A Study on Dose Evaluation for Tokaimura Criticality Accident Termination

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JAEA-Technology

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Verification of dose control method for Tokaimura JCO criticality accident was performed. Personal dose estimation for Tokaimura criticality accident termination was performed based on measurements of neutron and gamma ray doses taken before the work commenced, but the personal dose for the workers as a result of the termination work was found to be approximately 50 times higher than the previous estimation in which the dose rate at the work point was estimated by the extrapolation of semi-log plot of the distance - dose rate relation.

For this report, we reevaluated doses based on the extrapolation of log-log plot of the distance vs. dose-rate relation using close range measurements from 40 meters to 100 meters, and the results were found to match personal doses with an accuracy of between 60-80%. Therefore, the work can likely be done safely by taking into account three factors - [1] annual dose limits for workers, [2] dose to the workers from sources other than the pertinent work, [3] measurement error - and adopting 10mSv, or 1/2 of the annual value of 20mSv, as a dose guideline for tasks such as dose evaluation in dose fields with high levels of neutron radiation. It is also in accordance with the ICRP recommendations.

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臨界事故終息作業時の線量評価方法の考察

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　　1999 年 9 月、東海村の JCO 臨界事故の終息作業を行うに当たり、事前に中性子線とガンマ線の測定を行い、作業計画を立案したが、作業の結果作業員の線量は、沈殿槽近傍で事前評価の約 50 倍程度となった。本報告書では、始めに、事前評価が約 50 分の 1 の評価となった原因を探り、その原因に対する考察を行った。さらに、同様な臨界事故が発生した場合の、放射線の事前評価方法について報告する。

　　臨界事故時の線量測定に当たっては、レムカウンタによる測定など、手法は妥当なものであった。しかし、臨界発生地点と測定地点の間に、コンクリート等水分を含む建材を使用した建物・構造物がある場合、中性子線・ガンマ線は、遮蔽あるいは散乱しその比率も変化する。特に、距離が 100m 程度以上の遠距離データの取り扱いには注意を要する。臨界事故時には、作業地点の線量予測をする際に 100m より遠い地点の線量測定値を含めたことに加え、距離−線量率の関係を semi-log プロットして外挿して予測を行ったため、臨界事故地点近傍の線量予測が低い値となった。本報では、臨界発生場所から、建築物等による、遮蔽・散乱の殆どない 40m 程度から 100m 程度までの近距離の測定結果を基礎に log-log プロットの外挿により線量を評価した。その結果、測定値として 20mSv/h から、3mSv/h 程度まで、3〜4 点測定値を用い、60〜80%程度の精度で作業者の線量を事前に予測することができることがわかった。

　　臨界事故の終息作業のような、中性子線の高い線量場（作業者が場合によっては 100mSv 程度の線量を想定）における作業においては、線量予測等のための線量の目安は、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 3 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、安全裕度を持って作業できるものと考えられる。

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Contents

目 次

List of Figures

図リスト

1. Introduction

The importance of the 3 Ss（Safety, Security, Safeguard）was proposed by the Toyako summit held in 2008. In Japan with the upcoming restart of Monju and the beginning of operations by the Rokkasho Reprocessing Plant, there is an urgent need to develop countermeasures for criticality accidents during manufacturing of nuclear fuel. Unfortunately, lessons to improve future responses have not really been drawn from the results of dose estimation during the Tokaimura criticality accident of 1999.

At the time of the Tokaimura criticality accident, a termination work plan was formulated by measuring neutron and gamma radiation beforehand, but when the work was actually done, the personal doses of workers was approximately 50 times greater than the dose estimation. Our objectives in this report were: 1. Investigate the reasons why the prior assessment was 1/50th the size of the actual result, 2. Reevaluate the dose of individual workers by changing dose rate estimation method from semi-log plot to log-log plot of the distance vs. dose-rate relation using close range dose measurements, where factors such as shielding and scattering have little effect, 3. Consider better dose control methods for accident termination in case of similar criticality accidents.

2. Outline of the criticality accident

Criticality accident occurred on September 30th, 1999, at 10:35 am, at the JCO conversion test facility building which was in the operation for the re-conversion of enriched uranium.

The workers had been using the powdered uranium (U3O8), which is 18.8 percent enriched-uranium; the workers dissolved them in the stainless steel container into uranium nitrate solution, concentration of about 370gU / l. This work has been done by three workers. At 10:35, the 7th a solution in a stainless steel container was poured into the precipitation tank and the solution exceeded the critical mass limit of solution for uranium nitrate lead to the criticality accident.

The precipitation tank (referred to below as the "radiation source") was not geometrically safe for criticality. So criticality accidents would occur if much more than the criticality mass was poured. The total number of fissions during the criticality accident was estimated to be 2 x 10^{18}.

161 Residents within a range of 350 meters from the criticality tank were evacuated. Around 310, 000 residents within a 10km range were asked by the governor not to leave their homes. The two workers who received doses of 16 ~ 25GyEq and 6 ~ 9GyEq died. Another worker whose dose was estimated to be between 2 ~ 3GyEq is still living. This accident was rated as level 5 on INES scale. For details, please see references 1, 2 and 5.

3. Overview of criticality termination

The workers stood by in an administrative building near the front gate of the JCO Tokai site, and carried out the termination work by rushing to the back side of the conversion building located on the left side approximately 300 meters into the site in Fig. 1. The termination work was performed in three stages: [1] Polaroid photography and preparation, [2] water drainage, and [3] addition of boron solution. Within the overall work process, dose evaluation in the first stage of Polaroid photography was the most important measurement for properly

conducting subsequent dose control. The area where the work was conducted was determined to be about 3-5 meters from the radiation source.[1), 2), 3), 4)]

4. Concept of dose control

Dose control should cover the termination work of the accident and the radiation monitoring conducted prior to the termination work. The basic concept was prepared based on the ICRP recommendations and Japanese regulations.

The ICRP recommendations refer not only from the viewpoint of radiation protection but also from social and economic aspects. In this case, the decision should only consider the radiation protection aspect.

Based on the Japanese regulations, the radiation dose limit for employees is 50mSv and the dose limit for emergency exposure situations is 100mSv.

In fact, it seemed difficult to manage doses under 50mSv, so doses up to 100mSv were considered acceptable.

This concept of dose objectives had been discussed between Dr. Sumita and a Nuclear Safety Commission member. Dr. Sumita negotiated with the Nuclear Safety Commission by telephone and agreed with the Commission on the concept. [12)]

However, if in case only 100mSv is goal and it could thought to be exceeded and 50mSv had been taken as tentative dose control limit. In this case, the benefit is a reduction in the public dose and in the dose of the workers. The dose risk would only be to the workers who engaged in the termination work. Both justification and optimization were considered. As a result, the work was determined to be justified and would contribute to the reducing the dose to local residents. Optimization could be achieved through the dose reduction of the workers.

5. Examination of radiation protection during the work planning stage

To provide radiation protection for the workers during the termination work, neutron and gamma radiation were measured beforehand, and dose estimations were performed based on the results. First, we shall describe dose measurements and estimations in the work planning stage. Then, we shall discuss the doses actually received in the first round of the work carried out.

We also reevaluated the neutron dose based on close range measurements from 40 meters to 100 meters, and examined factors such as doses, measurement methods, and the n/γ ratio for the workers in the process of performing the termination work. Since this report is limited to the evaluation of external dose estimations during criticality accident termination, and focuses on the evaluation of actual dose levels in the radiation field. The discussion shall be presented in terms of 1 cm dose equivalent rates.

Dosimetry in the work planning stage

Neutron radiation was measured with rem counters, which are regarded as having low error rates over a wide

energy range. Measurements on the day of the accident were conducted by two measurement teams using two types of instruments; a rem counter made by Fuji Electric and a rem counter made by Studsvik.

Fig. 1 shows the JCO site and the dosimetry points. In long range measurements i.e. greater than 250 meters, there was some variation due to buildings, topography and other factors, but on the whole, the dose tended to attenuate with distance.[1), 2), 3), 4)] With close range measurements, on the other hand, there were large variation due to shielding and scattering caused by buildings, structures and so on.[3)] Therefore, to reduce this variation, evaluation was done by measuring from a direction with no heavy shielding etc. More specifically, measurement points were limited to an axis approaching the radiation source, and evaluation focused on measurements from approximately 150 meters to 40 meters collected by the same measurement teams using the same instruments. Fig. 1 shows the position of the 5 original measurement points ([1] to [5]-1) and measurement data for each point is presented in the Table in Fig. 1.

Fig. 2 shows the plotting of this data on a semi-log graph from the work planning stage at the time of the accident. The points almost form a straight line, and extrapolation indicated a neutron dose rate at the radiation source of about 18 mSv/h. The results of additional measurements [3), 6)] are shown as [5]-2 and [6] in Fig. 1. The neutron radiation measurement at point [5]-2 was obtained using a rem counter made by Studsvik, and the measurement results are indicated by ([5]-2) in the Table[7)]. The results of gamma ray measurement at point [6] are shown in the Table entry for [6].

6. Personal dose control based on the work plan and preliminary measurement results

The work plan

It was decided to perform the termination work in the following stages: [1] Polaroid photography and preparation, [2] water drainage, and [3] addition of boron solution. Within the overall work process, dose measurements in the first stage of Polaroid photography were most important for properly conducting subsequent dose control. It was decided to consider a range from 3-5 meters for the termination work. A minimum distance of 3 meters to ensures radiation protection.

Dose estimation from radiation dosimetry of the field

Neutron radiation was measured using two types of neutron moderating rem counters, the NSN10014 made by Fuji Electric[Note 1)] and the 2202D made by Studsvik.[Note 2)] Gamma rays were measured using an ICS-313 ionization chamber survey meter made by Aloka.[Note 3)] Two types of personal dosemeters were used: the PDM-303 My-Dose Mini made by Aloka (for neutrons)[Note 4)] and the PDM-102 My-Dose Mini made by Aloka (for gamma rays, with alarm).[Note 5)] Both of these instruments were calibrated in a standard neutron or gamma radiation field.

Dose estimations at the time of the criticality accident were based on a neutron dose rate of 18 mSv/h at the radiation source, indicated by Fig. 2, and two plans[6),7)] were considered. Both plans incorporated a safety factor of about 10 times. Since a safety margin of at least 10 times was incorporated into estimations prior to the first round

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Note 1): Measurement range 0.1 μSv/h to 9.999 mSv/h, Reading error ±20%; Note 2): Measurement range 10 μSv/h to 100 mSv/h, Reading error ±10%; Note 3): Measurement range 1 μSv/h to 300 mSv/h, Reading error ±10%; Note 4): Measurement range 0.01 to 99.99 mSv, Reading error ±40%; Note 5: Measurement range 0.001 to 99.99 mSv, Reading error ±10%]

of work (based on Fig. 2), it was determined that the termination work could be conducted below 100 mSv, with an adequate safety margin.

Results of the first Polaroid photography

For dose control during the work, it was decided to use both the work time control and pocket dosemeter alarms. In terms of time control, the workers were limited to 3 minutes of work, and in terms of dose control, they were told to turn back if their My-Dose Mini alarms (set to 5mSv for neutron radiation) sounded. They were also told to come back when the work was finished, regardless of their alarm status. In the end, the first team of workers turned back because their alarms sounded approximately 1 minute after starting the work. The neutron My-Dose Mini of one worker showed a reading of 111.9mSv. Another worker showed a reading of 91.2 mSv.[6] (This fact shows that there was a discrepancy of about 50 to 90 times in the approach to anticipating the safety margin.[10]) Therefore dose control for the work teams was modified to provide a greater level of safety in the second and subsequent rounds of the work. It was decided to shorten the work time control to 2 minutes[6]. Also, the alarm setting was changed to 2mSv for gamma rays.

7. Discussion of personal dose evaluation

Evaluation of error in dosimetry values

Possible sources of error in this series of measurements were: [1] error related to any nonuniformity in the critical state inside the radiation source, and [2] error due to shielding, scattering, energy characteristic changes or other phenomena occurring due to the separation between the radiation source and the measurement point, and the various buildings and structures between the two.

Evaluation after the criticality accident showed that the My-Dose Mini correction coefficient[3,7] for neutrons was 1.85. When divided by this correction coefficient, the 111.9mSv reading from the neutron My-Dose Mini of the worker in the first team is adjusted to 60.4mSv, and the reading of 91.2mSv for the other worker is adjusted to 49.3 mSv.[3,7]

There are a number of other potential sources of error. [1] For neutron radiation, instrument error and systematic error by the measurer were evaluated to include rem counter reading error of ±20% and personal dosemeter reading error of ±40% for an overall minimum error of ±60%. [2] Error in measurement position identification was evaluated to be 3.5 meters at the 35 m point, and approximately 5 meters at the 15 m point. Errors relating to the work location of the worker are likely to be the greatest contributor to distance error. [3] The person performing the work management determined the departure and return times of the work teams using an ordinary clock, and thus the work time measurements may each include about one minute of error. [4] Other factors, such as skyshine effects due to increasing distance, are also conceivable sources of error in dose measurement.

Reconstruction of personal doses

Here we compare the dose estimations derived from the results of measuring dose rates in the dose field with the personal dose measurements from the first Polaroid photography team and the dosimetry values from actual workers. For the latter, we use [1] the dosimetry results for individuals based on My-Dose Mini, and [2] the results from calculating doses for each individual based on the ^{24}Na radio-activation value measured externally for each

worker using a whole body counter.

We examined several samples taken from the criticality accident. A log-log graph should have been used to extrapolate the vicinity dose values from the distance -dose-rate relation using measurement data. Fig. 2 is a semi-log graph. In order to indicate dose rates in the field, we used a log-log graph. Fig. 3 plots values for neutron radiation measurement data for points [3], [4] and [5]-2 in Fig. 1. All points are within 100 meters of the radiation source and are unlikely to be affected by shielding or scattering. Fig. 3 also shows the line extrapolated to the vicinity (0-3 meters) of the radiation source, and the measurement errors. Fig. 4 is another log-log graph showing gamma ray measurement data for points [3] to [6] inclusive. As shown in Fig. 1, there is nothing that would have any considerable shielding or scattering effect on the straight line of measurement points between the radiation source and the 100 meter point. In Fig. 3 and Fig. 4, distance error is ±5 meters. Dose rate error for neutrons is ±60% (probably the minimum value for error). The error range for gamma rays is ±80% and takes into account error due to changes in the n/γ ratio and directional characteristics etc.

First, we consider evaluations based on the dose rates in the neutron radiation field. If we assume the worst case scenario, i.e., that work was conducted for 3 minutes at the 3 meter point, then the error range from Fig. 3 is 0.55-1.5 Sv/h. Determining the maximum and minimum personal dose over 3 minutes from these values, we find that 1/20th of the value for 1 hour is 28-75mSv. In comparison, [1] the reevaluated neutron dose values of the neutron My-Dose Mini for the first team of workers were, 49.3mSv and 60.4mSv respectively, and [2] the doses derived from the ^{24}Na method were, 69mSv and 79mSv respectively. These values almost correspond to the error range of evaluation values determined by the dose rates in the field.

Now we will consider evaluations of gamma rays. The range of error in extrapolated values evaluated using the survey meter was 0.15-1Sv/h from Fig. 4. Assuming the same conditions used for neutron radiation, the personal dose range would be between 7.5-50mSv. In comparison, the measurement values of the My-Dose Mini personal dosemeters of the first team of workers were 7.15mSv and 7.87mSv. These values are almost found in the lower limits of the error range.

The n/γ ratio was 9.6:1 at the 99.2 meter point, and 8.4:1 at the 55 meter point. At the 38.5 meter point, the neutron dose reading was 16mSv, and the ratio was 6.7:1. The average n/γ ratio for the longer range was 9:1.[1), 2), 3)] In comparison, the n/γ ratio determined from neutron and gamma My-Dose Mini measurements for the workers in the first team was 7.3:1. This is a reasonable range if we take into account the error ranges for the respective measurements.

8. Conclusion

Dose to the workers during criticality termination

To ensure data reliability, dose estimation for the worker dose control on the day of the criticality accident was carried out based on measurements by the same measurement team, using the same instruments over a comparatively long range and plotted on a semi-log graph. As a result, the dose rate in the vicinity of the radiation source was estimated to be 18mSv/h. However, this estimation was approximately 50-90 times too lower the actual the dose rate.

In this study, on the other hand, we decided to use the measurement point data closer to the radiation source.

There are likely to be almost no effects, due to shielding, buildings and so on, between the measurement points and the radiation source. More specifically, we plotted data taken from 3 points within an approximate 100 meter range (mainly ranging from 20-40 meters) on a log-log graph. We then reevaluated doses assuming the worst case scenario for radiation protection, i.e., the maximum work time of 3 minutes, at the minimum distance of 3 meters to the radiation source. The results showed that doses almost matched the error range for both the values measured by the My-Dose Mini, and the values determined based on the ^{24}Na measurements.

Although it is not an actual value, if we assume that work time was about 1 hour in total, and that each measurement was performed for around 20 minutes (to estimate dose levels on the high side), then the doses received during radiation measurement prior to the termination work would be about 5.3mSv at the 39 meter point, about 2.3mSv at the 55 meter point, and about 1.1mSv at the 99 meter point. The total is somewhat less than 10mSv, or around 1/2 to 1/4 of the dose during actual the termination work.

Dose and measurement approach during a work planning

When planning a work in a dose field with high levels of neutron radiation, such as termination of a criticality accident, it is crucial to accurately estimate the dose during a work. However, there is a conflict between achieving more accurate dose estimation, and minimizing the dose to workers involved in dosimetry.

Emergency exposure situations of ICRP recommendations should be applied. In this case, 100mSv, 50mSv dose limits are the temporary management objectives. Justification of the whole termination work brought great benefits. Optimization is achieved by minimizing the doses.

Based on the work experience during the Tokaimura criticality accident, three points must be considered regarding dose control for workers involved in dose estimation: [1] annual dose limits prescribed by law, [2] doses received by workers from sources other than the pertinent task, and [3] possible measurement error in the management of the total doses.

Therefore, a work can likely be done safely by setting a dose of 10mSv, which is about half of the annual value of 20mSv, as a guideline. A work time can be realistically set to 1 hour. For measurements to estimate dose, we believe that 3-4 points with little shielding and scattering should be selected, within a distance of 30-100 m and a dose rate of roughly 5-20mSv/h. Under the appropriate dose control conditions termination work may be carried out reasonably safely.

Acknowledgements

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On-road gamma and neutron measurement data

Location	Distance m	Neutron mSv/h	Gamma mSv/h
On-road [1]	150	1.42	0.1
On-road [2]	129	1.97	0.2
On-road [3]	99.2	3.35	0.35
On-road [4]	55	7.1	0.85
On-road [5]-1	38.5	10	2.4
On-road [5]-2	38.5	16	2.4
On-road [6]	15	20	20
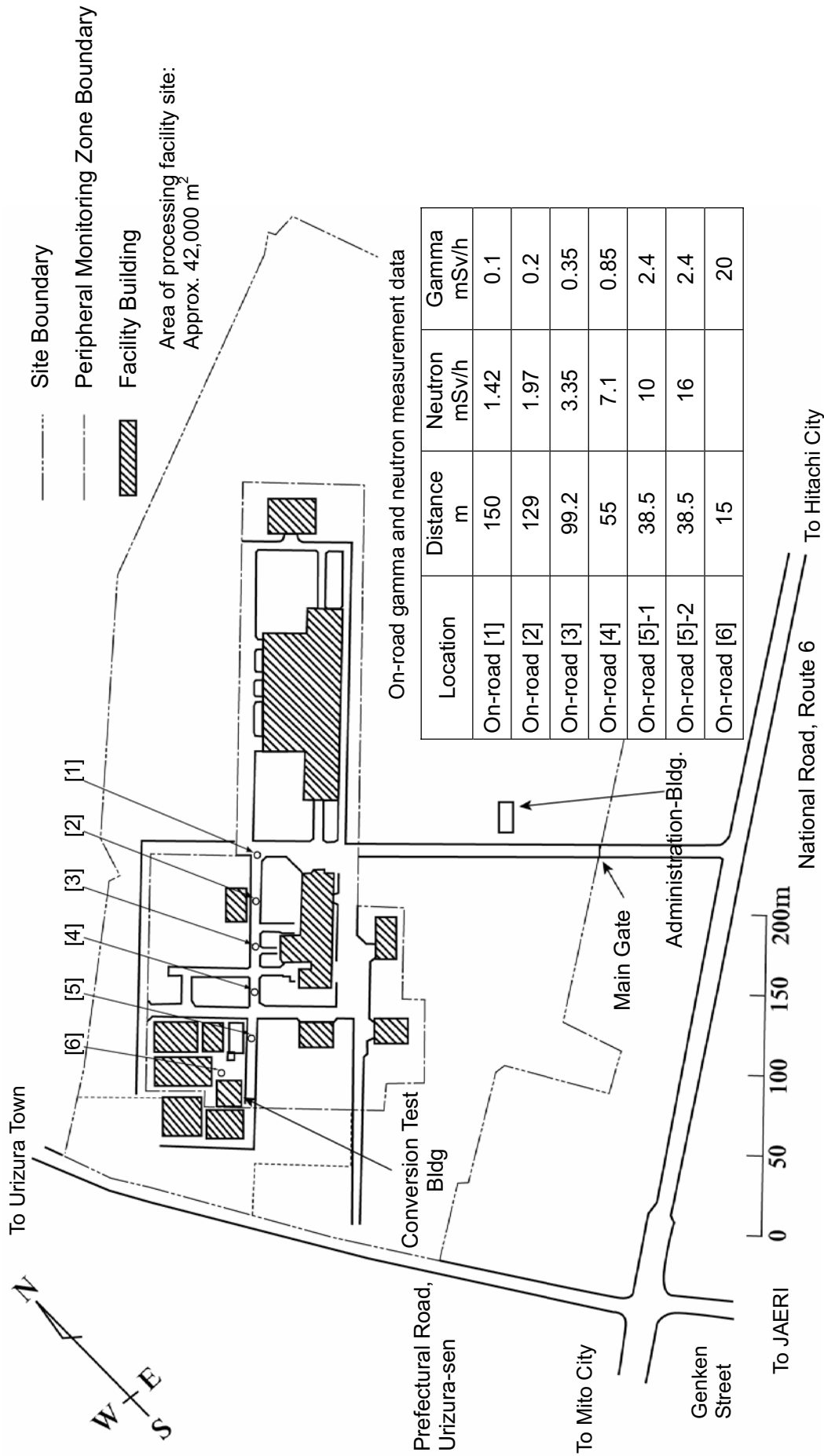
Fig. 1: Additional neutron and gamma measurement points and results

Results of dose rate measurement during JCO criticality accident on Sept. 30
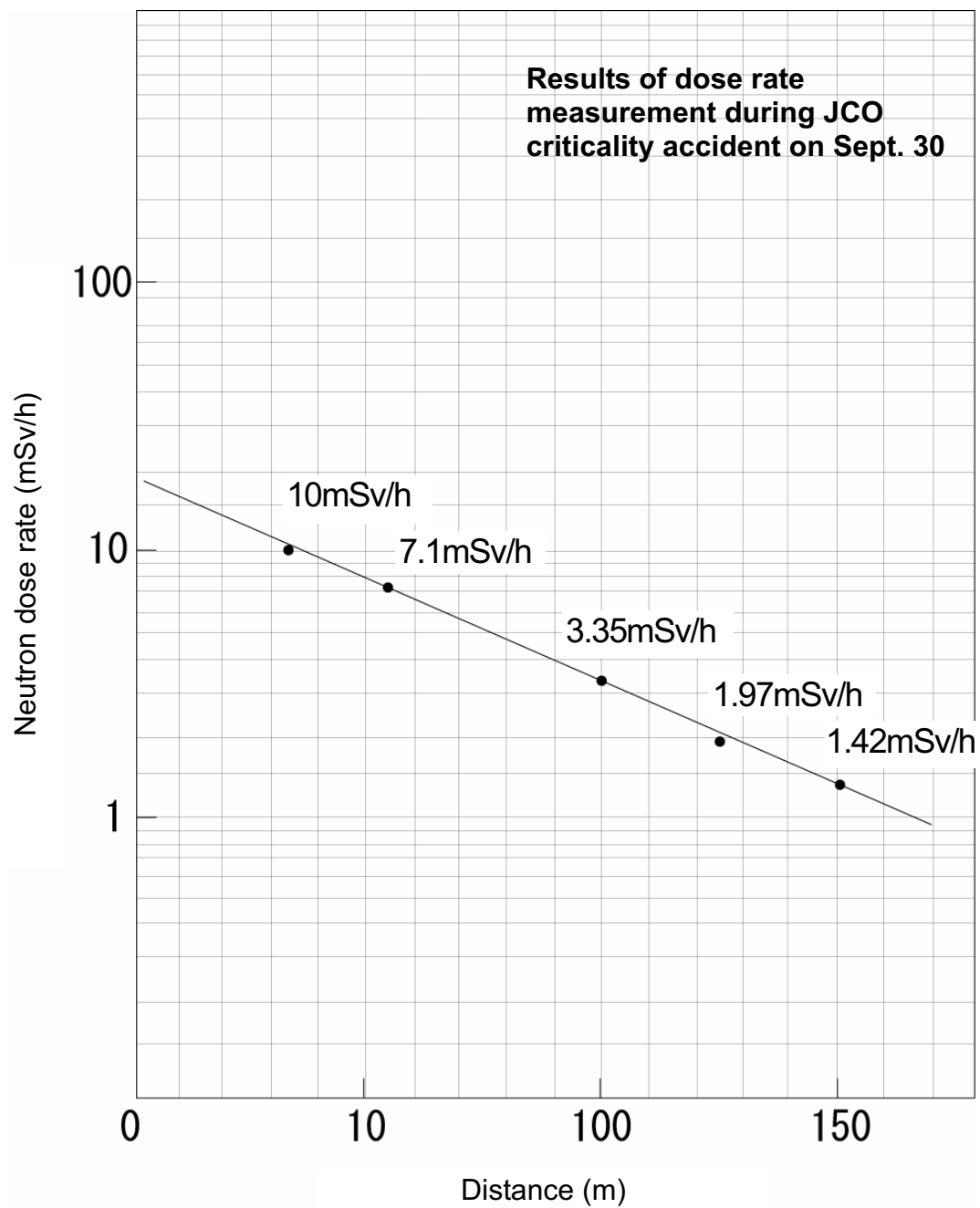
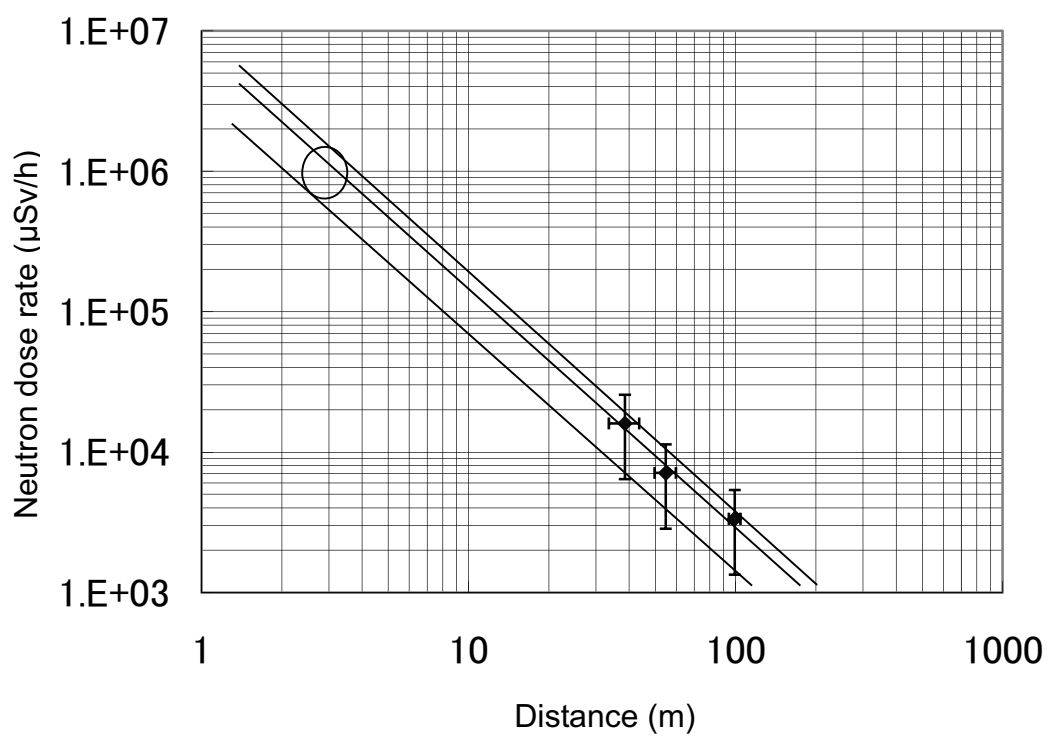Fig. 2: Plot of neutron dose rate
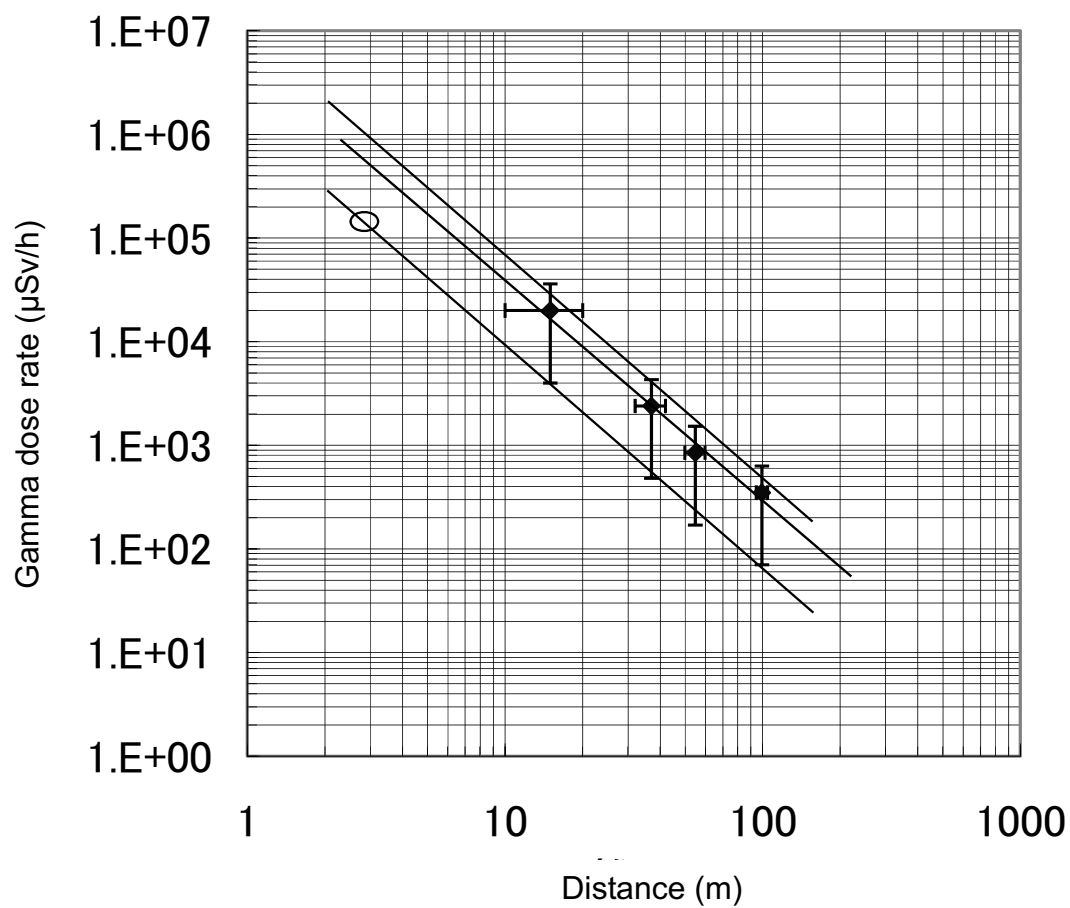
Fig. 3: Reevaluation of neutron dose using 3 measurement points

Fig. 4: Reevaluation of gamma dose using 4 measurement points

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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	$1L=11=1dm^3=10^3cm^3=10^{-3}m^3$
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	$1eV=1.602\ 176\ 53(14)×10^{-19}J$
ダ　ル　ト　ン	Da	$1Da=1.660\ 538\ 86(28)×10^{-27}kg$
統一原子質量単位	u	1u=1 Da
天　文　単　位	ua	$1ua=1.495\ 978\ 706\ 91(6)×10^{11}m$

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	
ベ　　　ル	B	SI単位との数値的な関係は、対数量の定義に依存。
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	$1\ Oe ≙ (10^3/4π)A\ m^{-1}$

(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	$1\ Ci=3.7×10^{10}Bq$
レ　ン　ト　ゲ　ン	R	$1\ R=2.58×10^{-4}C/kg$
ラ　　　ド	rad	$1\ rad=1cGy=10^{-2}Gy$
レ　　　ム	rem	$1\ rem=1\ cSv=10^{-2}Sv$
ガ　ン　マ	γ	$1\ γ=1\ nT=10-9T$
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	$1\ μ =1μm=10^{-6}m$

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