JAEA-Technology
2011-004

JAEA-Technology

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March 2011

Japan Atomic Energy Agency

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Supplemental Study on Dose Control for a Criticality Accident

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(Received January 27, 2011)

Tokaimura criticality accident is considered as a precious material for nuclear emergency response study. In the previous report "A Study on Dose Control for JCO Criticality Accident Termination" (JAEA-Technology 2009-043), we discussed how to control the dose received during the termination work of the criticality accident. We reevaluated the dose rate at work place based on the dose rate measurement data ranging around 40 to 100m from the criticality accident point, and compared it with the dose rate calculated based on the worker's dose received. They matched within 60% to 80% accuracy.

In this paper, we focused on the difference of the way in which dose rate attenuates between within 100 m from the source point and beyond 100 m and discussed the validity of using log-log plotting / semi-log plotting of dose rate - distance relation in order to extrapolate the dose rate at work place near the criticality accident point. In addition, we studied on the effect of the number of dose rate measurement data to be used for extrapolation.

We recommend that about 10mSv which is a half of 20mSv annual dose limit should be used as worker's dose control target for the high neutron dose field work to ensure enough safety margin considering the following three points;

1. annual dose limit for workers
2. dose received before
3. measurement error

Keywords: Radiation, Exposure, Disaster, Accident, Criticality, JCO

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事故時線量に関する補足的検討

日本原子力研究開発機構
原子力緊急時支援・研修センター
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(2011 年 1 月 27 日受理)

東海村臨界事故は、原子力の緊急事態に関する対応を検討する貴重な材料と考えられる。これまでに実施した、線量評価及び管理法に関する考察である JAEA-Technology 2009-043「臨界事故終息作業時の線量管理方法の考察」では、臨界事故終息作業時の線量管理方法について考察を行った。その結果、40m 程度から 100m 程度までの近距離の測定結果を基礎に、作業地点の線量率の再評価を行い、個人線量から推定される線量率と比較し 60～80%程度の精度で一致することについて述べた。

本報では、線源から 100m程度までと、それから遠方の距離における放射線の減衰の仕方の違いに着目し、方対数／両対数プロットの妥当性、及びプロット点数の影響について検討した。

その結果、中性子線の高い線量場における作業に対する線量管理のための線量の目安について、①作業者の年間線量限度、②作業者の当該作業以外の線量、③測定誤差、の三点を考慮し、年間 20mSv の 2 分の 1 の 10mSv 程度とすることにより、安全裕度をもって作業できることを確認するとともに、実際の線量管理を行う上での、両対数の利用できる範囲、測定点の数の持つ意味合いについて取りまとめた。

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1. Introduction

The first national field training will be conducted in Ibaraki prefecture for civil protection in 2011. The Tokai-mura nuclear criticality accident is thought to be a valuable material to examine the nuclear emergency measures. In our past report, we have discussed the method of dose control for termination of the nuclear criticality in order to derive useful lessons for the future contingency from the dose control conducted at the 1999 Tokai criticality incident.

In the report, the individual dose of workers estimated before the accident based on the measurements of neutrons and gamma dose dropped to about a fiftieth to ninetieth of the actual dose. So we investigated the probable cause of the lower estimation, and re-assessed the individual dose of workers to plot a preferable method of dose control for termination with the similar future accident in our mind. This report provides further dose review done after the last report, and examines radiation attenuation at two points, one is within a hundred meters from the radial source and the other further than that, to study the validity of the semi-log and log-log method and the impact of the number of plotting points. In addition, with the recent recommendation from ICRP in consideration, dose control methods to be applied to the contingency are examined.

2. Overview of criticality termination and dose revaluation

This section provides the overview of the criticality termination and dose revaluation described in the last report and adds further examination done since then.

The JCO nuclear criticality accident occurred in the conversion test building (hereafter, "conversion building") in the JCO Tokai works on September 30, 1999. (see the document 1, 2, 4, 5, and 11)

The criticality termination was conducted by the workers including JCO operators following the advice given by government experts as well as Nuclear Safety Commission.[1), 5), 11)]. The procedure was divided into the three parts of; 1 taking instant pictures (Polaroid) and preparation, 2. draining, and 3. boron water injection, in order to keep the workers' dose under the limitation. For the dose control, the assessment at the time of picture taking in the first step is most important. The operation was decided to be done in the range of three meters to five meters from the sedimentation tank (hereafter, "radiation source"). The total number of nuclear fission in criticality accident was finally assessed to be 2×10^{18}. [1), 2)]

The radiation protection of the terminating workers was done by controlling the dose under the limitation with safety factor in mind. Specifically, neutrons and gamma dose were measured before the work on which the dose control for the workers was based.

2.1 The first picture-taking and its assessment

The assessment of neutrons and gamma dose was mainly done based on the measurements at the points between 40m and 150m from the conversion building. The first assessment was done under the safety factor of ten times with the anticipated dose in the accident based on the measurements of neutrons and gamma dose. With that amount of safety margins, we expected the operational environment under 100mSv, which turned out to be wrong to have higher value.

In fact, the first group of workers returned in about one minute after they started operation due to the sounding alarm. My Dose Mini (used for neutrons) indicated 111.9 for a worker and 91.2mSv for another. 5). The values finally turned out to be 60.4mSv and 49.3mSv respectively after all, because they needed to be adjusted by the correction factor. [2), 6)] Specifically put, the values were reviewed afterward in terms of the correction factor of 1.85. Then the indication of 111.9mSv for the first group became to be 60.4mSv after divided by 1.85, and for another to be 49.3mSv in the same manner. [2), 6)]

Based on the dose measured for the first group, the dose was controlled for the following groups to be a half of the first one by shortening the working time, which resulted in successful dose control that contained the value to be in the limit for the operation.

2.2 Reviewing the individual dose

The estimated dose based on the measurement of the field dose rate and the measured individual doses of the first group were compared with each other using log-log plotting. For the latter, the values indicated by My Dose Mini measurement for the individual dose and the per-capita figures calculated and assessed from activated Na value indicated by the Whole Body Counter that measured the radiation externally to the body. As for the neutrons, the assessment based on the measurements at three points is shown in Figure 1. The middle line represents the estimated dose from the measured field dose rate, and the upper and lower lines show the range of error. Note that the measured individual dose are within the range. Gamma rays were measured at four points whose results are shown in Figure 2. The circle encloses the measured individual doses. As is seen on the figure, the circle touches the lower line of errors, which proves the validity of the estimated dose of both the neutrons and gamma dose.

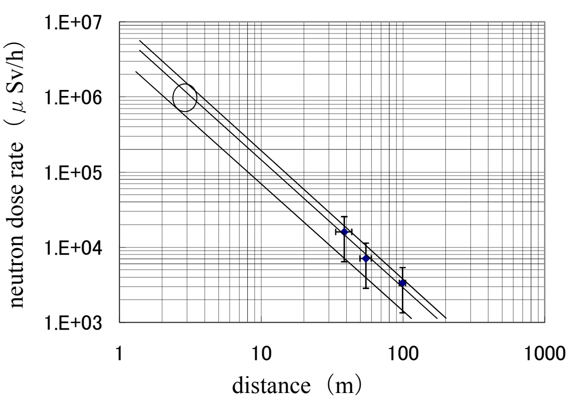


Figure 1. Dose revaluation by the neutrons measured at three points

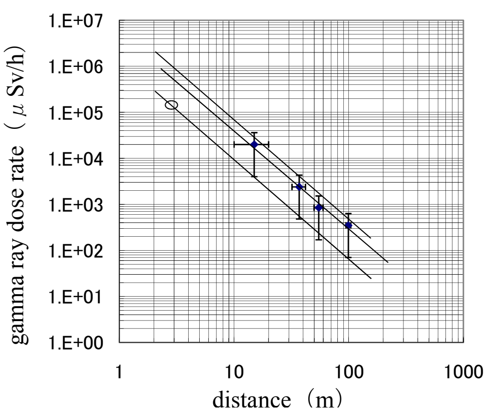


Figure 2. Dose revaluation by gamma dose measured at four points

In short, the past reports could be summarized as follows.

- To estimate the dose at the working place in the planning phase of the criticality termination, dose was measured at five points in the range of 40-150m from the conversion building to be plotted using semi-log graph. Because the result appeared to be quite linear, it was linearly extrapolated to the position of operation to anticipate the neutron dose rate of 18mSv/h.
- The measurements after the operation showed the average 550mSv for neutron dose rate with about 1500mSv/h at maximum, which revealed the value some ten times higher than the initial estimates,
- Afterward, of the five pre-operational measurements, the three points closest to the operational site (those within the distance between about 40 m and 100 m; note that the value for the closest point was replaced with the one obtained by another team) were picked up to be linearly extrapolated using log-log plotting. That procedure gave the figure of 550 to 1500mSv/h (adjusted by errors), which was almost the same value measured after the operation.

3. Dose evaluation method for the area within the range of about 100m from radiation source

This report provides consideration on the validity of semi-log and log-log plotting and the impact of the number of plotting points used for dose evaluation at the termination work place, which has not been assessed in the former report.

3.1 Validity of semi-log and log-log plotting

Figure 3 shows the dose measurements and distance from the conversion building, and fitting curves that are composed of the attenuation terms of absorption and scatters by air, and inverse-square of distance (excerpted from the reference 3). As seen in the figure, these curves properly represents the trend of the measured data.

The figure is a semi-log graph presenting the dose rate in logarithmic scale and the distance in linear scale. Note that the line representing 300m and less is convex slightly downward, while the segment representing the distance further than that is linear.

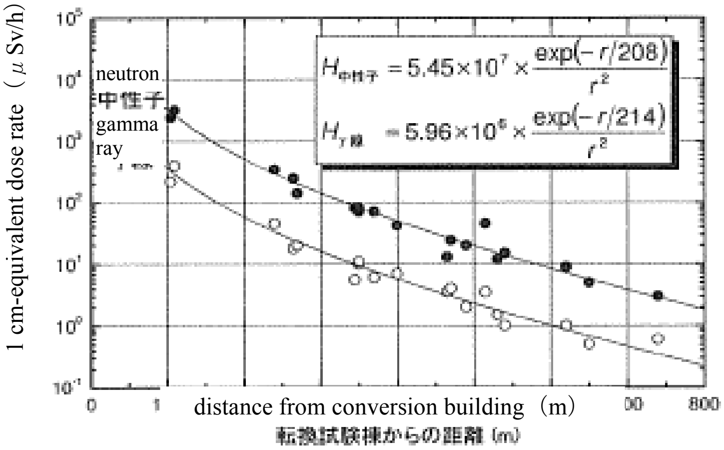
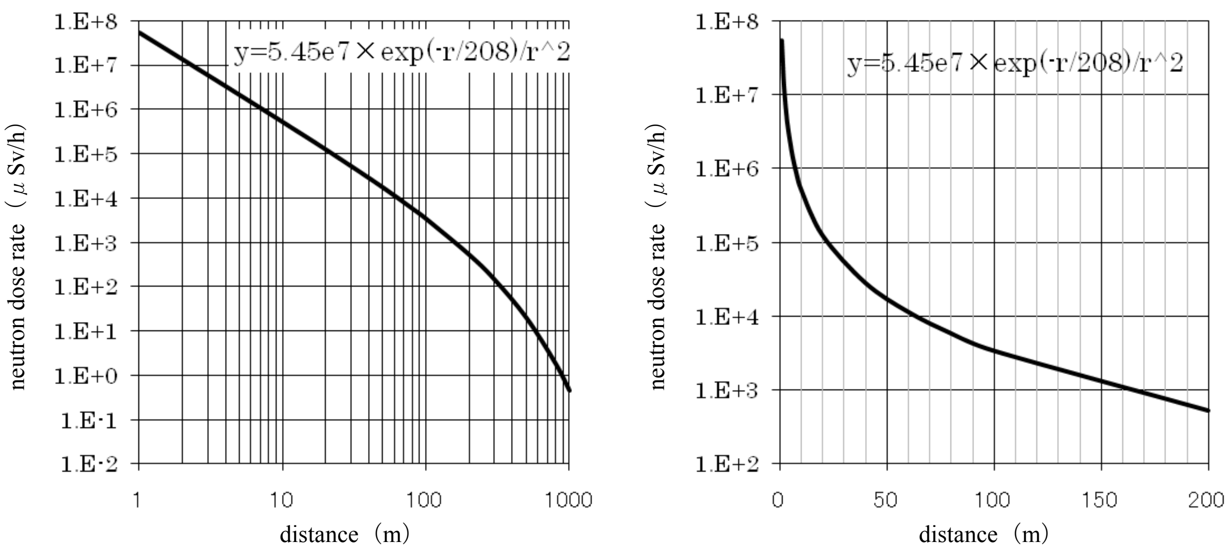


Figure 3　The relationship between distance and dose rate at a stable state of JCO criticality accident [3)]
(Fitting curve and the data measured at 12:45, September 30th)

For better understanding, the fitting curve of the neutron dose rate in Figure 3 is shown in log-log and semi-log graphs in Figure 4. The log-log plotting shows linearity at the points within about 100m, while the semi-log graph presents the linearity for the points further than that.



(1)log-log graph　　　　(2)semi-log graph

Figure 4　Semi-log and log-log graph showing the relationship between distance and neutron fluence rate

Figure 5 shows the logarithmic contribution of 1) the attenuation term of inverse-square distance ($1/r^2$) and 2) the attenuation term of absorption and scattering by air (exp (-r/208)) indicated in Figure 4. As is shown, the term 1) is the key factor, even at the 200 m point where (log(r) = about 2.3, the term 2) contributes far less than 1).

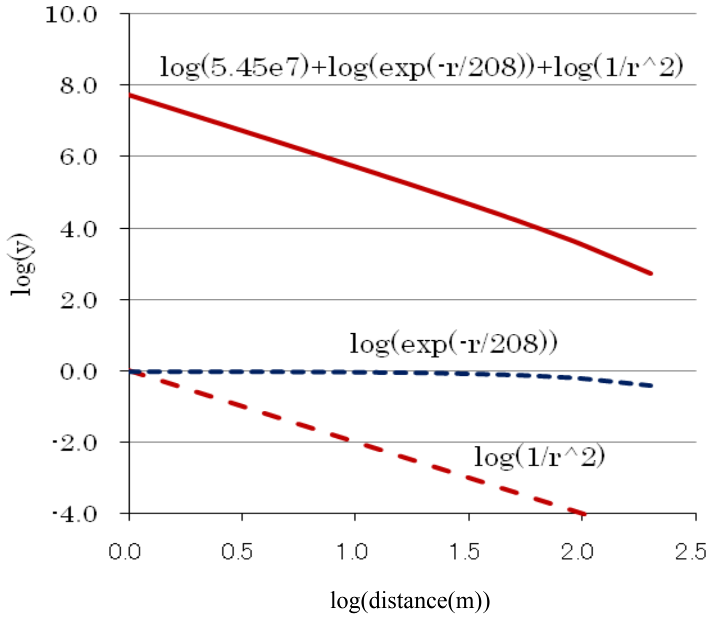


Figure 5 Contribution of each term in the fitting curve

Consequently, when the dose rate near the radiation source has to be extrapolated using measurement data of relatively distant points (more than 10m) from the source, log-log plotting should be applied instead of semi-log plotting which may result in significant underestimation. Naturally, getting measurement data of the points closer to the source is preferable. Also as shown in Figure 4 (1), if the measurements of the points 100m or beyond are the only available data, log-log extrapolation to the source position would result in overestimation by order, which indicates that at least two points within 100m are preferred to be available.

3.2 Impact of plotting points and measurement data

Table 1 shows the neutron dose rates available in the criticality termination planning phase. These values are measured by the same working team using the same type of instruments (survey meters) to reduce measurement variation. The datum of 10mSv/h at 38.5m, the nearest to the working place is full scale value of the instrument but the real value is supposed to be somewhat more than it . Additional measurement of 16mSv/h was taken by another team using REM counter. In the criticality termination planning phase, it was thought that the data measured by the same team using the same instruments were more reliable than otherwise, so 10mSv/h was used.

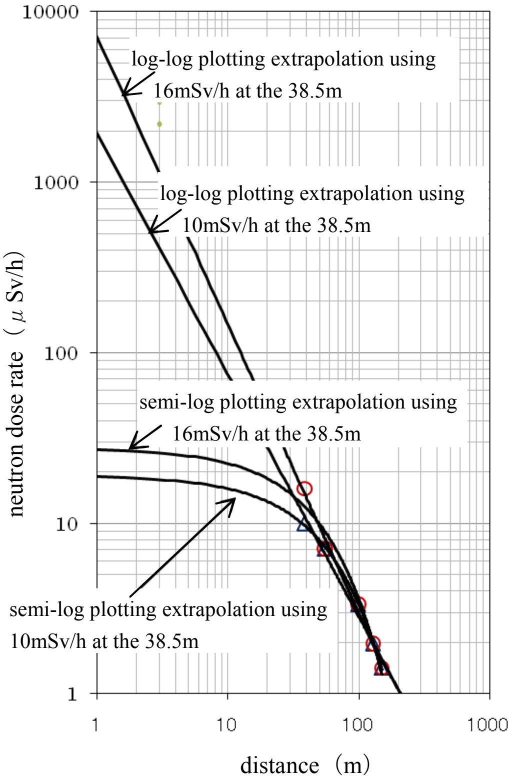
Table 1 Neutron dose rate in the criticality termination planning phase

Distance (m)	Neutron dose rate (mSv/h)
150	1.42
129	1.97
99.2	3.35
55	7.1
38.5	10 (first measurement) 16 (additional measurement)

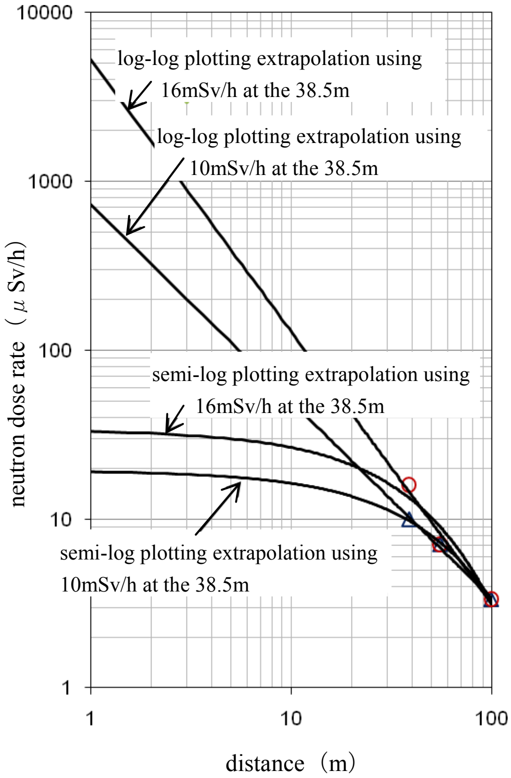
Figure 6 shows the fitting lines made from semi-log and log-log plotting using the five data measured in the criticality termination planning phase, and the fitting lines using the nearest three data of the five (one case with the first measurement data and the other case with additional measurement data). Because the figures are shown on log-log graph, the lines of semi-log plotting are curved.

The dose rates at 3 m extrapolated using fitting lines in Figure 6 are shown in Table 2. The findings obtained from Figure 6 and Table 2 are provided below.

- If linear extrapolation on log-log plotting is used, the dose rate at 3 m is about 200-400mSv/h when the first measurement data is used, and about 900-1100mSv/h when the additional measurement data is used. The latter gives closer value to the actually measured data (average 550mSv/h, max 1500mSv/h).
- When the additional measurement data (16mSv/h) which is considered to be more accurate is adopted, the difference between the evaluated value using the nearest three data and the value using the five data was about 20%, while the difference between the value using the first measurement data and the value using the additional one for the closest point to the radiation source, was three to four times. This suggests that, in view point of dose rate evaluation, it is more important to use the value deemed more accurate, than to reduce the plotting number of measurement data to the nearest three. Also, in the sense of pursuing safer value, the choice of the additional measurement of higher value could have been significant.
- In contrast, the linear extrapolation on semi-log plotting results in significant underestimation.
  However, the semi-log plotting using the first measurements of 10mSv/h which was actually used in the criticality termination planning phase (Figure 7), happened to be fall on a vary linear line by coincidence, as if implying the justification of the approach. (In Figure 7, 10mSv/h is plotted at 33.5m. This distance is an estimated one at the time of the planning phase. After that, the distance was revised to 38.5m.) If the additional measurements (16mSv/h) were plotted (indicated by ★ mark in Figure 7), doubts might have been raised.about the validity of linear extrapolation on semi-log plotting.



(1)Derived from the values for the five points



(2) Derived from the values for the three points

Figure 6 Semi-log and log-log extrapolation based on the dose rates measured in the criticality termination planning phase

Table 2 Neutron dose rate at 3m derived from semi-log and log-log fitting

(mSv/h)

Method of extrapolation	Fittings by five points	Fittings by three points	Actual measurement
Log-log plotting (38.5m point: 16mSv/h)	1116	899	550 on average 1500 max.
Log-log plotting (38.5m point: 10mSv/h)	410	202	
Semi-log plotting (38.5m point: 16mSv/h)	26	31	
Semi-log plotting (38.5m point: 10mSv/h)	18	18	

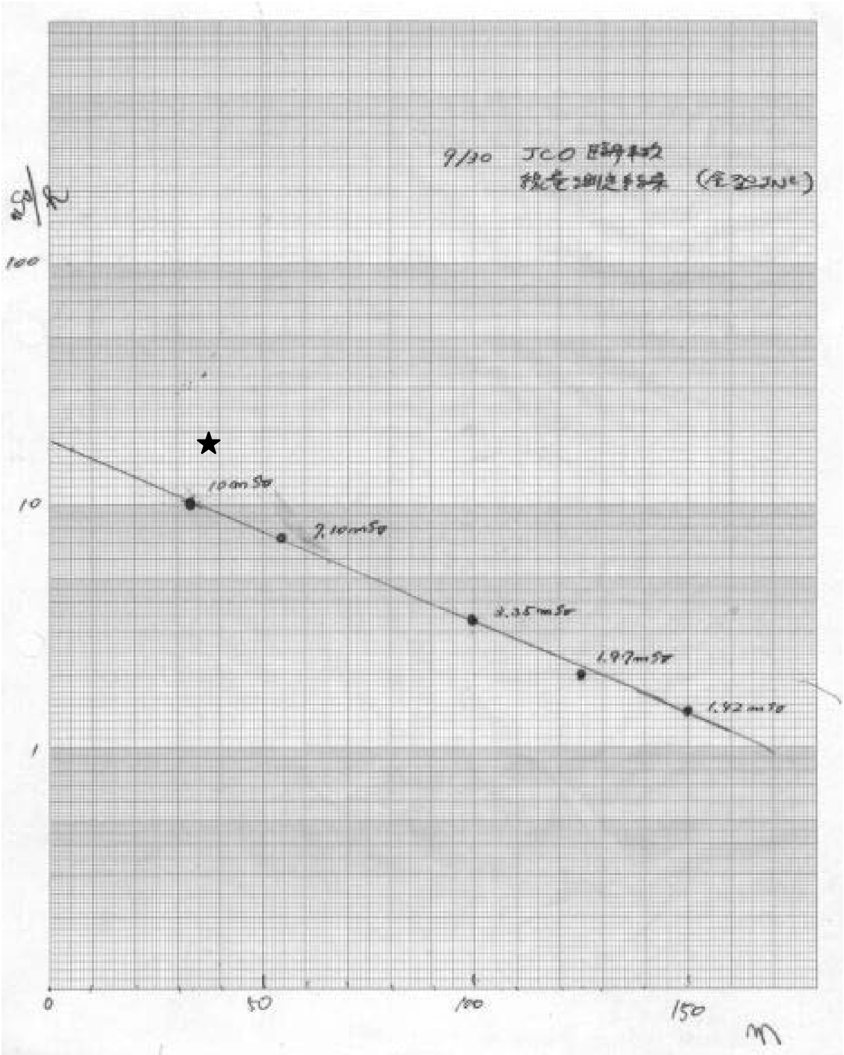


Figure 7 Original neutron measurement plotting

(★ represents the plotting of 16mSv/h at 38.5 m.)

3.3. Importance of the work planning and its readjustment for dose control

So far, the cause that brought the insufficient dose evaluation for the criticality termination work was discussed in detail. However, the safety of radiation-related work is not secured only by dose evaluation. In fact, the work plan based on the initial dose evaluation composed of multiple controls including use of safety factor to be multiplied the evaluated dose, appropriate work time control, use of dose meters with alarm function. The result of the first operation brought the recognition that the dose rate at work place exceeded the initial evaluation considerably. This was incorporated into and reflected in the following planning. Finally, the exposure resulted in being within the planed value.

4. The amount of dose to which disaster prevention service men are exposed

The main recommendations given by ICRP in relation with the amount of dose to which disaster prevention service men are exposed are mentioned below. ICRP Publication 26, recommendations by ICRP in 1977, marked the three concepts of justification, optimization, and dose control, as a basis of normal radiological protection. For a time of contingency, it stated, the necessary intervention must be made by government to lower the dose. Following the 1984 recommendations, ICRP Recommendation 1990 (Publication 60) succeeded. The existing Japanese laws are basically in accordance with the ICRP 1990 recommendations. Publication 60 also pursued justified intervention and optimized benefit at the time of accident. The following Publication 63 additionally mentioned intervention to the public, which was adopted in many countries including Japan.

The latest recommendation is Publication 103 in 2007, which also discuss emergency exposure. Publication 103 introduced the concept of projected dose and residual dose, in which a reference level of 20mSv-100mSv was presented to be used for justification and optimization. Whether Japan incorporates this into the national law is remained to be discussed in the future.

Taking into the consideration both the ICRP recommendations and the idea of radiological protection in the report from IAEA, the radiological protection at the disaster prevention service in the current phase should be managed in accordance with the laws shown below and the guideline of Nuclear Safety Commission.

① Main dose limitations applied to radiation workers stipulated in the Nuclear Reactor Regulation Law and the Radiation Hazard Prevention Act, among others, are shown below.

Limit of dose rate	100mSv/5 years in the effective dose 50mSv/year Crystalline lenses of eyes: 150mSv/year in equivalent dose Skin: 500mSv/year in equivalent dose
Limit of dose rate for emergency practice	100mSv in effective dose Crystalline lenses of eyes: 300mSv in equivalent dose Skin: 1mSv in equivalent dose

② To facilitate smoother implementation of disaster-prevention practices for nuclear facilities, Nuclear Safety Commission prepared a document called "Regulatory Guide: Emergency Preparedness for Nuclear Facilities," in which the following guidelines on the radiation dose were provided.

Disaster prevention service men who are engaged in disaster emergency response and disaster recovery	50mSv at most in effective dose

Of the disaster prevention service men, those who are engaged in on-site emergency operations (for instance, the staff except radiation workers in the applicable nuclear industries, experts dispatched by the government, law enforcement people, fire fighters, SDF personnel, and emergency medical persons, among others), emergency preparedness extension, saving life, and performing other emergency related duties that are indispensable to the operation	100mSv at most in effective dose Crystalline lenses of eyes: 300mSv in equivalent dose Skin: 1mSv in equivalent dose

※Definition of disaster prevention service men

Disaster prevention service men include those people who are engaged in emergency preparedness response such as public announcement and instruction transmission for the neighbors, evacuation of residents, traffic arrangement, radiation monitoring, medical treatments, and measures to prevent the development of disastrous situation in nuclear facilities, as well as those who works for disaster recovery by activities including removal of radio-contaminant etc.

The regulation of nuclear power plants and the Emergency Preparedness guideline stipulates a dose of 100mSv for the workers involved in disaster prevention as well as for operators in emergency. So far in Japan, this limit was applied only to the nuclear accident in Tokai-mura. Therefore, the Tokai case should be taken into account as an example to review the actual limit application.

5. Summary

5.1 In view of dose and its measurement method in the operation planning phase

In the operation planning for the field with high neutron fluence such as criticality termination place, accurate dose estimation for the practice becomes critical. However, pursuing more accurate projection contradicts with reduction of the measurement workers' exposure. Based on the experience in the JCO nuclear criticality accident, dose control for the measurement workers needs to be considered with the following three factors: annual dose limit specified in the applicable law, exposure of a particular worker out of the work concerned, and measurement error. This indicates a reference of 10mSv a year, a half of 20mSv, may ensure safe operation with margin. As for the measurements for projection, three to five points not significantly affected by shielding and scattering should be selected for measurement, using a reference of 30-100 m in distance and 20-5mSv/h in dose rate. The number of measurement points, on the other hand, the following reports of both accuracy and exposure should be taken into consideration to review the number.

5.2 Discussion on the number of measurement points and the scope of application of log-log plotting

The former report concluded that, using log-log plotting for the three measurement points, all the measurements were within the error and the method was adequate in terms of exposure rate. However, for the future operation planning, which of the logarithm, semi-log or log-log, should be employed for different rate of dose and scattering rate was discussed. Based on the analysis of measurement points in the past report, it could be said that they are roughly linear in log-log plotting within 100m, while beyond that threshold they are linear in semi-log. The analysis indicates that linear semi-log extrapolation using the points further than 200m would result in significant underestimation.

As for the number of points to be measured, there is approximately 20 percent difference between three and five. This indicates at least two measurement points are needed and the values should be accurate. Consequently, the above discussion should be taken into account to comprehensively optimize and justify the dose rate.

In the case of the Tokai criticality accident, the reflection of the measurements in the first operation on the subsequent dose control for the operators worked effectively. Therefore, what is deemed important for the operation control in the aftermath of accidents is not only the dose rate projection but also continual evaluation in the operation to utilize the outcome in the subsequent practices to achieve appropriate dose control.

5.3 Dose limit

The former report estimated, although without actual measurement data, the dose as about 10mSv in total for the prior radiation measurement, which was a mere fraction of the dose in the actual operation, . This value is within the national limit mentioned above. This also could be a reference for the target dose to be established for the future operations of the same type.

Finally, in response to the specific needs from field operations, optimization, justification, and reduction of dose rate should be discussed in detail with the latest international trend in mind.

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国際単位系（SI）

表１．SI 基本単位

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

表２．基本単位を用いて表されるSI組立単位の例

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

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

表３．固有の名称と記号で表されるSI組立単位

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

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

表４．単位の中に固有の名称と記号を含むSI組立単位の例

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

表５．SI 接頭語

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

表６．SIに属さないが、SIと併用される単位

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

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

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

表８．SIに属さないが、SIと併用されるその他の単位

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

表９．固有の名称をもつCGS組立単位

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

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

表10．SIに属さないその他の単位の例

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

（第8版，2006年改訂）