, he had persistent and profound immune deficiency and died of multi-organ failure on 211 days. In victims of very high doses including Worker A in the Tokaimura accident, probably over 12 GyEq, serious radiation injuries to regions other than bone marrow, such as lungs, gastrointestinal tract and skin, increases the risk of fatal multi-organ failure, even if bone marrow has been successfully controlled. Since treatment of these organs is not established, the prognosis of these victims is very poor.

The radiation level causing irreversible failure of bone marrow is not clear. There are reports on the auto-recovery of bone marrow in patients exceeding 10 GyEq but not 12 GyEq. As described above, there is also a problem to be resolved in recovered bone marrow, and the mechanisms are not clear. On the other hand, limited success of an allogeneic HSCT may lead to damage to other organ systems such as the lungs and the gastrointestinal tract. An early transplant can lead to severe graft versus host disease (GVHD) that victims cannot tolerate. Thus, a treatment strategy for bone marrow is an issue calling for extensive and far-reaching discussion. Recently, the European Group for Blood and Marrow Transplantation (EBMT) has proposed a treatment strategy for bone marrow injury by radiation. They reached a consensus that HSCT should not be performed on any radiation accident victim with the potential of endogenous hematopoietic recovery. Since autologous hematopoietic recovery could occur in most accidents with less than 12 GyEq, whether or not to perform HSCT is not an emergency decision, and it requires careful consideration of the possible risks involved. Furthermore, patients with multi-organ dysfunction syndrome (MODS) might not tolerate early transplant due to their co-morbidities. EBMT also suggests that the transplantation itself should not be carried out before a minimum observation period of 14 to 21 days had elapsed. On the other hand, the US Strategic National Stockpile Working Group recently proposed a limited dose range for which HSCT should be considered a therapeutic option for victims in a large-volume scenario. They recommended that for relatively low doses (2-4 GyEq), endogenous recovery of autologous hematopoiesis can be expected, but victims receiving higher doses (6-10 GyEq) may require allogeneic hematopoietic cell support from peripheral blood or cord blood. This group also suggested that the use of donor cells is sufficient for survival from acute hematopoietic syndrome associated with these higher doses of radiation. Therefore, the immediate needs of such patients (recovery of myelopoiesis) can be supported by the transient engraftment of donor cells; it would be possible to perform stem cell transplantation as “a bridge to autologous recovery”.

General lessons learned regarding medical response to the accident are provided at the subsection of 11.2.6. in the main body.

5. Discussion

There are few reports in the literature on radiation accidents describing the nature of the pathophysiology that may be necessary for treatment of heavily irradiated patients. This is probably because there are almost no case reports on the long survival of such victims. It is clear that these patients really need prolonged multidisciplinary intensive care under sterile environments. The high-level intensive care requires a tremendous amount of human and material resources, a problem that also needs to be addressed in planning the medical response to radiological accidents.

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ACRONYMS

AEB : Atomic Energy Bureau
AESJ : Atomic Energy Society of Japan
CTB : Conversion Test Building
ETAB : Emergency Technical Advisory Body
GACLC : Government Accident Countermeasure Local Center
IPSN : L'Institut de protection et de sûreté nucléaire
JAERI : Japan Atomic Energy Research Institute
JAPCO : Japan Atomic Power Company
JNC : Japan Nuclear Cycle Development Institute
MEXT : Ministry of Education, Culture, Sports, Science and Technology
MNF : Mitsubishi Nuclear Fuel Co. Ltd.
NFI : Nuclear Fuel Industries Co. Ltd.
NIRS : National Institute of Radiological Sciences
NISA : Nuclear and Industrial Safety Agency
NRPB : National Radiological Protection Board
NSB : Nuclear Safety Bureau
NSC : Nuclear Safety Commission
PNC : Power Reactor and Nuclear Fuel Development Corporation
RERF : Radiation Effects Research Foundation
SMM : Sumitomo Metal Mining Co. Ltd.
STA : Science and Technology Agency

IEU : Intermediately Enriched Uranium
NUCEF : Nuclear Fuel Cycle Safety Engineering Research Facility
STACY : Static Experiment Critical Facility
TRACY : Transient Experiment Critical Facility
UNH : Uranyl nitrate hexahydrate, $UO_2(NO_3)_2\cdot 6H_2O$